

Instrumented Compliant Wrist System for Enhanced Robotic Interaction

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Abstract

This thesis presents the development of an instrumented compliant wrist mechanism which serves as an interface between robotic platforms and their environments in order to detect surface positions and orientations. Although inspired by similar existing devices, additional features such as non-contact distance estimations, a simplified physical structure, and wireless operation were incorporated into the design. The primary role envisioned for this mechanism was for enabling robotic manipulators to perform surface following tasks prior to contact as this was one requirement of a larger project involving inspection of surfaces. The information produced by the compliant wrist system can be used to guide robotic devices in their workspace by providing real-time proximity detection and collision detection of objects.

Compliance in robotic devices has attracted the attention of many researchers due to the multitude of benefits it offers. In the scope of this work, the main advantage of compliance is that it allows rigid structures to come into contact with possibly fragile objects. Combined with instrumentation for detecting the deflections produced by this compliance, closed-loop control can be achieved, increasing the number of viable applications for an initially open-loop system.

Custom fabrication of a prototype device was completed to physically test operation of the designed system. The prototype incorporates a microcontroller to govern the internal operations of the device such as sensor data collection and processing. By performing many computation tasks directly on the device, robotic controllers are able to dedicate more of their time to more important tasks such as path planning and object avoidance by using the pre-conditioned compliant device data.

Extensive work has also gone into the refinement of sensor signals coming from the key infrared distance measurement sensors used in the device. A calibration procedure was developed to decrease inter-sensor variability due to the method of manufacturing of these sensors. Noise reduction in the signals is achieved via a digital filtering process.

The evaluation of the performance of the device is achieved through the collection of a large amount of sensor data for use in characterisation of the sensor and overall system behavior. This comes in the form of a statistical analysis of the sensor outputs to determine signal stability and accuracy. Additionally, the operation of the device is validated by its integration onto a manipulator robot and incorporating the data generated into the robot's control loop.

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Chapter 1. Introduction

1.1 Motivation

In recent years the role of modern robots has taken on a very different form than that of their early predecessors which rapidly gained popularity in manufacturing because of their quick, continuous and accurate operation in inhospitable or hazardous industrial environments. While the latter could be easily programmed to perform repetitive tasks with a high degree of precision, as they benefited from structured environments and very few, if any, unknown variables, modern robots must deal with more complex scenarios.

With advances in control theory and electronics, the possible applications for which robots are now being considered are innumerable. However an area which has attracted many researchers' attention is the operation of robots in unstructured environments. Unstructured environments are those in which little to no a priori knowledge of the workspace is available. Some examples of such workspaces are those where objects are not necessarily fixed in any particular orientation or position and may have unknown properties such as compressibility or mechanical degrees of freedom. Another example of such a workspace, which truly poses additional challenges, is when there are people present and most likely will either come into contact or be in close proximity to the robots.

Working with robotic manipulators in such unstructured environments can raise safety concerns especially in situations where human-robot interactions and the handling of fragile materials are a possibility. The vast majority of robotic manipulators currently in use in manufacturing tend to be designed in order to meet very specific requirements for repeatability in order to ensure the highest possible product quality. The need for repeatability however directly influences the mechanical structure of the robot leading to a very rigid frame and regularly requires heavy components to prevent small disturbances from the interaction with objects to cause large deviations from the desired pose that we wish to achieve with these robots. The weight and rigidity of these robots are the major concerns when humans are involved since there is an increased risk of injury if unwanted collisions between the robot and a person do occur. But since this type of robot structure is already so prominent, they represent a significant investment in terms of design and fabrication costs which should be leveraged for future research or for attempting to meet the requirements of new applications for robotics.

With these factors in mind as well as the consideration of the requirements for applications related to unstructured environments, research was conducted in order to determine how existing robotic platforms could be enhanced without making any significant changes to their fundamental building blocks such as their joint structures or their actuation mechanisms. Taking inspiration from how humans interact with their environment, it was determined that compliance was a key aspect required for any object manipulation tasks. Compliance allows for unforeseen contact with objects with a much lower risk of damage or injury. However, compliance in itself tends to affect the resulting pose of a robot and provisions are required to sense these changes in order to maintain accurate positioning. By doing so, we effectively provide a complex sense of touch to a robotic manipulator. Humans, along with their sense of touch, are also easily able to combine information gathered by their vision in order to help with pose estimation, surface following, or object manipulation, which are common tasks required of robots. Therefore, in order to further increase the adaptability of a robotic platform, some form of vision should also be incorporated. Although vision systems have been widely researched and integrated into robotic platforms, they tend to require a great deal of computational power in order to extract any meaningful information about an object's position or orientation. To prevent the need of sophisticated algorithms and vision sensors, a simpler alternative is required to extract the more pertinent information relating to object manipulation which is essentially the object's location and orientation. By providing a robot controller with such information, a proper approach plan can be formulated prior to initial contact with an object thereby reducing the risks of damage resulting from inappropriate contact.

This thesis presents the development of a sensing device capable of meeting these three major requirements, namely compliance, and a means of detecting the position and orientation of objects in close proximity as well as those in direct physical contact with the device. We refer to this sensing device as an instrumented compliant wrist which is meant to serve, in the case of manipulator robots, as an un-actuated end-effector attachment to be placed at the end of a serial linkage chain. The research which led to the conception of this device is first presented followed by a detailed explanation of the system's mechanical assembly and its overall operation, as well as its experimental characterization and validation.

1.2 Objectives

The objectives of the research conducted was to address some of the key issues with existing robotic technology while focusing on providing robotic platforms sensory information useful for motion

guidance tasks, namely surface following via pose estimation, and object interaction tasks. In order to achieve this while limiting the need for major structural modifications to a robotic platform or hindering its current range of motion, a self-contained end-effector sensing device proved to be an ideal solution. Some design requirements for the device are stated below.

The sensing device should:

- provide a level of compliance to the existing robotic structure;
- be able to estimate the position and orientation of the surfaces of objects which are contacted by the device;
- be able to estimate the position and orientation of the surfaces of objects without direct physical contact (but in close proximity);
- not impede the existing platform's range of motion;
- be as light as possible to limit the effects of added weight to a platform as well as maintain a useful effective payload;
- provide a simple communication interface to relay sensor data;
- provide simple means of integration.

As such, these requirements led to the following design goals for producing a sensing device to be mounted to robotic platforms.

- Develop a system capable of providing a robot controller with sufficient information to successfully operate both in close proximity with a target object and also maneuver itself while in contact with said object;
- Design a mechanical device that provides compliance characteristics while meeting specific mechanical requirements and remains versatile enough to be adapted to different non-compliant robotic platforms;
- Develop a two-stage sensing system to guide a robotic platform during pre-contact and in-contact phases;
- Implement a simple yet robust communications protocol to efficiently transmit sensory data from compliant device to external controllers of robotic platforms;

- Implement a physical prototype of the device in order to experimentally validate the functionality and accuracy of the resulting design using an industrial robotic manipulator as a test platform;
- Instrument the compliant device to provide accurate real-time position and orientation measurements of the surface with and without direct physical contact;
- Ensure accurate sensing via a calibration protocol and signal processing to minimize measurement errors;
- Derive a physical characterization of the proposed compliant device for operation with a robotic system.

The first of these design goals is the main and encompassing goal for the work conducted herein while those that follow highlight the sub-objectives required to accomplish conception of the overall system.

1.3 Thesis Organization

The following chapters contained in this thesis are organized as follows. Chapter 2 begins with a review of the most commonly used motion control methods and how each of these affects a robot's performance. Following this is a presentation of several implementations of compliant manipulators and their characteristics along with a discussion of the benefits afforded by their particular features. A similar review of more compact devices known as compliant wrists is also included. Finally, this review also provides a comparison of available distance sensing technologies in order to support the current selection of the proximity sensing solution. Chapter 3 provides an overview of a larger project which spurred the development of this particular compliant wrist design and illustrates one of the many situations where such a device can be of crucial value. Chapter 4 provides details of the major components used, and their integration in the final system prototype, while chapter 5 provides an explanation of each task performed by the device to achieve the desired operation. Chapter 6 offers a collection of results for describing the operation of both the individual infrared sensors as well as the overall operation of the compliant wrist prototype once mounted onto a robotic manipulator. Finally, chapter 7 summarizes the major aspects of this research, reiterates the research contributions made throughout the development of the device and provides a discussion of the findings while highlighting possible improvements to explore in the future.

Chapter 2. Literature Review

The development of a new sensing device for robotic platforms capable of meeting the objectives stated previously required an in depth look at the existing technologies used for robot motion guidance. This was done in the hopes of developing a simple device which could easily be integrated onto many different robotic platforms with minimal alterations. A review of the current technologies served not only as a means of learning about the advantages and disadvantages of current solutions but also as a source of inspiration for the resulting solution. Many existing compliant devices were found in literature which ranged from fully compliant robotic manipulators to simple end-effector attachments providing feedback into a robot's control loop. This chapter begins with a survey of different motion control schemes that have been successfully used to guide manipulator robots in an attempt to support the decision made to develop a sensor providing position feedback rather than force or torque feedback. Following this, we present several compliant devices and provide a detailed analysis of their operation. Finally, a comparison of multiple distance sensing technologies is presented since distance measurements were deemed to be the most efficient form of data from which to extract object pose estimations due to the low computational bandwidth required.

2.1 Motion Control

Any time a robot is used to perform a task, a means of controlling its motion is required. The most basic task that a robot can perform is to alter its pose in order to reach a desired position. This requires the application of control signals to each of its actuators in a very specific manner while monitoring the actual position of the robot and attempting to reduce the error between the desired position and the current position. Each control method makes use of different types of feedback information in order to achieve different goals. Using system control theory, the structure of these robot controllers can be modified to incorporate as much or as little information as necessary. These days it is quite rare to find an open loop robot control system due to the inaccuracies of such systems and so some form of feedback is generally available. Feedback serves to provide a robot controller with a measure of the error associated to the current value of a variable with respect to its desired set point. A complete review of control theory is beyond the scope of this thesis however several control schemes that have been successfully implemented are presented in the following sections, all of which incorporate some form of feedback.

2.1.1 Position Control

In a position control scheme, also known as point-to-point, the feedback information that is available can be obtained from a variety of sources [1]. Position control is by far the simplest control method to implement since it relies solely on the single position parameter. PID controllers are very useful in achieving the desired accuracy of a positioning system on an actuator basis. The most intuitive source of this position information is obtained directly from each actuator via encoders or a position transducer such as a potentiometer which describes the current position or motion of that actuator. The term servo motor describes a motor equipped with such means of position sensing in order to form a local closed loop system for that particular motor. However, there exist other methods for obtaining position information. In the case of a manipulator robot, it is often the goal to determine the position of the end-effector. This can be done using the individual joint positions combined with knowledge of the manipulator's forward kinematic model. Another method which has gained popularity is the use of vision systems making use of specialized image processing algorithms to determine the position of a robot's end-effector in a workspace.

2.1.2 Force Control

In this section, several different types of motion control methods are lumped together as they all relate in some way with the forces present during contact between a robotic manipulator and its environment [2], [3]. When forces and contact are involved, the term interaction control is used rather than motion control to highlight this fact. Motion control could only be used for interaction with the environment if all variables were modelled accurately such as the robot's kinematics and dynamics as well as the environment's geometry and mechanical features. A robot itself can be modelled easily enough since it remains relatively constant. However describing an environment can be difficult and is not practical if the environment is to be allowed to vary in any way.

Force control can be divided into two categories each having several interaction methods. The first category is indirect force control, to which compliance control and impedance control belong. These types of interaction relate position errors to contact forces through some form of conversion medium such as mechanical stiffness or impedance which may or may not be adjustable parameters. Compliance control can be further divided into both active and passive strategies [4]. The passive compliance strategy is essentially still a form of motion control however the effects of the compliance allow for the estimation of forces based on known stiffness values of the compliant components. The stiffness of the

environment however can also come into play which can greatly affect the accuracy of the estimated forces if precise information about the environment is not available. Active compliance on the other hand relies on force input sensors, normally located at the joints [5], to simulate compliance via adaptive movements of the robot. Impedance control tends to treat the robot and its environment as a single complete system to be controlled and employs the concept of energy transfer between the two [6], [7]. To achieve this type of control, attempts are made to implement a dynamic relation between position and force to be controlled together as opposed to controlling each of these values separately. The second category is direct force control which operates by comparing a measured force and a desired force to produce a force error driving signal. In this category we have the inner motion, outer force control strategy which nests a motion control loop inside of a force control loop where the motion information is readily available from a robot manipulator. This parallel control results in force control actions to dominate motion control actions to ensure limited interaction forces. Another popular control scheme is known as hybrid control which aims at controlling forces along directions where physical constraints exist while controlling motion in unconstrained directions [8].

2.1.3 Multi-Modal Control

Beyond the control methods mentioned previously which combine force and positional information in an attempt to control robots are those which attempt to incorporate an even greater degree of information about the environment. Force measurements coming from sensors and pose measurements based on joint encoders are known as being of the proprioceptive type, meaning that they provide information of the robot structure itself. This is in contrast to the exteroceptive type which deals with external stimuli. Force sensors can fall in either of these definitions depending on their intended purpose. Force and torque sensors mounted directly at joint locations are of the proprioceptive type while those intended to measure forces resulting from contact with external objects are of the exteroceptive type. In multi-modal control systems, information pertaining to the environment is combined with information pertaining to the robotic platform in an attempt to better describe interactions between the two. By far the most common form of exteroceptive information that has been explored for this type of control is visual feedback coming from cameras [9]–[11] although several other sensing technologies, such as range finders [12], have also been used. Visual feedback is useful in providing details of a relatively large workspace while force feedback provides localized information during contact, making these two types of senses complimentary to each other [13]. Hosoda *et al.* [14] provide an example of a system whose goal is to create a parallel controller structure

which quickly processes sensory information from multiple external sensors to effectively perform tasks in the context of simultaneous use of force and visual feedback. Visual servoing is commonly separated into two configurations, the first being eye-in-hand [15], [16] where the camera is mounted near the end effector of a robot manipulator and is therefore mobile, and the second being static camera servoing where the camera is mounted in a fixed location so as to supervise the overall workspace and track the motion of the end-effector [17]–[19]. However, more recent developments have spawned a possible third configuration resulting from ongoing research into humanoid robots where cameras are located in place of eyes in the head of these robots [20], [21]. These robots have cameras that are neither in hand nor stationary allowing them to be positioned as desired relative to the end effector.

There are many advantages to the incorporation of visual information in a control loop for robots. However the extraction of useful information from cameras can pose many difficulties [22]–[24]. The solutions to many of these problems require very computationally demanding algorithms for the extraction of features for use in object pose estimations as well as a calibration process. More recently, sensors have been developed for combining range data with visual data, of note being the Kinect sensor [25], [26]. This sensor has the advantage of directly providing a distance value for each pixel which can be useful in determining geometric properties of objects but it still provides a great deal of information which requires processing prior to use. A more ideal sensor should be able to more readily provide the desired information without having to develop special purpose algorithms for each task to be performed.

2.2 Compliant Devices

Motion control and planning are essential components for robotic systems since all robots perform tasks by moving through their environments. The problem of obstacle avoidance and preventing unwanted contact with the environment is directly related to motion planning. Planning movements for robots with many degrees of freedom (DOF) such as complex robotic manipulators can be computationally difficult even in highly structured environments since the configuration space has high dimensionality [27], [28]. Working in unstructured environments can potentially impose a number of additional constraints during motion generation due to the incomplete nature of the workspace model. Countless methods have been developed in an attempt to improve the performance of robots in all types of scenarios [29] but as important as the control of a robot's motion and the planning of trajectories can be, the structure of the robot itself should not be overlooked, as evident by the research

compiled in [30]. Any task can be greatly simplified given the right tools which is often the case in nature due to the careful specialization of biological systems which were adapted to their particular environments over time. One key aspect that biological systems have over many robotic technologies are their intrinsic elastic properties and material flexibility. This is often referred to as compliance in robotic contexts and object manipulation tasks are a great example of when compliance is an essential part of a robot structure. Compliance provides an adaptable interface between the environment and robots relaxing the strict constraints often seen in complex motion planning techniques attempting to simulate such adaptability with rigid structures.

In the following sections we will discuss the development of multiple compliant devices starting with whole compliant manipulators in order to depict their useful properties and the advantages these robots have over more rigid structures. This will be followed by the examination of several systems capable of providing a degree of compliance to a robotic manipulator which may or may not have existing compliance incorporated into its structure.

2.2.1 Compliant Manipulators

Compliant manipulators are those which have been designed and built to have intrinsic compliance either in the form of flexible links or by incorporating compliant structures directly into the connecting joints. An interesting design for a manipulator making use of the latter was described in [31]. The work presents a series elastic robotic arm with reasonable performance given its low fabrication cost. The majority of the manipulator's structure is composed of plywood offering a low weight to strength ratio. The authors highlight the fact that robotic manipulators tend to be very expensive due to their high precision actuators, which are required for several manufacturing tasks. The authors also mention that their robotic arm is designed with research purposes in mind and that by making the device as low cost as possible, its adoptability by researchers could be increased further. Several design trade-offs aimed at increasing the safety of the manipulator in unstructured environments are also provided such as the selection of stepper motors with high torque at low speeds in exchange for brushless and brushed motors with highly-reduced gear ratios. Their use of plywood inspired the choice of material with which to build our compliant wrist. Selecting a plastic composite not only reduced the cost of fabrication but also helped keep the weight of the device to a minimum.

As mentioned, the manipulator in [31] made use of series elastic actuators which incorporated a degree of compliance directly into the joints themselves. The original series elastic actuator was

developed in [32]. This type of actuator was developed by discarding the “stiffer is better” premise and directly incorporating elasticity (i.e. compliance) in their actuator. The “stiffer is better” rule arose from control methods used for industrial robots with which higher stiffness leads to improved precision, stability and bandwidth of position control. Although these facts might sound like necessary advantages, a high degree of stiffness is not without problems even in simpler position controlled systems. A small error in position with a stiff manipulator can exert very strong forces on surfaces making force control of such manipulators a difficult task. Instability issues which have been observed in such cases have interestingly enough been solved by incorporating ad hoc compliance by adding soft wrappings to the endpoints in order to reduce the effective stiffness.

Electric motors, which are the most commonly used form of actuation in robotics, tend to have low torque density, i.e. a relatively limited torque per volume [33], [34]. In order to increase the torque, gears must be used but these introduce additional problems such as friction, backlash and even noise. Unfortunately, the torque increase goes in both directions; if unwanted large and sudden loads, such as those which occur during collisions with objects, are applied to the manipulator, these are amplified and reflected back to the gears leading to possible damage to the gear teeth. A simple conclusion from these facts is that stiff actuators and robots are poor choices for object manipulation tasks in unstructured environments or similarly when trying to achieve force control since collisions are essential to these tasks.

In the context of force control, elasticity has the effect of making this type of control easier since the elasticity results in requiring larger deformations of the robot structure in order to exert forces comparable to those of stiff robots, transforming the control problem into one of position control. This results from the fact that the series elastic actuators make use of springs which are rather predictable devices with simple mathematical models which allow the conversion of position values to force values and vice versa depending on what value is being measured. With this in mind, one could argue that direct sensing of forces to obtain accurate force measurements is hardly a necessity for object manipulation tasks. Much like humans who can feel forces being applied to the body but lacking the means of precisely measuring those forces, simply being aware of these forces by inferring them nevertheless allows for the ability to react to them when sensed. The original design of the compliant wrist called for both compression and extension springs foreseeing that by knowing the spring constants of each of the springs used in the assembly, estimates of the forces applied to the device could eventually be obtained, providing an even greater degree of sensory information.

Another manipulator which makes use of the series elastic actuator concept is found on a robot called the Obrero [35]. This manipulator was developed to provide sensitive manipulation for humanoid robots. The authors attempt to provide a manipulator able to perform manipulation which is as much about perception as action and that intrinsically responds to the properties of the objects that are to be manipulated. They also mention that this sensitive manipulation should be the primary sensor with the possibility of incorporating vision information but simply as a complement to the information provided by the manipulator. The fingers of the manipulator each consist of three links with two of these links being equipped with high resolution force sensing resistors providing a large amount of tactile information during object manipulation. Each link is also actuated by a compact series elastic actuator in order to have mechanical compliance directly at the fingertips of the manipulator.

The previous concept of making touch the primary information during motion guidance is analogous to how humans are able to interact with their environment in multiple scenarios including those where their vision is impaired such as when no light sources are available. Although the work of Bach-y-Rita and Kercel [36] is not focused on engineering aspects, it does provide useful insights as to how the human brain can make use of one type of sensory information and effectively translate it into another form. This is what is referred to as sensory substitution. At present, the most successful sensory substitution system which humans make use of is Braille. Instead of using visual information to perform the task of reading, the necessary information is acquired through a person's finger tips. This is in part possible due to the large amount of processing power our brain attributes to our sense of touch.

Figure A.1 shows the commonly accepted relative proportions of how our brain attributes its sensory processing capabilities. As can be seen, the hands take a significant portion and the figure shows just how important our sense of touch truly is. Basing ourselves on this idea, it is clear that a sense of touch can potentially be far more useful in the field of robotics than any vision system during object manipulation tasks. Research with humans [37], [38] has shown that even with the help of vision, if the sense of touch is impeded in any way such as with the use of local anaesthetic or due to cold temperatures, these had detrimental effects to manual dexterity during grasping tasks again highlighting the importance of this sense.

The Obrero manipulator was similarly inspired by human manipulation of objects realizing that humans are able to perform many tasks without ever relying on vision. It should be mentioned however that humans are not very good at achieving precise positioning outright but rather make use of the vast

amount of sensory information their touch provides in order to compensate for any errors that may occur during initial contact. Feature extraction is also practically automatic thanks to a highly innervated skin. All of these human sensors are highly integrated directly into the joints and limbs and come conveniently packed in a flexible and compliant envelope. The integration of all these features in robotics is another difficult challenge to overcome and even with current technologies allowing for greatly reduced sizes we have yet to match the sensory density achievable in biological systems. Despite this fact, attempts are still required in order to make progress towards this goal. The Obrero manipulator was designed to favor sensing over precision, which seems to be how humans are designed as well. The researchers responsible for this manipulator also tried to make improvements to the series elastic actuators to make them more scalable in size [39], since the original rotary actuators required custom made torsional springs and the linear types required ball screws limiting the minimum size these actuators could be made. Again, the sensor was equipped with a rotational position sensing device (i.e. a potentiometer) to measure the rotation of the motor's shaft. This new actuator was also designed very carefully to allow for simple and direct position to torque conversions with high linearity, eliminating once again the need for direct force and torque sensing.

Various designs of series elastic actuators [40]–[43] have been developed, all based on the concept that added compliance in a structure is inherently safer, and have found their way into several other custom-made robot manipulator arm designs such as the Agile Arm [44] as well as those used by Cog [45], Domo [46] and Twendy-One [47]. However this can pose additional control problems in itself. Reducing the stiffness of an actuator and introducing elasticity in the form of springs can lead to oscillations in the arm's motion at the resulting system's natural frequency. Care must be taken to ensure that the oscillations will eventually be compensated with some damping action which could potentially be generated by the actuators themselves or with an increase of a manipulator's inertia. But despite the few shortcomings of series elastic actuators, they prove to be virtually essential for the future design practices of robots that will be operating in unstructured environments due to their close relation with biological systems [48]. Unfortunately, the development of robotic systems which are able to take advantage of these innovative ideas can be a costly endeavour, and the modification of existing robotic platforms in the hopes of achieving similar goals can be even more so, since this often requires radical retrofitting of the platforms if it can be accomplished at all [49]. With the large supply of industrial robots currently in operation, it would be preferable to apply the concepts used in compliant manipulators to them without incurring the high costs or time investments associated with such an

undertaking. The goal of this research was to minimize the effort required to achieve this while still providing the necessary features, including compliance, to a robotic platform in order to accomplish proper object manipulation tasks.

2.2.2 Compliant Wrists

The term compliant wrist is primarily used to indicate the physical location on a robotic manipulator that this type of compliant device will be mounted. In most cases, industrial robotic manipulators are equipped with task specific tools at the end of their arms. A few of these devices have already been developed but seemed to have had limited success in terms of adoptability in the field of robotics. The operation of these previously developed devices is described along with a discussion of their advantages and disadvantages.

The idea of adding compliance to industrial robots is far from being a novel concept. The wrist described in [50] dates back to 1982 and was developed for improving the accuracy of industrial robots in manufacturing applications. They discuss the compromises made between speed, payload and accuracy for typical industrial robots where high speed is desired for increased productivity. Higher speeds with large payloads can greatly affect the resulting positional accuracy of manipulators and could possibly introduce oscillations or even instability. In this work, the compliant wrist is instrumented to provide position information to the robot controller by measuring small positional deviations in the wrist resulting from positioning errors of the manipulator. The development of a novel robotic finger for a hand with wrist combination structure which reiterates the need for compliance for realizing dexterous manipulation is presented in [51].

Another compliant wrist sensor [52], [53] making use of capacitive principles was designed to measure the bending moments in the X and Y directions, the force in the Z direction as well as the torsion moment around the Z direction. Consisting of two opposite electrode surfaces each equipped with 4 sensitive capacitance patterns along with an elastomeric (rubber) material in between the surfaces, the sensor combined the information received from these 4 patterns into an unambiguous result for distinguishing the three moments. The overall sensor was realized as 7 cm diameter printed circuit boards with a natural rubber component measuring 6 mm in thickness serving as the compliant medium between the electrodes. The limited thickness of the compliant layer provides only a very limited range of movement and therefore limits the applications of the device. This is to be expected since the primary application for which it was conceived was peg-in-hole insertion tasks for industrial

robots. The use of a capacitive device in this case however, prevented the device from having arbitrarily large compliance due to the inherent nature of capacitance based distance measurements.

Other devices falling under the category of compliant wrists have been developed with very different goals. One such example is given in [54] for use in tele-operated robot applications. This particular design is based on the Stewart platform [55] providing 6 DOFs and makes use of linear compression springs in place of actuators to provide passive compliance. The work focuses on ensuring linearity of the springs to provide accurate force estimation and optical encoders for measuring compression distances thereby achieving a resolution of 0.4N. Providing upper limb prostheses with added functionality was intended for the design of [56]. Current upper limb prosthetic technologies often provide very few, if any, DOFs in their structures since the focus is primarily on weight reduction and robustness. Prosthetic devices are meant to replace parts of the human body and should therefore have similar characteristics such as compliance. This particular wrist is equipped with a special mechanism to be controlled via electromyographic signals in order to select the desired degree of compliance offered by the wrist depending on the actions to be performed by the user of the prosthetic device.

One endeavour which resulted in a compliant wrist came from trying to evaluate a design method based on passive compliance analysis [57]. The resulting structure is similar to a Stewart platform however in this case, the parallel linkage chain has only three links and three DOFs. Although parallel link structures have many useful properties such as high rigidity, high accuracy and large load carrying capacity [58], the resulting kinematic model ends up being somewhat complex due to the movement of the joints and position of attachment points. Despite the thorough displacement analysis performed to determine the limits of possible motion in constrained directions as well as calculations to convert joint stiffness values into Cartesian stiffness values, only three linear potentiometers were mounted onto the device to measure distances between the moveable contact face and the base of the structure. This resulted in the estimation of two rotations about axes X and Y, as well as the translation along the Z axis. The relative positions of the sensors also added slightly to the complexity of the extraction process for these parameters.

The popularity of series elastic actuators is again seen by being incorporated into compliant wrist designs such as in [59] which is meant to be used in conjunction with physical rehabilitation devices. Robotics used in rehabilitation are essentially centered on physical interaction between humans

and robots leading to heavy use of interaction control schemes [60]. The work makes use of the series elastic actuation architecture to fulfil several requirements of rehabilitation robots. These devices, along with sensors to measure the force or deflection of the joints, act as mechanical filters that decouple the non-linear behavior of geared actuators from the output while enabling the use of force-feedback control. This introduction of physical compliance allows for the deployment of more accurate interaction control schemes.

Many of the previous works related to compliant wrists have shown that compliance in manipulators is indispensable regardless of the chosen application. Manipulators which do not already have this invaluable feature could greatly benefit from the addition of compliance into their structure. The most direct method of doing so is by adding an additional link in their serial linkage chain. Any modifications to an existing platform might require a complete re-evaluation of the control scheme depending on the level of structure dependency incorporated into the robot controller's model. All of this leads to additional costs especially when modifications to the existing platform increase in complexity. Simplicity should be sought in all aspects of robotics as this allows for quicker adoption of incremental innovations. It was seen from [57] that structure considerations are important for design where the choice of the joint connections led to a very complex kinematic representation. For this reason, a simpler compliant structure would be desirable, despite the probable need for approximations and assumptions in modelling the device. Structures such as the one described in [61] show that many benefits can be gained even with the addition of a simple device offering two DOFs. Their ARTS compliant wrist, named after the Advanced Robotics Technology and Systems (ARTS) laboratory which developed it, is a cable driven mechanism composed of two platforms connected by a thrust spring and was designed to work with the Cyberhand [62]. The two DOFs provided by the wrist are able to dramatically increase the available workspace of the Cyberhand for a given initial position of the wrist itself. This mindset was instrumental during the development of the proposed compliant wrist.

The first design of a compliant wrist which initially inspired the development of the compliant wrist presented in this thesis was the one developed by Paul et al. [63]–[69]. This appeared to be the most detailed collection of works regarding a compliant wrist structure, its applications as well as possible control schemes which could be applied to guide the motion of a robot. The original wrist [67] consisted of two plates separated by a compliant, damped rubber structure to provide passive compliance and was equipped with a sensing mechanism to measure the deflections of the 6 DOFs allowed by the compliance. The sensing mechanism was composed of a serial linkage chain with

potentiometers at each joint in the chain for angular measurements. This allows for the determination of the final position of the moveable plate not attached directly to the robot by applying the same forward kinematic methodology as one would for a serial manipulator. The second iteration [63]–[65] included modifications to the overall compliant mechanism as well as the physical structure in order to allow the mounting of an end-effector tool onto the wrist. The sensing mechanism remained relatively unchanged with a serial linkage chain still providing measurement of the 6 DOFs available. By carefully selecting the rubber compliant components, calculations could be made for determination of the stiffness of the structure along each DOF with a large degree of accuracy.

Their initial investigations [70] on the use of such a device to control a robot actuator showed that stability was achievable using a variety of compensation mechanisms like proportional, proportional-integral, proportional-derivative and proportional-integral-derivative compensators in either position or force control. This is an important realization since control system theory is directly applicable and raises concerns regarding the behavior of robots. It is of importance to know what will be the steady-state response of such a system. In open spaces, an actuator has very few variables to deal with depending on the desired action, which could be to reach a desired position or speed for example. The use of position sensing devices for actuators can produce signals that provide information about that actuator's position and this information is essential to the proper control of an actuator as it gives feedback information about the error between the desired position and the currently measured position.

The feedback information produced by such a sensing device is easily integrated into the control loop of an actuator which is evident from the popularity of servo motors which do just this. Such a system and goal are well defined. However when dealing with constraints that arise during object manipulation or physical contact with the environment, additional information beyond position alone must be taken into account to produce the desired action. If we take for example a rigid manipulator which is given a desired position to reach which coincides with space occupied by an object, the robot will have no means of detecting the collision when it occurs, possibly preventing it from reaching its desired position. This will lead to the robot continuously attempting to reach this desired position due to the constant error signal indicating that the final position has yet to be reached.

To solve this problem, force sensing devices have become another very popular type of information incorporated into robot control loops to allow them to detect such collisions and, once

contact is made, the amount of force applied to the robot by its environment can effectively be measured and controlled. Many control schemes exist for both such cases as well as the combination of the two into one system. The successful application of such a control scheme to their compliant wrist was demonstrated in [71] using carefully measured stiffness values of the compliant rubber material to determine contact forces based on position. This fact helps reinforce the idea that direct force sensing is not essential as this information can be obtained by inferring equations or even approximations depending on the task at hand.

One application which was examined for the compliant wrist proposed in [63] was its use for robotic exploration of surfaces, for identifying the necessary attributes required for stability of those surfaces during standing or walking. The attributes of interest in this case were hardness, compliance, penetrability and surface roughness rather than geometric properties of the surfaces involved. Another wrist was designed for performing similar surface exploration tasks but this time with the goal of extracting geometric features of the surface being contacted. By using a simple structure for providing the passive compliance, this compliant wrist, equipped with a tactile sensing array on its contacting plate, was able to provide both gross position and orientation estimations as well as finer geometric surface profile information [72]–[76]. The latter however allowed very little displacement and angular movement due to the manner in which it measured these values. By attaching rotary potentiometers to sliding shafts, motion was highly constrained.

An interesting point also raised in [35] is the concept of bandwidth which must be considered during object manipulation tasks. Bandwidth is simply another term for the concept of reaction time and essentially expresses how often behavior or motion corrections can be achieved. In mobile robotics the types of sensors that are primarily used to determine the distance to an object are non-contact sensors allowing the robot a greater amount of time to prepare itself prior to making contact. Whereas, during object manipulation, contact sensors are more commonly used. These types of sensors can only provide feedback once contact has been made with the environment, and it is argued that, in order to react to the sudden changes in conditions, a significantly higher bandwidth is required to prevent damage to either the environment or the robot itself.

However, according to results found in [77] and [78] human reaction times are fairly low for several types of stimuli such as visual, auditory and tactile. The mean reaction times, that is the time required for a person to react at the onset of a particular signal, for all types of stimuli are well above

200 ms corresponding to a bandwidth of approximately 5 Hz. Despite these values, humans, being a traditional benchmark when comparing performance of robots, especially the sense of touch [37], are still able to successfully interact with their environments leading to the conclusion that reaction time is not the deciding factor.

Sensor fusion in humans and the ability to make use of our memory, logic, and feature extraction capabilities is unparalleled by today's robotic standards. Therefore focus must be made in the development of new sensing technologies and multimodal data processing algorithms. Currently, the majority of sensors available tend to be designed to perform a single task and are generally classified as such, e.g. distance measurement sensors, force detection sensors, etc. The goal should be to design sensing technology that provides multiple functions in a single and efficient form.

An example of such a sensor is presented in [79] which was inspired by the dual layer structure of human skin. The sensor is reportedly capable of producing an output dependent on the stress direction imposed onto the sensor's structure. Experimental results show that more than six different types of movements can be differentiated by a single sensor based on normal and shear forces applied to the device. Similar information could be obtained using strain gauges. However these tend to detect forces in a single direction and would require multiple devices.

Many other types of tactile sensors have been developed [80] showing that a lot of attention has been given to this field of research. Some sensors make use of novel mechanical structures such as the one found in [81] to leverage the differential capacitive principle allowing the sensor to detect forces in three separate directions. With the notion of multiple modality sensors in mind, it was decided that, rather than simply devising a method to provide feedback solely during contact, it would be more beneficial to add an additional function to our compliant wrist, namely the ability to detect objects in close proximity. This not only provides additional information to the robot but also allows it to take advantage of the pre-contact information to reduce the need for such high contact bandwidth.

After reviewing a vast array of compliant wrist implementations it was decided that direct force sensing via force/torque sensors is not always an essential component for such a device since it is very task dependent and that providing instrumentation capable of measuring deflections of the compliant components caused by contact forces was a satisfactory alternative to allow multiple forms of motion guidance to be employed for robot control during tasks such as surface following and object interaction. Simplicity of design is a desirable trait for several reasons such as the fabrication process, assembly of

the device and integration onto existing robotic platforms. This motivated the search for a distance sensing mechanism which would meet the requirements of the problem as well as provide the simplest structure possible.

2.3 Distance Measurement Sensors

Any compliant structure offering a significant degree of compliance and therefore noticeably large movements should be equipped with sensors capable of detecting these deviations in order to allow a robot to compensate for the errors in position caused by this compliance. The following subsections detail several different technologies that have been applied to distance sensing applications. A short description of each type is given and their benefits and disadvantages are compared. Information for these sensing technologies were extracted from a multitude of references, some of which covered several different types of technologies [1], [80], [82]–[84].

2.3.1 Resistive

Resistive position sensors which are commonly referred to as potentiometers are passive devices requiring no additional circuitry or power sources to perform their function, be it linear or rotary position sensing. These devices can be used in either rheostat mode or voltage divider mode. As a rheostat, the resistance value between the moving wiper of the potentiometer and one of its fixed terminals is directly used to determine position. As a voltage divider, a reference voltage is applied across the two fixed terminals of the potentiometer and the output signal is the resulting voltage across the wiper and one of the fixed terminals. There are many advantages to using potentiometers including ease of operation and a low cost. One slight disadvantage is that the device requires physical contact and sliding action of its internal components leading to eventual wear out. Measurement range in a linear direction is limited simply by the physical construction of the device. However for the rotary type, if without the use of Vernier drives, the rotation range is limited to slightly less than 360 degrees.

2.3.2 Infrared

When considering the type of sensor to use in a particular application, their measurement precision, range and accuracy are not the only parameters of import. Non-contact sensors provide several advantages over sensors requiring to be affixed to multiple contact points. One of the advantages is clearly foregoing the need for a complex structure meant to accommodate the physical constraints imposed by the sensing device. With a lack of contact, they also have the ability to

theoretically provide a faster response due to less friction between moving parts; this also greatly minimizes hysteresis effects normally present in physical systems. Infrared sensors fall within a broader envelope of sensors known as structured light sensors [85], [86] where light patterns are used to determine distances. A complete review of each type of these sensors is not warranted here and the review will be confined to the more cost effective sensors readily available to hobbyists. These sensors combine an infrared light emitting diode, a position sensitive detector (PSD) [87] and on-board electronics for signal pre-processing to produce voltage signals representing distance estimates. The output signals are generated based on a geometric principle known as triangulation [88], [89] which uses the angles of the triangle formed by the light source, the object and the light detector. The voltages can then be measured and associated with the distances that produced them in order to form the relation between the two. Lenses are used to obtain different operating distances ranging from anywhere between 4 cm and 150 cm with ranges varying from sensor to sensor. Due to the use of on-board electronics, these types of range finders have update frequencies ranging from 10-80 Hz [90]–[95]. As with any other light dependent sensors, these types of sensors can be somewhat sensitive to ambient lighting conditions and the surface which is being detected.

2.3.3 Inductive

Inductive sensors are non-contact devices which allow for the measurement of distances by creating magnetic fields and detecting changes to those fields when objects interact with them. Since metallic objects are more reactive to magnetic fields than most other types of materials these sensors tend to require a metal component attached to the surface whose distance is being measured. The sensors consist of four major components such as a ferrite core with coils, an oscillator, a Schmitt trigger and an output amplifier to produce a detectable signal. The oscillator is responsible for generating an oscillating magnetic field which radiates outward. The amplitude of this magnetic field is reduced by the Eddy currents induced in the target's metallic component signalling that an object is present. The closer the object, the greater the interference with the magnetic field, resulting in a lower amplitude of oscillation of said field. Due to the sensing mechanism, these sensors are well suited to harsh environments but require precise calibration depending on the specific material to be detected. Inductive sensors have extremely high resolutions capable of reaching nanometer scales, frequency responses known to exceed 80 kHz but with typical values falling between 500 Hz to 5 kHz and typical measurement ranges of 0.5 mm to 60 mm [96]–[98].

2.3.4 Capacitive

Capacitive sensors are also non-contact devices used for one of two tasks, the first being distance measurements and the other thickness measurements. When used for measuring distances, the target object must be conductive since the target will act as one side of a capacitor. The gap between the two sides of this capacitor tends to be comprised of air and should be void of contaminants in order to maintain signal integrity. This type of sensor makes use of an electric field as its sensing mechanism. The use of electric fields (as well as magnetic fields in inductive sensors) can lead to complicated equations if the gap between the two conductors or the positioning of the target becomes irregular, which limits the effective use of these types of sensors if accurate distance sensing is required in uncontrolled scenarios. Without carefully establishing the sensor's environment, reliable information is not guaranteed. Under favorable conditions, these types of sensors are also capable of reaching nanometer resolutions with frequency responses of 20 kHz or higher and measurement ranges of 10 μm to 80 mm. The frequency response is limited due to the need to charge up the objects which often present some form of resistance thereby impeding the charge and discharge rates [99]–[102].

2.3.5 Magnetic

Similar to inductive sensors, magnetic sensors also make use of magnetic fields to determine distances. However instead of reacting to changes in a field generated by the sensor itself, measurements of the strength and direction of magnetic fields produced by external objects are used due to the vector nature of magnetic fields. The most commonly used magnetic sensors are known as Hall Effect devices and these measure the strength of a magnetic field producing an output which is proportional to it. Due to the very weak signals produced, Hall Effect devices are usually coupled with additional electronics to generate amplification resulting in a useful voltage signal. These sensors remain in high demand since they can be implemented using CMOS technology reducing their fabrication costs and allowing integrated circuitry to be added to improve their overall performance characteristics. A major limiting factor is their detection range which is dependent on magnetic fields and large distances require strong magnetic fields which can cause complications with electronic circuits [103]–[105].

2.3.6 Ultrasonic

Ultrasonic sensors again act at a distance using pulses of sound and measuring distance based on the amount of time required for a sound pulse to reach its target and return an echo to the receiver. These sensors are capable of providing very precise measurements under the correct conditions and

have the advantage of not requiring special devices attached to the target and can easily detect clear or light reflecting objects. They also have a very large detection range reaching upwards of 6000 mm. There exist several considerations which pose implementation problems and these include limits of the angular and radial resolution as well as the fact that depending on the desired operating range, an appropriate timing window must also be defined allowing enough time for the signal to return to the receiver. When compared to computer operating and sampling speeds, sound travels in air very slowly, which translates to a much lower possible frequency of operation for this type of device [106]–[108].

2.3.7 Summary

The choice for using infrared sensors during this work was greatly influenced by the combination of its non-contact sensing capabilities and the cost associated with these particular sensors. The signal conversion was also much simpler than signals obtained from those making use of electric and magnetic fields which often impose very strict requirements on the setup such as metal surfaces, known materials between sensor and objects, or constant gap sizes between the two, as well as complex equations. These sensors also provided a compact and direct method of estimating distances to objects in the workspace as an added benefit to detecting deflections during compliant motion [109]. It should be noted that for the previously discussed sensors, there exists a difference between frequency response, which is essentially related to how quickly a sensor can react to changes in distances of objects, and update frequency which is essentially how quickly the sensor produces an updated output value. The update frequency specified for the selected infrared sensors was approximately 80 Hz which provides adequate bandwidth in accordance with reaction times achievable by people.

Chapter 3. Context and Design Considerations

The research presented herein was spurred by a larger project in which robot manipulation of delicate objects was required in order to fulfill the overall requirements. This project was described in [25] as a vision-guided robotic system for automated and rapid vehicle inspection with the conceptual setup depicted in Figure 3.1.

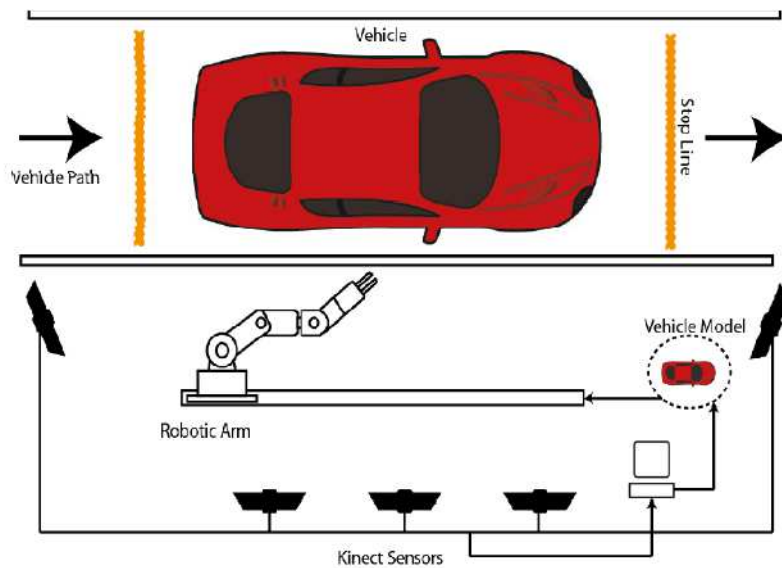


Figure 3.1 : Rapid Vehicle Inspection System [25]

It was comprised of several components which were brought together to analyse a scene containing vehicles and attempt to identify areas of interest, according to predetermined criteria, of those vehicles. Scene analysis of this type finds many potential applications such as in the automotive field during vehicle assembly and maintenance or damage inspections. Another possible application would be security screening at border stations where an automated process could potentially decrease inspection times. In this type of scenario, it is highly likely that a human element would need to be considered, either due to the presence of passengers within the vehicles or security agents nearby the vehicles. Also, the cost of a vehicle can vary greatly but is generally a large expenditure for most buyers adding an additional requirement of there being a low risk for damaging the property if direct contact is required between a computer-operated device and a vehicle.

All of these scenarios require accurate representations of a scene for a robot to interact with it and to perform tasks such as, in the context of vehicles, drilling, welding, or even simply gliding over a

surface or wiping it clean. In order to accomplish this, a calibrated network of Kinect sensors were incorporated into the system allowing for a three dimensional (3D) reconstruction of a scene containing a vehicle. From the scene, the generated 3D model along with the color images of the vehicle in question would be extracted and further analysed with pattern recognition algorithms [110] allowing for the identification of the previously mentioned areas of interest.

The 3D vehicle model was intended to later be used for the automated control of a robotic manipulator to interact with the surfaces of the vehicle within the areas of interest. This is where the research presented in this paper comes into play. Visual guidance of the robot using the depth information of the Kinect sensors was achieved with good results [111] in regards to gross path planning and obstacle avoidance, however, the system had several limitations.

Firstly, the visual data, both color and depth, produced by the array of Kinect sensors could not be acquired and merged together in real-time with the desired resolution. For a static environment, where no changes in physical arrangements are occurring, this would generally not pose significant problems. However, in a realistic scenario involving vehicles and their operators, such conditions cannot be assumed. Therefore the current system, as it stands, would not perform optimally in unstructured environments.

Secondly, even if the Kinect sensors could provide real-time depth information, the sensors would suffer from temporary occlusions as the robotic manipulator moved throughout the scene creating gaps in the model. This means that as the robotic manipulator would begin approaching a particular object or area of interest, there would be a high degree of uncertainty while controlling the manipulator.

Thirdly, the resolution of the sensors was dependent on the distance between the sensors and the objects, with lower resolutions being observed at greater distances. At the distances used for generating the 3D models, uncertainties on the order of several centimeters were commonly observed in the depth measurements [112].

These shortcomings led to the desire of being able to more accurately determine the distance between the robot manipulator and the areas of interest. In order to precisely control the motion of a robotic manipulator in close proximity to or while in contact with the vehicles in question the previously mentioned issues needed to be addressed. Also, due to the conditions found in the envisioned scenario,

namely the human element and valuable property, the use of a rigid manipulator raised additional concerns.

If we consider the depth measurement errors of several centimeters mentioned earlier, it is easy to see that it would be unwise to expect a rigid manipulator to come into direct contact with vehicles, given their relatively complex surface shape, or to be operated in the presence of humans. If the system controlling a robot believes a surface to be a considerable distance further than its actual position, the system will attempt to move the manipulator into the position it believes the surface to be which will result in a collision with the object. A collision between two rigid objects leads to significant impact forces, which in the case of unstructured environments, and with the possibility of a human element, creates a risk of physical injury or a high risk of damaging the property.

In order to reduce the forces felt by both a robot and the environment with which it is attempting to interact, concessions are often made to allow compression of physical structures to compensate for the inevitable inaccuracies of the distance measurements used for controlling the robot's position and motion. As the literature suggests, compliance can be of great use when attempting to compensate for positioning errors during physical interactions between robots and their environments. However, despite the compliance having the beneficial effect of reducing the risk of injury and property damage and allowing for positioning errors, without a means of detecting the amount of deflection incurred by the added compliance during physical interaction, the controlling system would have no way of knowing the actual position of the robot. This last issue of position uncertainty due to the compliance also needed to be addressed in order to have a reliable method of controlling the robotic manipulator's position.

The instrumented compliant wrist solution that was developed had as its main goal to provide a robot controller with sufficient information in order to successfully operate both in close proximity with a target object and also maneuver itself while in contact with said object. In an effort to provide such information as well as to address all of the concerns raised above, a dual layer sensing configuration was conceived along with a physical mechanism meant to integrate a degree of compliance.

The first layer was incorporated into the device to allow for the detection of objects in the vicinity of the manipulator in real-time. The sensing devices selected were infrared range sensors with a higher resolution for distance measurements than those provided by the array of Kinect sensors leading to a higher degree of precision and confidence during motion control. These sensors were arranged in a

specific pattern to provide the added functionality of estimating the orientation and position of objects during inspection of the areas of interest or, in the case of manipulation tasks, aiding in the motion planning prior to contact. Essentially, this sensory layer attempts to overcome the existing limitations of the Kinect sensor array by allowing the robot control system to function without a time consuming approach for acquiring a highly detailed model of the robot's workspace.

The second sensing layer was required to accomplish the task of estimating the amount of deflection imposed onto the compliant wrist during object manipulation, or similarly, during physical interaction with the environment. Again, the sensors were arranged in a pattern allowing them to determine the orientation of objects with which the compliant wrist was interacting. This added sensory information could also allow the system to determine whether it was in contact with objects providing a collision detection functionality in the process.

The physical structure of the device was designed to offer a significant amount of compliance to act as the contact interface between a rigid manipulator robot and the environment. This compliance also serves as a physical buffer of sorts providing the control system additional time to respond to changes in sensory data, and simplifying the control scheme in the case of transitions between a state of free motion (non-contact) and constrained motion (contact).

Although many improvements can be foreseen to the robotic manipulator working stand-alone in terms of automated guidance provided with the addition of the compliance and sensing mechanisms found aboard the compliant wrist, information used for localizing objects in a workspace or for deciding which objects to manipulate would still need to be supplied to the robot controller in order for a system making use of the compliant wrist to be fully operational. In the case of the previously mentioned project, the problem is well defined and such information is acquired by the vision system and consists of color images and depth sensing measurements supplied by an array of Kinect sensors.

The compliant wrist was originally meant to act as a tactile sensor in a multi-modal control scheme in which it injects additional supporting information into the robot's control loop. However, as is the case in many robotics applications, each component should be designed to act independently of each other so that the information coming from multiple sources can be fused together based on the current situation. The following chapter provides a description of all of the components used in the compliant wrist which allowed it to serve as a stand-alone module which could be easily integrated onto a multitude of robotic platforms including manipulator robots.

Chapter 4. Mechanical and Electronic Design

The design objectives for this thesis culminated into the development of a custom compliant device which, in its implementation, was made to incorporate all of the aspects required to meet the primary goal set forth in section 1.2. In this chapter, the physical design of the device will be presented along with a discussion of the design considerations. Also included are discussions of each of the components and modules which, coupled with the compliant device, provide the necessary functionality to achieve the operational goals.

At the core of the developed compliant wrist assembly are two plates separated by components allowing for deflection of the upper compliant plate under externally applied forces. Instrumentation capable of dynamically measuring this deflection is embedded within the wrist assembly providing the sense of touch for the device. Additional instrumentation has also been added to the periphery of the bottom plate to measure the location of an object's surface before it ever comes into contact with the upper compliant plate, providing the proximity detection capability of the device. The combination of these two sensory layers provides the necessary measurements for fine tuning the movements of the robot both while maneuvering in close proximity to the surface with which it is meant to interact before contact occurs as well as adapting its pose to conform to the surface's orientation after contact occurs. Specifics of the mechanical assembly, its operation and hardware considerations are given in the following subsections.

4.1 Mechanical System Design

Investigation of the compliant device's mechanical assembly led to the production of multiple iterations before attaining its final form. In order to more effectively explain the physical structure of the compliant wrist, an image of the latest prototype is provided in Figure 4.1. The figure shows the primary mechanical components providing the desired functionality of the device.



Figure 4.1 : Compliant Wrist Prototype

Starting at the base of the structure is an enclosure used to house the electronics such as the microcontroller, the wireless communications module, the wiring used for interconnecting the electronics, as well as a power source. This enclosure also provides a power switch and a USB connection port which provides access to the microcontroller for reprogramming purposes or tethered operation, if required. This enclosure was the last component to be fabricated in an attempt to forego multiple iterations since during the design process for the compliant device it was unclear which components would be essential to its operation. Once all of the physical components and modules had been selected, it became a matter of organizing them in fashion which allowed the device to be easily assembled and disassembled as well as providing external access to the microcontroller and allowing several indicator LEDs to be visible from the exterior of the enclosure. A simple assembly process, especially in a development situation, can lead to significant time savings when attempting to make modifications to a device and this mindset was maintained in the development of all components of the compliant wrist.

The upper section of Figure 4.2 shows the power switch next to a green LED indicator showing whether or not the device is active, as well as two additional red LEDs which are used to show data transmission activity during wireless communications while the lower section shows the micro USB port. The image is sectioned since all of these features could not be positioned on a single face of the enclosure, mainly due to the shape and layout of the electronics of the microcontroller. Although not critical to the operation of the device, these indicator LEDs were instrumental in the testing phase of the

device. The green LED indicated when power was available to the device when operating in tethered mode. It was also used to indicate if the battery used as the power source in untethered mode had any remaining charge to supply the device or if it had been depleted. As for the red LEDs, these were indispensable when the wireless communication protocol was being developed and evaluated. Having two LEDs, one for indicating data being received by the onboard microcontroller and the other for indicating data being transmitted, gave a clear indication of any data losses occurring between external devices such as the robot controller or the implemented software test platform and the compliant wrist. Finally, the USB port served two purposes. The first was to allow the microcontroller to be reprogrammed without being removed from the enclosure thereby foregoing the need to disassemble the device. The second was to provide power to the device for extended periods of time to streamline the testing and validation phase as the microcontroller did not offer any means of using a rechargeable battery as the power source without additional electronics and therefore was meant to minimize the number of batteries expended. Although the USB port does allow for communications, this feature was not implemented as the rate of communications provided by the XBee modules was sufficient. The choice of having the device powered by batteries was mainly to allow the device to be able to be operated without physical connections to the device as these tend to hamper integration into existing robotic platforms.



Figure 4.2 : Enclosure Features

The mechanism which provides the compliance sits above the electronics enclosure and is shown with more details in Figure 4.3. Compliance was determined to be an essential part of any robotic manipulator expected to function in unstructured environments and therefore a method of providing such a capability to initially non-compliant robots was needed. The mechanism itself achieves its compliance with a combination of compression and tension springs which apply forces on the upper

plate to maintain an equilibrium state when no external forces are applied to it. Under influence from external forces, the upper plate can be made to rotate freely about its pivot point centered on the plate. One known drawback of the compliant wrist mechanism is the fact that it is possible for the upper plate to rotate about the longitudinal axis of the central shaft however there are no means of detecting this motion. This may be of import in situations requiring complete knowledge of the space occupied by the device.



Figure 4.3 : Compliant Wrist Mechanism

Passive compliance provides a simpler and more cost-effective alternative to active compliance for obtaining the desired capabilities. Elastomers and springs are natural systems which offer such passive compliance by providing low stiffness constants allowing them to be deformed under contact forces. Although both options are widely available, springs have the advantage of being easily manufactured to obtain the desired stiffness relying on simple factors such as the diameter of the wire used for making the spring, the resulting diameter of the spring once the wire is coiled as well as how tightly together the coils are wound, i.e. the pitch of the spring. Taken a step further, machined springs can be designed to provide very precise spring constants to provide a highly linear relationship between force and displacement using Hooke's law.

In the initial prototyping phase, the use of springs allowed for a quick trial-and-error process for experimenting with different stiffness values. Using individual springs also allowed for limited control over the positioning of these springs to obtain the desired final stiffness of the device. Additionally, the

method used to position the center compression spring, namely a hollow shaft allowing for translational motion between the two plates ensured that the position of the moveable plate would remain centered on the translational axis during its rotational movements, simplifying the equations required to describe the mechanical system.

Again, Figure 4.3 represents the final prototype configuration of the compliant structure. This core component required several modifications throughout the development phase as new information was gathered from preliminary tests and experiments. Initially, a large elastomeric structure such as a rubber shock absorbing sleeve similar to the one shown in Figure 4.4 was considered to act as both the connection between the movable contact surface and the base of the device. However this would have posed several assembly problems and required the outsourcing of a custom fabricated component. One of the main concerns of using an elastic structure such as this was the amount of stiffness offered along translational directions perpendicular to the thrust bearing direction. Any additional movements which could not be directly measured would have required complex modelling of the device or unwanted approximations leading to additional errors in accuracy.



Figure 4.4 : Side Bearer Rubber Mount [113]

Although the key concepts for the compliant structure remained relatively unchanged, the modifications which occurred throughout its development will be discussed as the individual components are introduced. It is useful here to refer to the initial prototype of the compliant structure and the included instrumentation in order to compare and highlight the differences and the changes

which occurred as needed to improve overall operation. Figure 4.5 depicts the first iteration of the compliant wrist without any electronics enclosure.

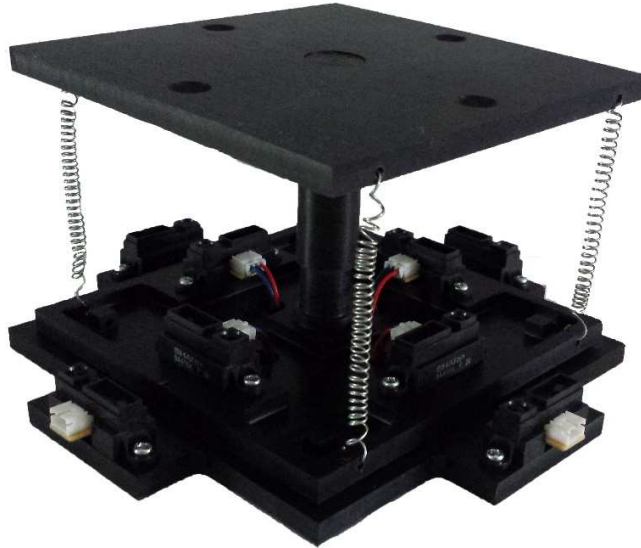


Figure 4.5 : First Compliant Wrist Prototype

Both Figure 4.3 and Figure 4.5 show the four infrared (IR) sensors which are mounted to the bottom plate and positioned in such a way as to allow for direct measurement of the distance between the sensors and the movable upper plate. These are referred to as the internal sensors due to their physical location on the device. Note that Figure 4.5 also depicts four additional IR sensors located at the outermost periphery which act as the proximity sensory layer and will be discussed later.

The internal sensors were initially arranged symmetrically around the plate with the center of each sensor aligned with the center of the plate. It was believed initially that the infrared light emitted from the sensors was projected at an angle and that the voltage produced by the receiver was based on the distance of objects located between the emitter and the receiver of the sensors. This came from misleading imagery found from multiple online sources and are exemplified in Figure 4.6. In reality, the sensors emit a cone of light in a direction which is normal to the face of the sensors and only the portion of light reflected from the object is responsible for the sensor's response. A more accurate, albeit still simplified, representation of the sensor operation is given in Figure 4.7. The oval shapes represent the lenses used for the sensors, one for the light emitted from the LED and another for the light reflected from objects, while the position sensitive detector (PSD) is the detector responsible for generating a voltage value proportional to the object's distance. Depending on the object's distance, the light will be focused onto the PSD and the voltage value will be dependent on the physical location upon which the

reflected infrared light falls. This is an important distinction as the upper plate is able to rotate about multiple axes simultaneously. During preliminary tests for evaluating the operation of the distance conversions in the system, gross discrepancies arose due to the misplacement of the sensors. The original placement of the sensors made it so that when the upper plate was rotated about the axis which was aligned with two sensors, one sensor would detect a further distance than the other as the emitted beam of light was not centered on the point of rotation. Figure 4.8 attempts to illustrate this scenario with two sensors aligned along the axis of rotation with each sensor detecting different distances. Note that in the figure, the vertical offset between the two sensors is meant only to illustrate depth. In actuality, both of these sensors would be positioned on the same plane. Once this behavior was detected, the sensors were repositioned so as to have the center of the emitters of each sensor aligned with each other as well as their respective axis of rotation, either X or Y depending on the sensor's location, as shown in Figure 4.9. This led to a substantial decrease in inter-sensor distance variations due to plate deflections.

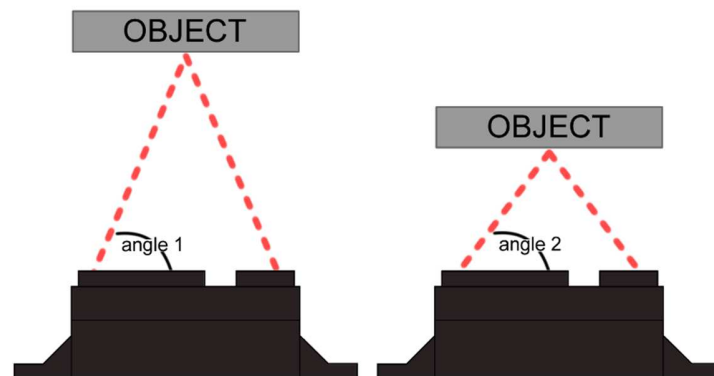


Figure 4.6 : IR Sensor Detection Point [114]

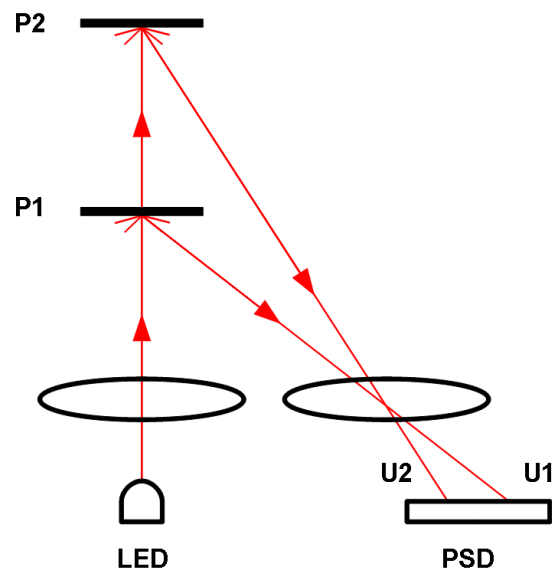


Figure 4.7 : Correct IR Sensor Operating Principle [115]

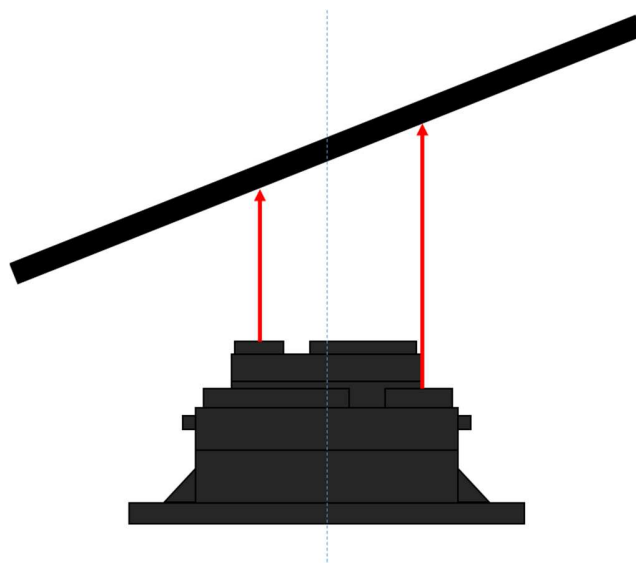


Figure 4.8 : Distance Estimate Errors due to Sensor Placement

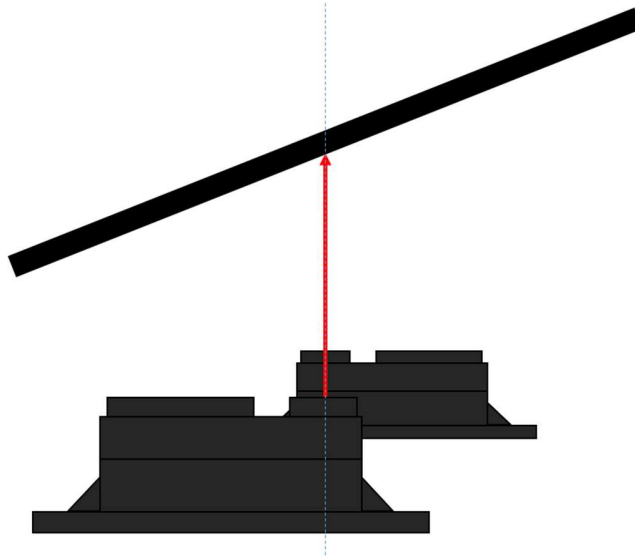


Figure 4.9 : Correct Sensor Placement for Infrared Beam Alignment

Figure 4.10 provides a top down view of the final positioning of the sensors on the compliant wrist after incorporating the necessary changes which allowed for the proper alignment of the sensor beams.

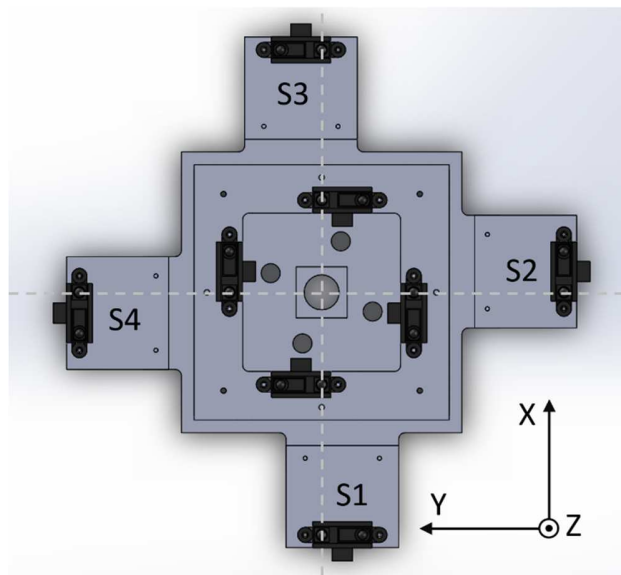


Figure 4.10 : Sensor Arrangement

The next component of interest in the compliant mechanism is the slide shaft located at the center of the mechanism. The slide shaft is composed of four parts. The first, which is fixed to the center of the bottom plate of the compliant mechanism, is the bottom half of the shaft which has been hollowed out to house a compression spring. The upper half of the shaft has also been hollowed in order

to allow it to slide over the bottom half and the compression spring. These three components are responsible for the sliding motion and provide the translational degree of freedom of the mechanism. The fourth part is a Teflon® (polytetrafluoroethylene or PTFE) ball which is located at the tip of the upper half of the slide shaft providing a very low friction point of contact between the upper plate and the shaft giving the wrist its two rotational degrees of freedom.

The slide shaft has undergone several adjustments in order to find a length that would accommodate the available compression springs and provide a sufficient amount of displacement during operation. The difficulty in finding a suitable length arose from the method used to attach the upper plate to the shaft itself. In order to allow the upper plate to rotate about two axes, namely the X and Y axes as defined in Figure 4.10, it was decided that the plate would require a tension force to maintain contact with the low friction tip of the shaft while not impeding the rotational movement. This was achieved by incorporating four tension springs, one attached between each of the four corners of the two plates as shown in Figure 4.5. The joining of the four corners of the top and bottom plates with these extension springs kept the upper plate in contact with its pivot point and also added stiffness to the wrist. Furthermore, the combination of opposing forces from both the compression spring and extension springs maintained the wrist in an equilibrium and tensioned state.

As evident from Figure 4.5, the extension springs procured were not the ideal length and needed to be deformed in order to span the distance of the center shaft. This led to a degradation of the integrity of the springs which prevented their use in the final design. This problem was further compounded by the fact that the original length of the center shaft afforded the device very little translational movement once the extension springs had been attached to both plates.

In order to achieve a significantly more useful translational distance between the two plates, the center shaft and the compression spring needed to be lengthened. A compression spring which could accommodate the new shaft length was selected among those which were originally acquired for the initial design.

However, a search for suitable extension springs produced no viable results and a lacking in the necessary background in mechanics to perform a thorough analysis of the forces between all components prevented from generating spring specifications for custom fabrication of adequate springs. This led to the selection of a material which could easily be resized to the desired lengths without lengthy and costly outsourced fabrication. Elastic bungee cords were substituted in place of the tension springs as these could easily be cut to size allowing for quick modification of the length and

tension forces provided. This material substitution prompted a design change for the next iteration and called for eye loops to be fastened to the upper and lower plates to which the cords could be tied.

The original goal for the use of springs in this mechanism was to provide a means of estimating forces acting upon the device based on the amount of deflection sensed by the IR sensors. Quality springs which are precisely manufactured can have very linear spring constants which allow a simple conversion between distances and forces. As this was not critical to the operation of the device, the loss of this additional information was traded in order to achieve the more critical functions which were large range of motion in multiple directions and means of detecting these movements.

In the first iteration, the upper and lower plates were also machined in an attempt to lower the overall weight of the device however the savings in weight were superseded by the loss in rigidity of the material. Since the tension being applied by the springs was focused on the corners of the plates, this generated a slight but still noticeable curvature in the material. Not only did keeping this extra material increase rigidity, it also had the additional benefit of greatly simplifying the manufacturing process as the second iteration required only drilling operations to be performed. The removal of the additional material was a lengthy process since it was performed manually with conventional milling tools.

The attention now moves to the second set of sensors referred to as the external sensors again due to their physical location. These are the outermost four sensors seen in Figure 4.5 mounted on the slightly extruded sections. The mounting surface for the external sensors is in fact a completely separate piece which was designed to be attached to the rim of the designed electronics enclosure and this served to simplify assembly. This came in the form of a square bracket with protruding sections to which the sensors could be attached. These too were incorrectly positioned in the initial prototype in the same way as the internal sensors. The second version of the mounting surface, which accounted for the infrared beam locations of the sensors and aligned these, is shown in Figure 4.11.

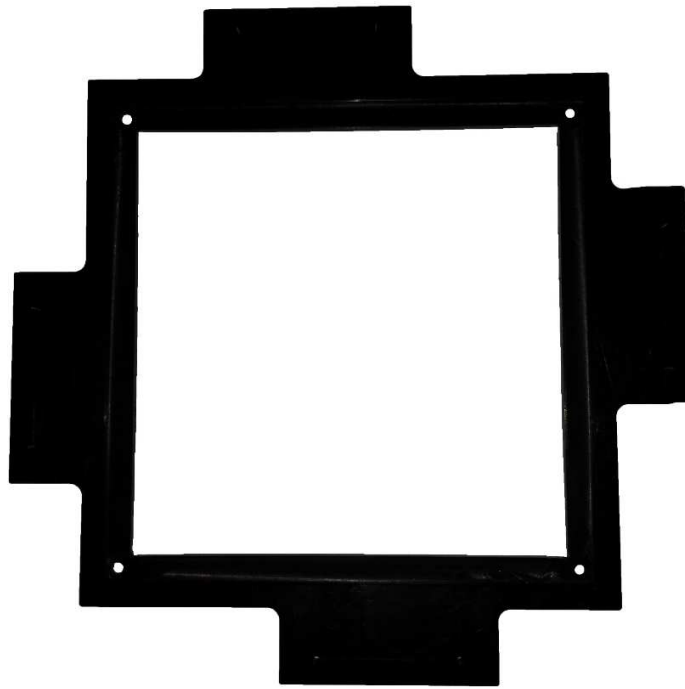


Figure 4.11 : External Sensor Mounting Bracket

Although the external sensors were not meant to measure deflections of a planar surface, ensuring the alignment of the infrared beams served to simplify the interpretation of the incoming data and allowed for code re-use as the same algorithms could be applied for calculating the kinematic parameters discussed in section 5.3. These external sensors needed to be mounted around the periphery of the device as these sensors were meant to allow the compliant wrist to detect external objects in proximity of the wrist along the same direction as that of the center shaft.

The differences seen in this bracket when comparing the short arms in Figure 4.11 to the final prototype of Figure 4.1 were necessary due to alterations made to another component of the device. The length adjustments made to the center sliding shaft, namely its increase in length, highlighted another behavior of the infrared sensors which had not been factored initially. It was mentioned that the infrared sensors emit a cone of light rather than a narrow beam. When the center sliding shaft had its initial length, the proximity of the external sensors to the center of the device posed little problem. However, after the shaft was lengthened, placing the moveable plate further away from all of the sensors, the edges of the moveable plate were now obstructing the light emitted by the external sensors causing erratic measurements. The actual shape dimensions of the cone are not documented in the device's datasheet therefore, the necessary distance from the edge of the moveable plate for the

external sensors could not precisely be identified. This resulted in fabricating additional “arms” for the bracket to allow for the adjustment in position of the external sensors. Trial and error led to the final positioning which accounted for the movable plate’s furthest distance when deflected and an additional safety buffer to ensure stable readings.

When taking into consideration the project for which this compliant wrist was initially conceived there was a possibility that the compliant wrist would need to come into contact with curved surfaces and perhaps also maintain contact while moving along those surfaces. It was realized that a large planar surface acting as the interface between the compliant wrist and those curved surfaces was not the optimal solution. Consider the scenario of a flat surface attempting to make contact with a mildly concave surface (which are common occurrences in vehicle exterior panelling); in such cases only the edges of the flat surface would be in contact with the concave surfaces. Although this in itself might not pose significant problems, any attempt to glide along the concave surface would give rise to the sharp edges of the flat surface being dragged across the concave surface. In an attempt to alleviate this possibility, an optional removable layer was designed for the compliant wrist to act as the direct contacting interface between the compliant wrist and such curved surfaces.

The optional contacting layer comes in the form of two additional plastic plates with holes shaped to accept four 0.25 inch diameter PTFE balls as shown in Figure 4.12. The balls are slightly protruding from the planar surface and these serve to allow the contacting surface to roll over surfaces with which it comes into contact. This is possible since the slight protrusion of the balls slightly raise the edges of the square plates away from contacted surfaces and also because the recesses made to accept the balls have the same curvature allowing the balls to roll freely. An additional benefit of these PTFE balls is that PTFE is a very soft material which could reduce the risk of damaging objects that are manipulated.



Figure 4.12 : Rolling Contacting Surface

This rolling contacting layer was designed to be attached to the planar contacting surface of the compliant wrist via four countersunk screws at the corners of the plate as shown in Figure 4.13.



Figure 4.13 : Rolling Contacting Layer Mounted onto Compliant Wrist

Finally, provisions were made for allowing the device to be mounted onto robotic platforms. Four bolts, located at the bottom of the electronics enclosure, provide a simple means of mounting the device to almost any robotic platform large enough to accommodate the device. All that is required is a dedicated attachment plate for any particular platform to be fabricated and mated to the bottom of the enclosure using nuts to fasten the device in place. Figure 4.14 shows the bottom of the compliant wrist's electronics enclosure which has four bolts protruding and includes the nuts used to secure the device onto an attachment plate such as the one shown in Figure 4.15.



Figure 4.14 : Bottom of Electronics Enclosure showing Mounting Bolts and Nuts

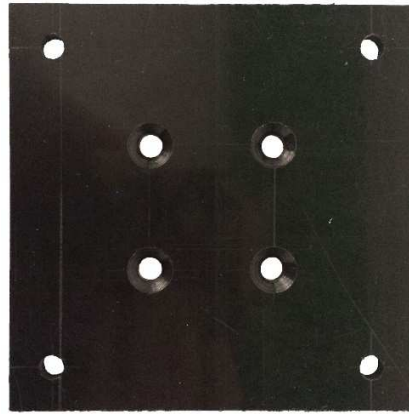


Figure 4.15 : Compliant Wrist Attachment Plate

This particular attachment plate was fabricated for use with the CRS-F3 robotic manipulator. The manipulator in question was designed to have end effector attachments and thus already had an existing mounting location for the attachment plate. The four central holes in the attachment plate are used to secure the plate to the manipulator while the four corner holes are used to accept the bolts of the compliant wrist. Once the bolts are inserted, the nuts can be used to secure the compliant wrist to the attachment plate securely fastening the entire module to the manipulator, as shown in Figure 4.16.

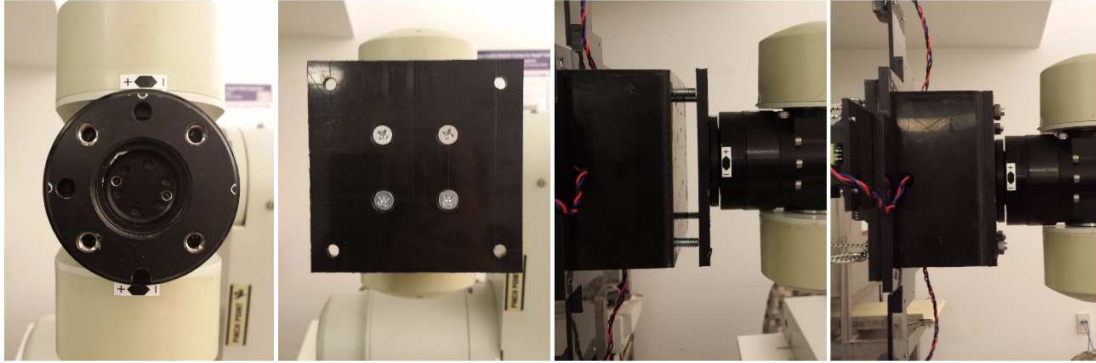


Figure 4.16 : Mounting of Compliant Wrist onto CRS-F3 Manipulator

Figure 4.17 and Figure 4.18 provide references for horizontal and vertical dimensions, respectively, while Table 4.1 provides the values corresponding to lengths identified in the figures. These do not represent an exhaustive list of every possible dimension but rather the dimensions considered to be of interest such as the spacing between individual sensors as well as the offset distances of the contact surface required to determine the “at rest” conditions of the sensors. Due to the fact that the rolling contacting surface was deemed to be an optional component, the distance labelled “E” in Figure 4.18 does not take the additional thickness of this component into account. It should also be noted that the few selected distances can be applied multiple times due to the symmetry of construction.

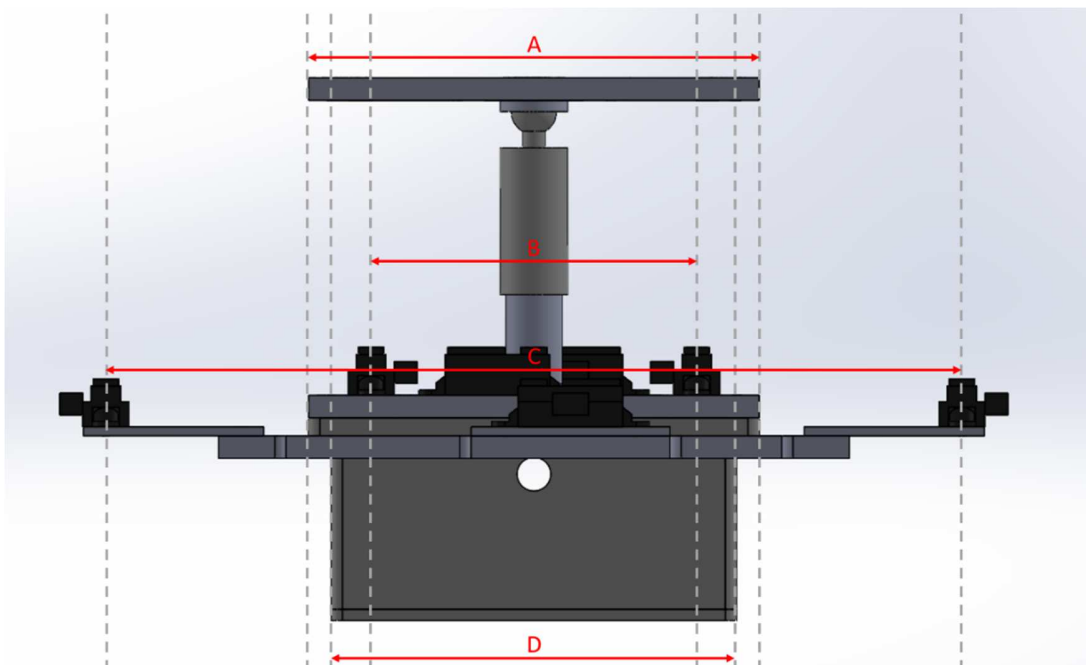


Figure 4.17 : Compliant Wrist Dimensions (Horizontal)

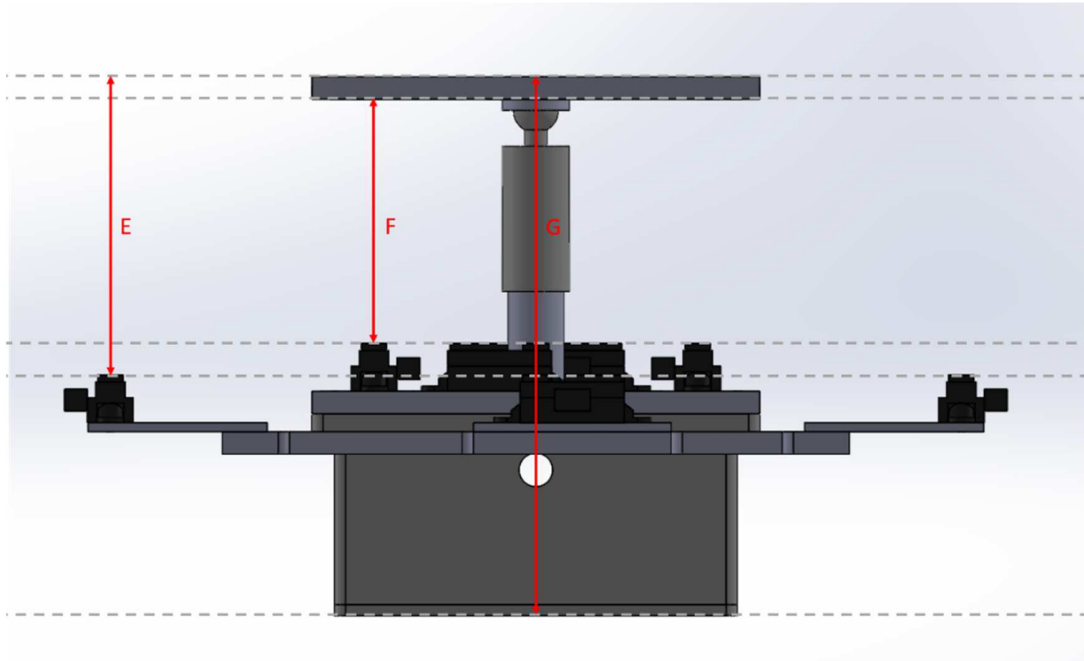


Figure 4.18 : Compliant Wrist Dimensions (Vertical)

Table 4.1 : Compliant Wrist Dimensions

Dimension	A	B	C	D	E	F	G
Value	127 mm	92 mm	264 mm	114 mm	117 mm	95 mm	192 mm

4.2 Electronic System Design

Figure 4.19 illustrates at a glance a typical setting in which the previously described compliant wrist module would be useful. A few key components are required to create a closed feedback loop between the compliant wrist module and a robot seeking to make use of the information it provides. The data path for this loop begins at the compliant wrist and ends at the robot, passing through the intermediary robot controller. A robot controller is typically responsible for gathering information from various sources and formulating a clear action that the robot should take based on the available information. By mounting the compliant wrist to the end effector of a manipulator robot, rudimentary senses of touch and vision are made available to the robot controller during motion, provided via the internal and external arrays of infrared sensors, respectively, which are aboard the compliant wrist.

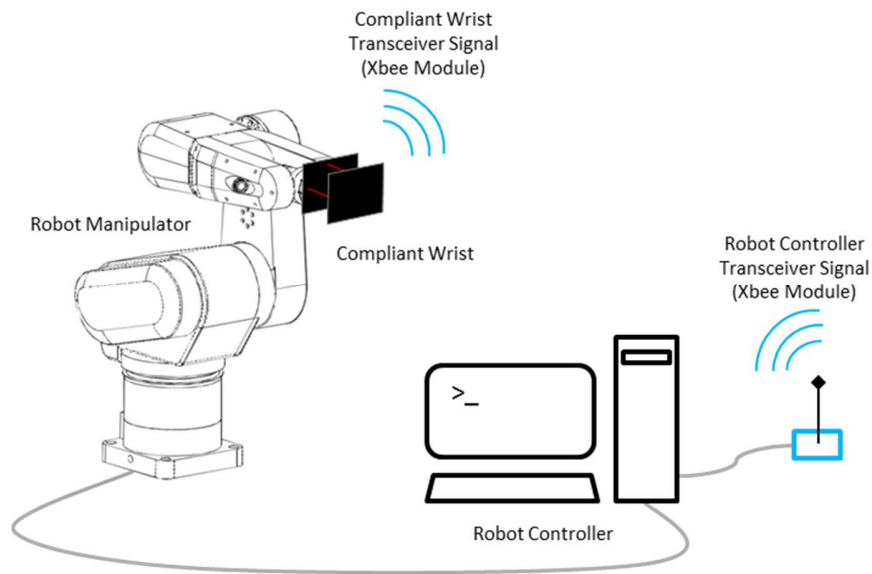


Figure 4.19 : Conceptual System Operation Diagram

Ideally, the compliant wrist module would be wirelessly communicating its data with a robot controller, be it one aboard a mobile robot or a separate terminal connected to a stationary manipulator robot, as adding physical connections to any platform comes with its own drawbacks such as limiting the available range of motion of the robot. In Figure 4.19 the wireless communications is illustrated by the blue arcs in the vicinity of the compliant wrist module and the transceiver connected to the robot controller terminal. This is the medium through which all information generated by the compliant wrist is delivered to the robot controller. The communication channel is bidirectional allowing the robot controller to send commands to the module to make data requests as necessary. This is in contrast to having a one way communication scheme where the compliant wrist continuously broadcasts its data. This information, coupled with the state information of the robot, is likely to be used by the robot controller within the implemented trajectory planning algorithms it uses to direct the motion of the robot.

Wireless communications and having the device rely on batteries for power was a design choice which was meant to increase the compliant wrist module's versatility. These two key features allow the device to be self-contained in the sense that no physical connections to external devices are required. In the event that a physical connection to the device does not impede the robotic platform's movement or operation, there is still the possibility of providing power to the device via a USB cable. The previously mentioned power switch effectively disconnects the onboard power source from the microcontroller. This can allow the compliant wrist to operate for extended periods of time by tapping into an external

power sources which would not be limited in size due to the size constraints of the electronics enclosure.

In order to achieve a completely self-contained module to be integrated onto various robotic platforms several electronic components were required. The following subsections discuss the development of the electronic backbone of the device and highlight the functions of the major components selected to provide the necessary computational power and interface connections for the compliant wrist module.

4.2.1 Microcontroller

In order to achieve the desired functionality set out in the design goals, some form of onboard computing capability was required. This came in the form of a microcontroller. Microcontrollers combine a multitude of digital hardware components with the ability to be programmed leading to an extremely versatile device capable of acquiring information from various external devices, processing the information as desired as well as communicating the processed information via an array of interfaces. In the case of the compliant wrist, the incorporated microcontroller was tasked with sampling the infrared sensor output voltages, digitally filtering those incoming signals, performing the necessary conversions from voltages into distances, extracting additional kinematic information from the sensors' distances as well as handling data requests and communications with external devices with the goal of communicating the compliant wrist's current state.

By incorporating a microcontroller directly into the compliant wrist, almost all of the computational requirements are handled prior to being received by a particular robot controller further lightening the computational load of the controller and allowing it to focus primarily on decision making tasks such as path planning and controlling the robot's movements.

One of the most commonly used type of microcontroller to date for robotics projects belong to the Arduino family of microcontrollers. The work that went into providing a quick and simple interface for programming the device made it very popular. However, a microcontroller manufactured by Microchip was selected over the Arduino family of devices due to its many advantages such as an increase in processing speed five times greater than that provided by Arduino, increased memory and flash space, nearly double the available pin connections, double the analog inputs, and greater overall

flexibility of peripherals. All of these advantages are provided by the Microchip family of microcontrollers for nearly no increase in price all while maintaining the simple programming interface.

The increase in speed was necessary to achieve the desired performance of the compliant wrist due to the large quantity of calculations required for the successful operation of the device. When initial development began, the Raspberry Pi device and its vastly improved performance were not yet available, although speed of firmware development might have been a deciding factor due to the existing familiarity with Microchip based devices.

The computing power of the instrumented compliant wrist is provided via a ChipKIT uC32™ prototyping platform, shown in Figure 4.20, which has at its core a Microchip® PIC32MX340F512H microcontroller capable of operating at 80 MHz. The analog to digital conversion (ADC) unit available on this microcontroller provided the 8 necessary inputs (12 available) with which to sample the distance measurement sensor output values for future processing. This microcontroller's ADC is only capable of sampling one input at a time through the use of a multiplexer and therefore does not provide temporally synchronized samples. It also makes use of successive approximation to convert an analog voltage value to a discrete digital representation. Additionally, the microcontroller provides two universal asynchronous receiver/transmitters (UARTs) which were used to provide the module with the necessary communication capabilities to transmit information to external devices. Another indispensable feature of this microcontroller is an onboard section of flash memory which can be used for storing small amounts of data which will persist between power cycles allowing for the storage of settings information.



Figure 4.20 : ChipKIT uC32 Microcontroller

As will be seen in the following chapter, the microcontroller is not only responsible for collecting data from sensors but also for the pre-processing of that information. The software developed to operate on the microcontroller provides digital filtering in the form of tunable finite impulse response filters. Details of the acquisition of voltage values from the analog sensors are provided in section 5.2, a list of filtering methods available are provided in section 5.2.3, the voltage to distance conversions are covered in section 5.1.1, the types of kinematic parameters and how they are extracted from the sensors' distances are presented and explained in section 5.3, while the implemented communications protocol is described in section 5.4.

4.2.2 Infrared Sensor Unit

The distance measurements allowing for deflection calculations both during contact and prior to contact are obtained via eight analog Sharp GP2Y0A41SK0F IR Range Sensors, one of which is shown in Figure 4.21. This sensor has integrated electronics combining PSD, an infrared light emitting diode and a signal processing circuit. The resulting voltage output is produced according to a triangulation method. The nature of the PSD is what generates the analog voltage.



Figure 4.21 : Infrared Distance Measurement Sensor

These particular sensors have a suggested operational range of 4 to 30 cm. However the data sheet provides an example of sensor outputs for ranges extending to approximately 40 cm [90]. According to the data sheet these sensors also have an update frequency ranging between roughly 50 to 80 Hz for the output voltage. In order to minimize the complexity of the circuitry in the system, the IR sensors are connected directly to the analog inputs of the microcontroller without any anti-aliasing filter

circuitry with all of the additional signal processing discussed in Chapter 5 being conducted digitally by the microcontroller.

The reasons for selecting this type of sensor technology, i.e. infrared sensors, were summarized in section 2.3.7. The analog output option was selected to take advantage of the microcontroller's onboard ADC as this provides an efficient means of acquiring analog readings. The selected sensors provide a simple interface requiring only three connections, two for powering the sensors with 5V and ground, and a third for its signal output. Most digital sensors encode data in binary and require either multiple connections in parallel to transfer data or the use of popular interfacing technologies such as I²C or SPI to serially transmit data. The digital infrared sensors which were commonly available at the time of sensor selection however only had a digital output indicating whether an object was present or not in the detection range. Since that time, a new type of sensor (the VL6180) has been developed which combines multiple sensing technologies including a time of flight proximity sensor with an operating range of 0 to 10 cm. Time of flight sensors have the additional benefit of being less prone to noise and would therefore merit further investigation as an alternative to the currently used sensors. Due to the popularity of the selected infrared sensors, electronic component manufacturers have already integrated the VL6180 device onto a circuit board which has the same physical footprint as the SHARP IR sensors simplifying the substitution of the sensor into existing projects and designs. Despite its ease of substitution in a mechanical sense, the limited range provided by this sensor and the need for a different interface in order to retrieve information from the sensor would not have made evaluating this sensor a trivial task and therefore the IR sensors were kept in the design.

4.2.3 Radio Module

Wireless communications with external devices is achieved with the use of a Digi International XBee S1 radio, shown in Figure 4.22. These radio modules were selected due to their ease of interfacing with the UARTs available on the microcontroller. These types of radios are normally setup as local area networks with each radio assigned its own identification number or address allowing for multiple devices to communicate with each other. These networking functions are already embedded inside the firmware of the individual devices and do not require additional work other than the initial programming of the addresses and the baud rate at which they will communicate with the peripheral device to which they are connected. Wireless transmission rates are executed at a speed of 250 kbps while transfers of data between the radio module and peripherals can be performed at a range of

speeds depending on the peripheral's requirements. The particular module selected is classified as being low power and therefore has a limited indoor range of up to 30 m, which is largely sufficient to support operation of the compliant wrist on a manipulator robot, but may pose limitations for mobile robots with centralized control. The line of XBee products does however include modules which are able of longer transmission ranges albeit at the cost of high power consumption for these particular scenarios where the greater power requirements might be met.



Figure 4.22 : XBee Radio Module

4.2.4 Radio and IR Sensor Shield

In an attempt to limit the overall size of the compliant wrist module a custom made circuit board was designed and is shown in Figure 4.23. This particular board design was made to conform to the connection footprint of the selected microcontroller so that it could be directly connected to it as an additional layer. The common term for such a board, when combined with the kind of microcontroller being used, is a shield. The goal of the design was to consolidate the wireless communications module mentioned above with all of the additional wiring required by the IR sensors into a more compact form rather than having loose connections on a prototyping board which could easily come loose during robot motion.

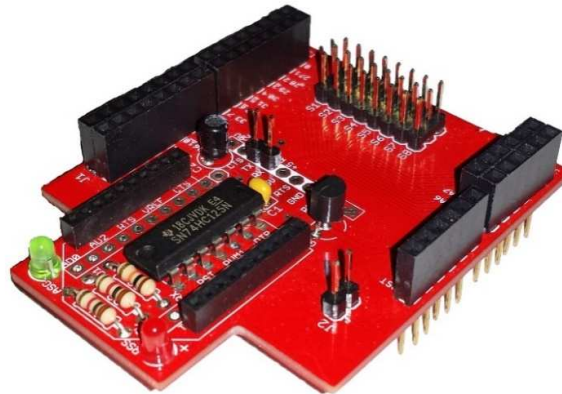


Figure 4.23 : Custom Microcontroller Shield

Eagle files are used to create board layouts for printed circuit boards. An internet search led to the files used to create a breakout board for the radio modules, i.e. a board which provides access to the necessary connections of the module. The resulting circuit is shown in Figure 4.24.

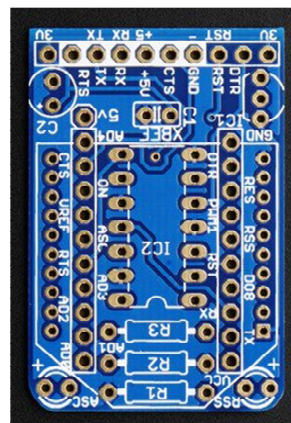


Figure 4.24 : Radio Module Breakout Board

This was copied into the custom design and can be seen in Figure 4.25 which shows the custom shield populated with the necessary components enabling the operation of the radio module. Also included in the figure are the pins and wiring added to connect the outputs of the sensors to the ADC inputs of the microcontroller and direct power from the microcontroller to the sensors. These correspond to the three rows of 8 pins, identified by the markings on the board S1 through S8. Two additional pins were connected to the RX and TX signals of the radio module to drive the two LEDs mentioned previously for showing communications status.

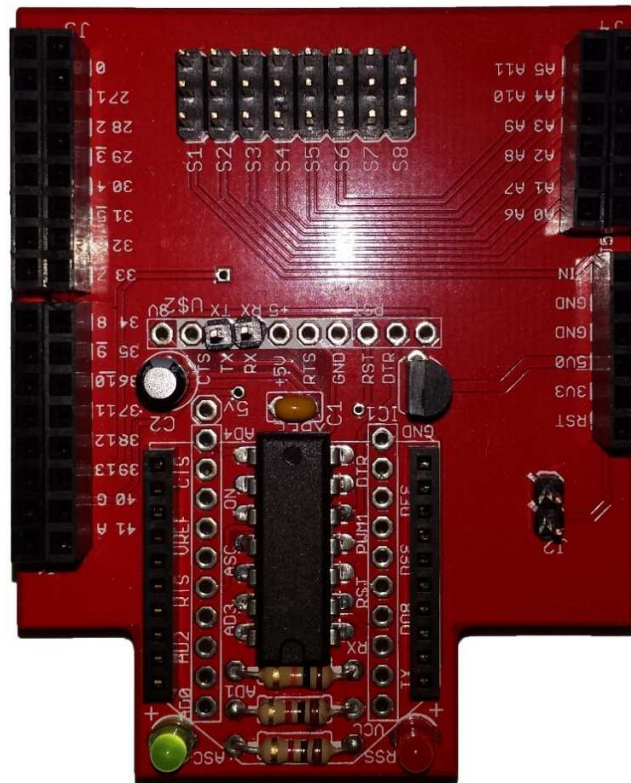


Figure 4.25 : Custom Shield Layout

This circuit board allows the XBee radio and all eight IR sensors to be easily connected to the necessary microcontroller pins for control and also greatly simplifies the assembly process and reduces clutter in the electronics housing by eliminating dozens of additional wires leading to a more compact design. An example of how connections are made to the shield for an XBee module and a single IR sensor is shown in Figure 4.26.

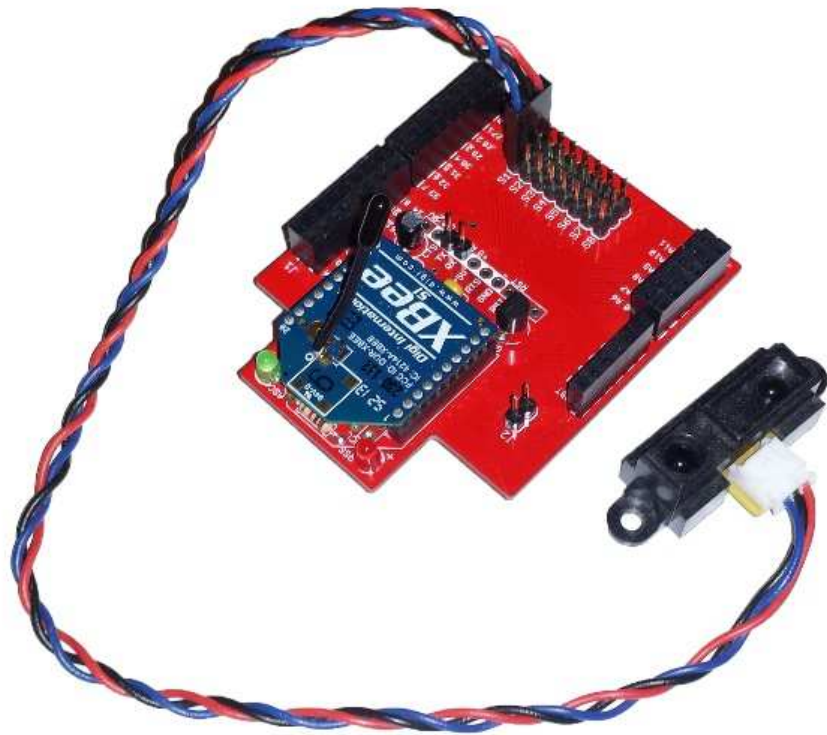


Figure 4.26 : Shield with Radio Module and IR Sensor Connections

The benefit of adopting a shield design for the footprint of the board is that additional functionality can be easily added to the current implementation with third party shields since the unused pins are still accessible through the current shield. Figure 4.27 shows how the custom shield can be connected to the microcontroller.

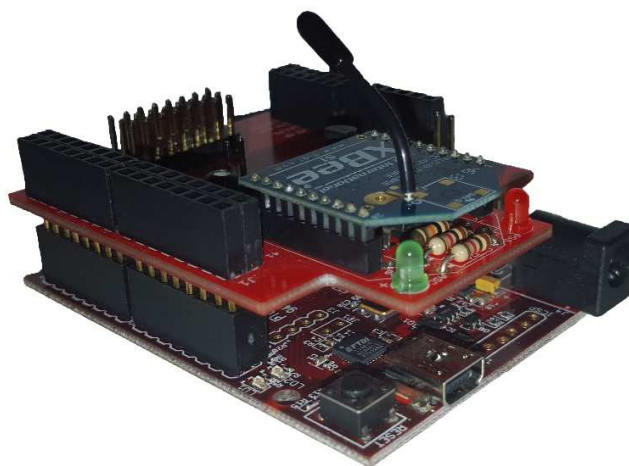


Figure 4.27 : Microcontroller and Custom Shield Connection

Shields essentially connect to all pins available on the microcontroller while making those connections available to any other shields which might be required by the system and form a vertical stack. The number of shields which can be used are limited only by the available pins each shield uses and the current drawn by each device as the microcontroller has a limited output dictated by the physical hardware. One example of these shields was used for the collection of data during the experimental protocols and provided access to an SD card for data logging. This shield is not included in the image as it is not an essential component to the compliant wrist's operation. The pairing of the compliant wrist's mechanical structure with IR sensors and the electronic components just mentioned result in a self-contained device capable of relaying vital physical state information of the device's surroundings to a robot controller so that it may incorporate the data into its control loop and increase the versatility of the robotic platform whose motion it is guiding.

Chapter 5. Embedded Software Development and Operation

The previous chapter introduced the physical components which were designed and integrated to form the compliant wrist system's structure and the devices meant to provide the necessary functionality. This chapter builds on the notions previously introduced and describes primarily the inner workings of the compliant wrist. In order to achieve the operational goals set forth, a great deal of effort went into the development of software which would allow the compliant wrist system to gather data from its environment, process it and relay meaningful information to a robot controller, independently from the exact nature or brand of the robot. The control system developed to orchestrate the behavior envisioned in Figure 4.19 is graphically summarized in Figure 5.1 where the objects contoured by solid lines represent physical hardware and peripheral devices while dashed lines represent the implemented software constructs in an object oriented programming paradigm.

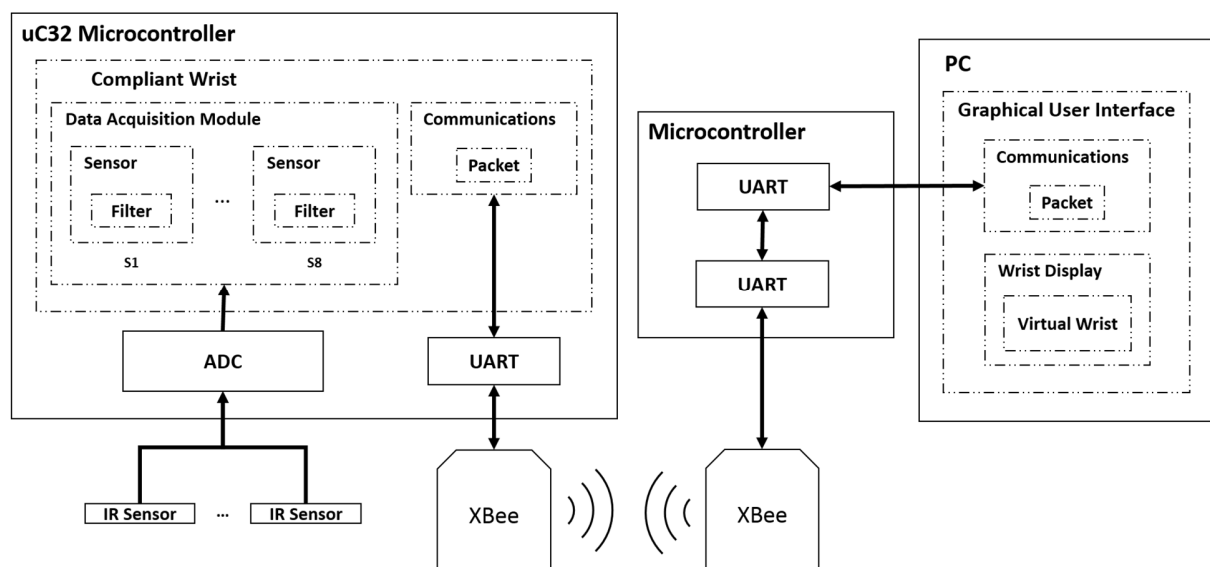


Figure 5.1 : Compliant Wrist System Diagram

The figure shows again two devices communicating wirelessly via the XBee modules. The compliant wrist system is represented by the components in the left section of the image while the robot controller, conceptually represented by a PC connected to another XBee acting as the PC's transceiver, is depicted on the right section of the image.

The microcontroller introduced in the previous chapter is at the core of the compliant wrist system. The latter is represented in software by its own class which models the physical aspects of the compliant wrist device such as the location of each IR sensor on the compliant wrist relative to its defined

origin, stores the voltage measurements acquired from the IR sensors and computes the distances corresponding to those voltage measurements. This part of the system is also responsible for manipulating the distance measurements to obtain the translation along the Z axis, the rotations about the X and Y axes from each sensor set, four separate normal vectors, as well as transformation matrices describing the 3D homogenous transformations. The reason for extracting this additional kinematic information from the distance measurements is that a more compact representation of the compliant wrist's pose exists in the form of a transformation matrix. In this case, the pose can represent one of two things depending on the scenario. In the first scenario, the compliant wrist is not yet in contact with an object and the distance information coming from the external sensors can be used to gather information on the object itself while in the second scenario, the compliant wrist has made contact with the object and the distance information coming from the internal sensors can be used to gather information on how the compliant wrist is being affected by the object with which it is interacting. The translation and rotations parameters, along with the known physical constraints of the device, are all that is required to generate a fully defined transformation matrix to express the information just mentioned. These parameters and their functions will be further discussed in subsequent sections of this chapter.

The data acquisition module is responsible for controlling the sampling rate of the analog-to-digital conversion (ADC) peripheral onboard the microcontroller to which the eight individual IR sensors are connected. It contains buffers for storing the incoming samples of the ADC and digital filters for additional signal processing prior to output generation. All of the information gathered from the sensors, i.e. the raw sensor voltages, converted sensor distances, rotations, translations and normal vectors, is made available to external sources, such as a robot controller. To achieve this exchange of information, one of the two universal asynchronous receiver-transmitters (UART) included on the microcontroller was connected to an XBee radio module.

The right portion of the diagram in Figure 5.1 illustrates the setup for the visualization platform developed to aid in system configuration, testing and data collection. It currently comprises of a personal computer equipped with a similar microcontroller and another XBee radio module giving it the ability to wirelessly communicate with the microcontroller located onboard the compliant wrist. A graphical user interface allows for the modification of settings of the software components in the compliant wrist and also provides a means of actively visualizing the operation of the compliant wrist. Details of the development of each component of the system are provided in the following subsections.

5.1 Infrared Sensors

The infrared distance measurement sensors are the key components for the instrumentation of the compliant wrist module. They allow for the detection of objects in proximity to the device as well as an indirect means of detecting physical contact between the device and its environment by measuring deflections of a movable plate interface. In order to effectively integrate these sensors into the compliant wrist system, several issues needed to be addressed and are presented in the following subsections.

5.1.1 Voltage/Distance Conversions

The output of the chosen infrared sensors is an analog voltage. The voltage output and the corresponding distances have a nonlinear relationship and an example of the sensor's response is provided in the sensor's datasheet in the form of a graph [90]. However, exact values for the data points shown in the graph are not provided and therefore the reproduction of the curve shown in Figure 5.2 is an assumed approximation.

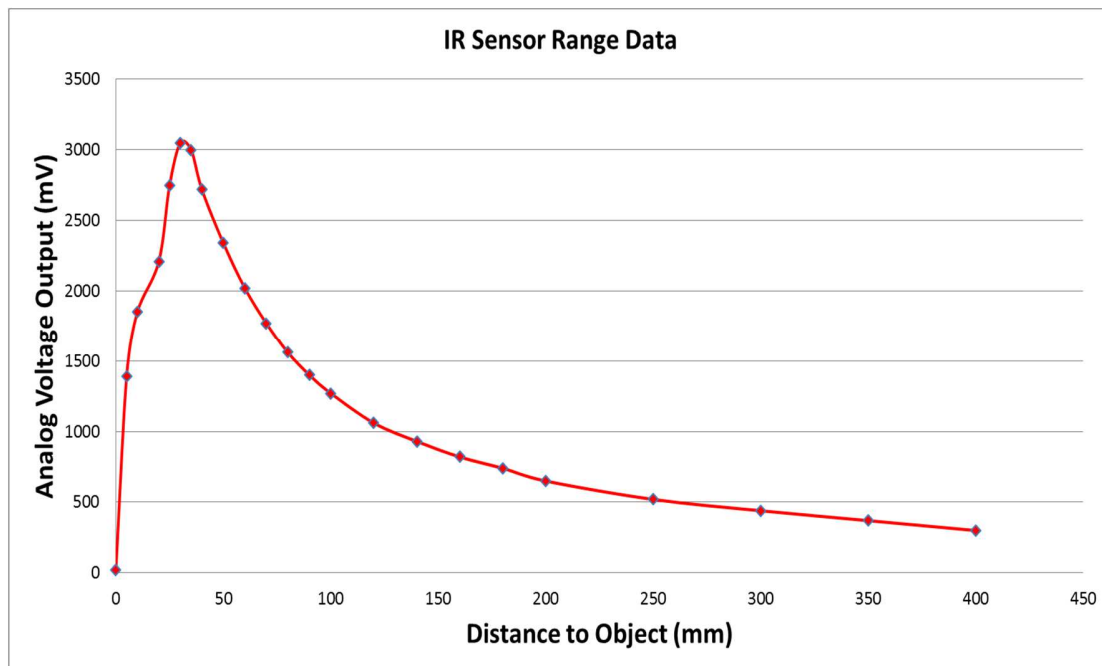


Figure 5.2 : Voltage to Distance Characteristic Curve

The corresponding approximated values which were extracted from the datasheet are given in Table 5.1. As the exact values presented in the datasheet could not be obtained from the manufacturer, those presented in the table were selected as being the baseline or target values for reference. Since

only a finite set of data points are provided, there exists a need for data interpolation to obtain a meaningful distance conversion for voltage values between those provided. The shape of the curve in the datasheet clearly shows that not only is the behavior of the sensor non-linear, but the output also cannot technically be described by a function in the strictest sense since it has two different distance values associated to a single voltage value. The solution to this problem was to limit the physical workspace by ensuring that objects appearing in front of the sensors would not be able to enter the undesired range. For the case of the selected sensors the shortest distance which could be achieved was approximately 30 mm and any object appearing in front of the sensors at a distance shorter than this would be confused with objects that are believed to be further away.

Table 5.1 : Voltage to Distance Data Points

Data Point	Voltage (mV)	Distance (mm)
1	20	0
2	1390	5
3	1850	10
4	2210	20
5	2750	25
6	3050	30
7	3000	35
8	2720	40
9	2340	50
10	2020	60
11	1770	70
12	1560	80
13	1400	90
14	1270	100
15	1060	120
16	930	140
17	820	160
18	740	180
19	650	200
20	520	250
21	440	300
22	370	350
23	300	400

In order to determine if the IR sensors were suitable for the desired application, the generated outputs had to be further examined through experiments. During these preliminary experiments with the distance measurement sensors it was found that the provided values in the datasheet were simply

an example of what to expect when recording distances with these sensors and that the actual output for each individual sensor was unique. Initially, the generated voltages of the IR sensors were converted to distance values according to the response curve given in the datasheet with the conversion from voltage to distance for intermediate values being made with the use of the Catmull-Rom spline interpolation technique [116]. However, when two sensors were positioned at equal distances from a planar surface it was found that there were some variations in the output signal between the two sensors resulting in different distance measurements.

The datasheet had suggested that a linear approximation could be made for the output if the inverse of the distance relationship to the voltage was considered which would have been an ideal solution in providing a simple conversion method to obtain the sought after distance measurements. However the differences between each sensor also prevented this option from being used. It was found that not only did the sensor outputs differ from one another, but the difference between the sensors was not a simple offset. Rather a completely different response was found which varied across the range of distances which were examined, namely the range of distances going from the lower limit of 30 mm to the upper limit of 400 mm as depicted in the datasheet. This upper limit was also verified experimentally and was used instead of the suggested upper range of 300 mm. These differing responses prevented the reliance on the provided data as well as on a simple equation for measurement conversions. Figure 5.3 shows a comparison of the response of four different sensors obtained experimentally (Sensor 1, Sensor 2, Sensor 3 and Sensor 4) against the theoretical response curve (Data Sheet) provided in the sensor's data sheet. In this particular case, the sensor voltages generated at shorter distances tend to be greater than expected, while those generated at longer distances tend to be lower than expected with slight variations among the sensors. This experiment revealed that the distance/voltage relationship curve available in the datasheet did not guarantee sufficiently accurate results for the intended application. When trying to estimate the position and orientation of an object, if all sensors do not agree with the ground truth then unwanted errors will be introduced into the system.

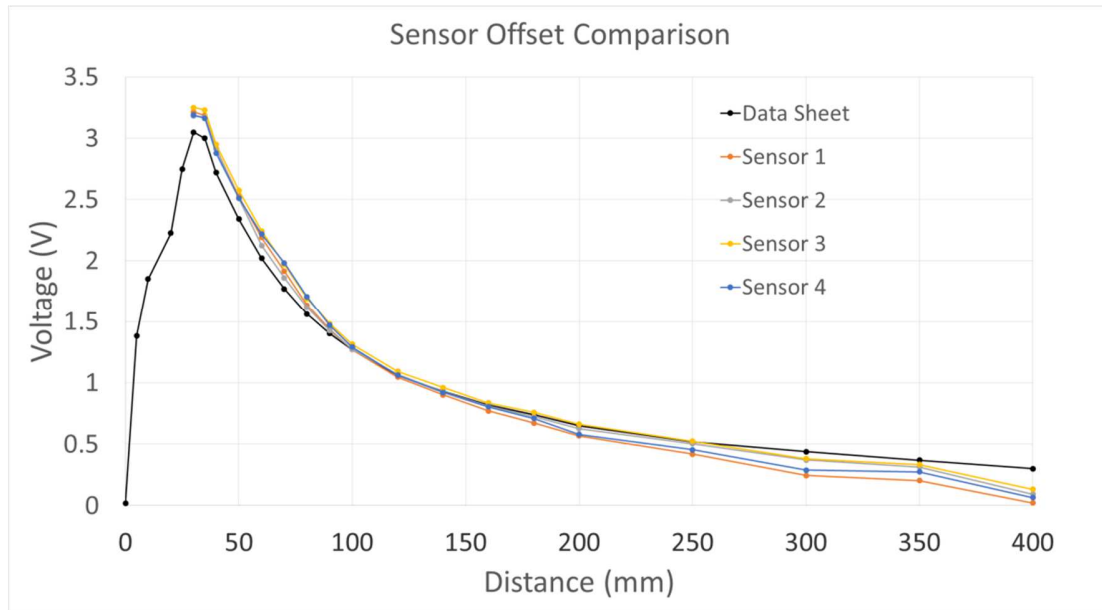


Figure 5.3 : IR Sensor Output Comparison

In order to achieve uniformity between sensor outputs, a means of obtaining similar conversions of voltage to distance had to be developed. Since the voltage values generated by the sensors varied between sensors for similar distances, a means of shifting the output of the sensors was required. The simplest solution was to implement these level shifts in software and a calibration procedure was defined in order to determine the appropriate level shifts for a multitude of known positions. This allowed for the generation of custom voltage to distance conversion curves matching the true response of the individual sensors. This calibration procedure is presented in the following subsection.

5.1.2 Calibration Procedure

The IR sensor calibration procedure was developed in order to improve the accuracy of the compliant wrist's distance estimates, both for proximity and contact interaction monitoring. In essence, this procedure entails fitting the true response of the IR sensors to a desired response curve. This is done by examining the response of a sensor when an object is placed at known distances in front of the sensor and adjusting that response via a series of voltage offsets, one for each of the chosen distance values.

As mentioned previously, not all distances are valid when trying to obtain a relationship between the distance being reported by the sensor and voltages they produce. When looking at Figure

5.2 we can see a curve composed of 23 points. These data points come directly from the data sheet and of the 23 provided distance/voltage pairs, only 18 were found to be of practical use, namely the rightmost 18, since the first 5 voltage values corresponding to distances below 3 cm cannot be discriminated from the voltage values corresponding to distances above 3 cm. The 18 calibration points are listed in Table 5.2 and correspond to entries 6 to 23 of Table 5.1.

Table 5.2 : Calibration Voltage/Distance Pairs

Data Point	Voltage (mV)	Distance (mm)
1	3050	30
2	3000	35
3	2720	40
4	2340	50
5	2020	60
6	1770	70
7	1560	80
8	1400	90
9	1270	100
10	1060	120
11	930	140
12	820	160
13	740	180
14	650	200
15	520	250
16	440	300
17	370	350
18	300	400

The calibration procedure involved the mounting a flat surface onto a 1D motorized track, equipped with an encoder to provide accurate distance measurements. Figure 5.4 shows the motorized track which was used to carry out the calibration of the sensors. From left to right are the power source and track controller, followed by the motor which was linked to the encoder by a belt drive. Next are the infrared sensors mounted at the origin of the track and connected to the microcontroller (a more detailed image is provided in Figure 5.5). The last component was a sled which could be moved from left to right by being connected to guide rails and a worm gear. The motor was used to actuate the worm gear and control the position of the sled to which the previously mentioned flat surface was attached. The goal was to position the flat surface at the distances corresponding to the 18 selected points so that the converted sensor outputs could be compared to those distances.

In order to ensure a viable calibration, the IR sensors were positioned such that the spacing between the sensors during the calibration would be the same as the spacing of the internal sensors when mounted on the compliant wrist. This was done in an attempt to have similar operating conditions in both cases with focus being placed on the internal sensors as the distances reported by these sensors needs to be as precise as possible. Calibration was performed with all sensors operating simultaneously and therefore there could have been minor effects of cross-sensor interference at larger distances where the IR light cones might have overlapped. However, when examining the sensor outputs both with all four sensors in operation and comparing them with the outputs of the sensors operating on their own, no discernable differences in output were perceived. This is most likely due to the fact that there was very little interference at shorter distances and any interference at larger distances were overtaken by the highly fluctuating nature of the signals at those larger distances.

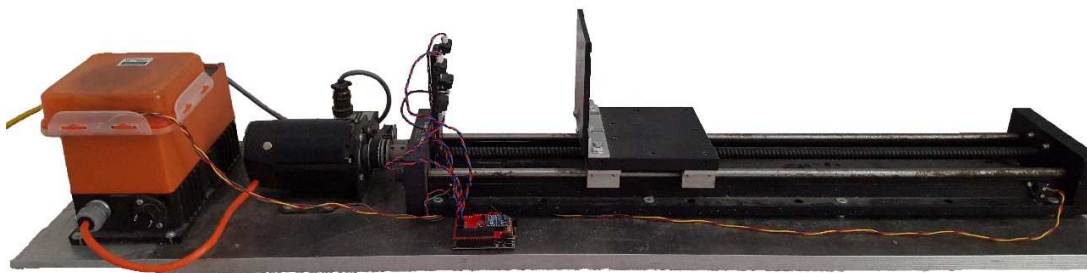


Figure 5.4 : Calibration Equipment

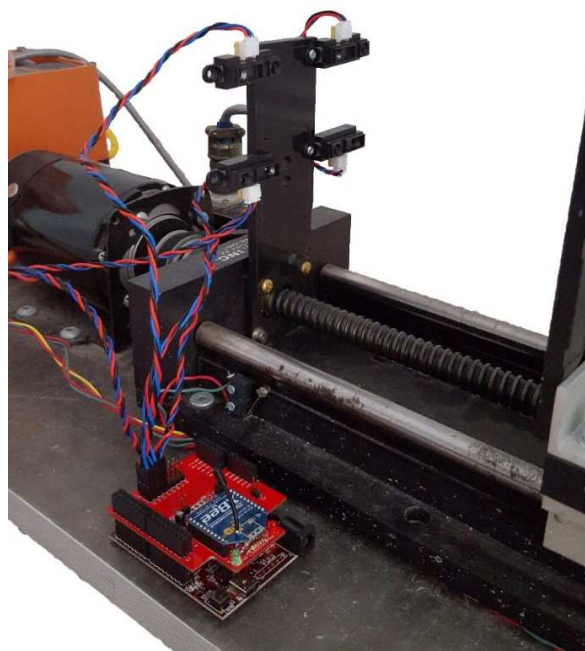


Figure 5.5 : Calibration Setup

With the target surface positioned at each of the 18 distances, the actual voltage values provided by every individual sensor were measured and converted to distances. If the converted distance obtained from the sensor differed greatly from the true physical distance indicated by the track's encoder, the voltage output was offset until the distances more closely resembled the true physical distance. This resulted in a series of 18 voltage offset values for each sensor. It should be noted that would a sensor become defective and need to be replaced, a recalibration of the device would be required to match the replacement sensor's output with those of the sensors still aboard the device as new offsets for the replacement sensor would be required. For this reason, it was decided that the voltage offset values should reside in the device's persistent memory rather than be hardcoded into the device's firmware which would have necessitated the device to be reprogrammed after every calibration.

Exact tolerance values for the voltage offsets were difficult to define as the signals being generated by the sensors oscillate to varying degrees and the oscillations increase as distance to the target surface increases. Software tools were developed to provide a visual representation of the calibration's accuracy and further details explaining how the calibration was performed are presented in Appendix C, section C.3.

By performing this procedure on all of the sensors, it was possible to compensate each of the individual sensor response curves so that they would resemble each other as much as possible with the intention of matching a single ideal response in order to reduce the errors associated with using sensors with different responses. This had the effect of simplifying the implementation of the physical compliant wrist without introducing bias in the distance and transformation estimates.

During the initial trials of this procedure, a rudimentary algorithm provided the means for updating the voltage offsets by manually entering the desired offset values and having the microcontroller update its internal settings so that the distance conversions could be printed out to a computer display in real-time to inspect the results. It was immediately evident that this procedure was essential to the proper operation of the device as the outputs of 2 sensors were very closely matched upon setting the voltage offsets for the range of distances being evaluated; however it was also evident that a more sophisticated method of carrying out this procedure would be required to both improve accuracy and reduce the time required to calibrate multiple sensors.

This was one of the first cases which spurred the parallel development of companion software which could be used to interface with the compliant wrist's microcontroller to modify its internal settings without requiring the device to be reprogrammed to experiment with new values. What began as an attempt at providing a more efficient means of validation and testing development of the compliant wrist's operating system became a full-fledged control and setup application to be used in conjunction with the compliant wrist. The implementation details and explanations about how this application served to improve the system as a whole is provided in Appendix C.

5.2 Data Acquisition

The analog voltage sampling hardware along with the analog to digital converting hardware available on the chosen microcontroller were used to capture the information coming from the physical IR sensors. However, the hardware alone was insufficient to produce the desired outputs for the system to operate as intended. For this reason a software data acquisition system was devised. In order to provide the desired system flexibility, this system was separated into multiple independently adjustable sections. Referring again to Figure 5.1, the data acquisition module encapsulates eight sensors which themselves each encapsulate a filter. This highlights each component of the system and the fact that these are all capable of being modified to suit the needs of the desired application. The following subsections describe the possible adjustments available to the user and describe how each of these affect the operation of the data acquisition system.

5.2.1 Data Acquisition Sampling Frequency

In order to provide an additional level of flexibility to the system, the sampling frequency of the data acquisition system was also made to be adjustable. Sampling frequency plays a large role in the filtering process as it can dictate the overall bandwidth available during signal processing. The datasheet for the microcontroller's processor [117] states that the maximum sampling rate for the ADC is 1,000,000 samples per second (1 MHz). Since there are eight analog input channels being used for the operation of the compliant wrist, this upper limit is not achievable for each channel and is therefore only a fraction of this number. The sampling method incorporated into the compliant wrist's operating system made use of interrupts in order to obtain a very accurate sampling frequency. However, due to the way in which the custom operating system was implemented, the true maximum rate at which all channels could be sampled was very difficult to determine.

A great deal of effort went into making the compliant wrist module operate in real time so that it could service multiple peripherals without hang-ups on any one particular action. This made the data acquisition system particularly difficult to implement since sampling rate needed to be limited in such a way that successive program interruptions would not have adverse effects on other parts of the system. Several factors had to be considered so that the overall program execution could be completed. These included the filtering operations which needed to be completed for each new incoming sample so that a proper sensor output was maintained, servicing of the communications channel so that incoming data requests could be processed, and performing calculations to reflect the current system's overall state. This made it very difficult to reproduce errors and to debug the system since there were no provisions for simulating specific conditions encountered during live system tests.

Despite the problems encountered during the development of the data acquisition portion of the operating system, estimates of the upper limit for channel sampling rates were obtained via trial and error. Continuous operation was achieved with sampling rates upwards of 850 Hz per channel. Since the sensors have a maximum update frequency of 80 Hz according to the IR sensor datasheets, it was concluded that the computing speed of the microcontroller was great enough to allow for the use of oversampling in order to minimize aliasing of the input signal and to provide a more stable output.

5.2.2 Sensors

The sensor objects implemented in software served mainly as storage for both the incoming data stream of voltage samples and the output stream of data, be it filtered or unfiltered. Additional provisions were included to allow for each sensor to control its own sampling frequency by applying a divisional factor to the current data acquisition system's sampling frequency. While these software components were being developed, it was not known how quickly the overall system would be able to process information and therefore the previous method as well as the ability to effectively turn the sensors on or off were considered for their possible benefits. By turning off a sensor, newly incoming samples would not be stored nor processed by applying the currently selected filter thereby reducing processing loads. Since the system was designed to provide information on request, by allowing the user to configure which sensors are actively being sampled by the ADC, sampling rates for particular sensors could be increased if needed.

5.2.3 Filters

One of the most commonly used digital FIR filters for dealing with random noise is the moving average filter. It is an intuitive choice to say the least since it makes use of multiple samples over time to increase the certainty of a measurement. Each of the output samples in time are simply a weighted average of a select number of input samples with each weight having a value of 1 divided by the number of total samples selected, that is at least for a normalized average. It is also the most basic form of windowed filters using a rectangular window with unity as the underlying function that is being windowed.

This is the type of filtering which was carried out during preliminary evaluation of the IR sensors which had been selected in order to improve the stability of the output being generated. However, in an attempt to avoid haphazardly applying an incorrect filtering method to sensors which had not been statistically characterized, additional care was given to establish a more robust and quantifiable filtering strategy. The main reason for this being that a few online sources [118]–[120] had mentioned specific causes of noise possibly interfering with the sensors' outputs such as power line interference or even interference from ambient lighting which might not necessarily be completely random. Therefore, without knowing the specifics of the sensor response, measures were taken to allow the user to treat the incoming signals with a variety of filters in order to obtain a final response better suited to a specific application. The solution came in the form of a filter module embedded in the operating system which could be configured to produce a wide variety of filtering solutions.

There are two main categories of filter responses, those which are known as finite impulse response (FIR) filters and the other being infinite impulse response (IIR) filters. Both have their advantages and disadvantages, however, FIR filters were eventually selected. IIR filters have the very useful advantage of being quickly computed however they are restricted to very well defined responses such as the Butterworth and Chebyshev responses as examples. This is due to the fact that the responses must be recalculated based on the desired characteristics which involves conversions between the time domain and the frequency domain. IIR filters can also potentially be unstable. FIR filters, although requiring more computational time to execute, can be easily synthesized to reproduce nearly any filter response imaginable if time is not a factor. Also, these are guaranteed to be stable due to the lack of feedback upon which IIR filters rely for their fast execution time. The latter FIR filter option

was chosen since the type of filter that would be required to obtain a useful sensor response was not known beforehand and thus multiple options would be readily available.

FIR filters in digital processing are represented in the same way as any other signal, a series of values in time, where the time scale depends on the eventual signal to which it will be applied, since in the digital world, the time spacing between samples or consecutive values in a signal must be specified to give the signal meaning. These series of values are referred to as the filter kernel. These filters and their effects can be applied to signals by means of convolution where the signal we wish to modify is convolved with the filter kernel.

In signal processing, both the time domain and frequency domain play a significant role in the resulting output of a signal therefore the effects of filtering on the characteristics of both domains should be considered depending on the desired outcome. A convenient fact is that many properties which are applied in the time domain have a dual effect in the frequency domain. Windowed-Sinc filters exploit this fact by allowing for the simple generation of multiple types of frequency responses via a truncated sinc function. This truncated sinc function is then modified via additional weighting through the selection of a specific window coming from a set of well-defined window functions. In order to obtain the different types of filters such as low pass, band pass, or high pass, additional properties of time domain filter impulse responses, such as spectral inversion, can be exploited.

The sinc function results from taking the inverse Fourier transform of a pulse shaped frequency response in the frequency domain which is the ideal filter response when attempting to eliminate a desired band of frequencies contained within a signal. The sinc function however is an infinite length signal which is impossible to reproduce perfectly and therefore truncated versions of this function are used instead. This truncation in the time domain has negative side effects on the frequency response of the resulting filter. Pure truncation of the sinc function is equivalent to applying a rectangular window to the signal. Much effort has been dedicated to improving the frequency response based on the desired characteristics such as pass band and stop band ripple and cut-off frequency roll off. These improvements came in the form of windows with different shapes, each of which can be expressed by simple equations.

The filter module that was implemented in software was inspired by the descriptions found in [121] which allowed for the use of the previously mentioned filter types in conjunction with multiple windowing options. The module currently allows for the selection of a window from a set of 17 of the

most common windows which are listed in Table 5.3. The equations for each of the windows were extracted from multiple sources [122]–[124]. Most of these were modified slightly for purposes of simplifying the implementation as well as adhering to the definitions found in the source material and appear in the table as they were implemented in software. The operation of each function was then verified by comparing the generated filter coefficients through the use of existing MATLAB functions. In the equations, M is equal to $(N-1)/2$ with N being the desired window length with $0 \leq n \leq N - 1$ where n is the coefficient index. The functions for these windows generate symmetric windows which ensure that the filters have linear phase and the resulting filter order is $N-1$. For the power of cosine window (filter #14 in Table 5.3), the exponent x is the desired power to which the user wishes to raise the function.

Table 5.3 : Window Filter Equations

Window Name		Window Equation
1	RECTANGULAR	$w(n) = 1$
2	BARTLETT	$w(n) = 1 - \left \frac{n - M}{M} \right $
3	PARZEN	$w(n) = 1 - 6 \left(\frac{ n - M }{N/2} \right)^2 + 6 \left(\frac{ n - M }{N/2} \right)^3 \text{ for } n - M \leq M/2$ $w(n) = 2 \left(1 - \frac{ n - M }{N/2} \right)^3 \text{ for } n - M > M/2$
4	WELCH	$w(n) = 1 - \left(\frac{n - M}{(N + 1)/2} \right)^2$
5	HAMMING	$w(n) = \alpha - \beta \cos\left(\frac{2\pi n}{N - 1}\right)$ $\alpha = 0.54, \beta = 1 - \alpha$
6	HANN	$w(n) = \alpha - \beta \cos\left(\frac{2\pi n}{N - 1}\right)$ $\alpha = 0.5, \beta = 1 - \alpha$
7	BLACKMAN	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right)$ $\alpha = 0.16, a_0 = (1 - \alpha)/2, a_1 = 0.5, a_2 = \alpha/2$
8	EXACT BLACKMAN	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right)$ $a_0 = 7938/18608, a_1 = 9240/18608, a_2 = 1430/18608$
9	NUTALL	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right) - a_3 \cos\left(\frac{6\pi n}{N - 1}\right)$ $a_0 = 0.355768, a_1 = 0.487396, a_2 = 0.144232, a_3 = 0.012604$
10	BLACKMAN NUTALL	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right) - a_3 \cos\left(\frac{6\pi n}{N - 1}\right)$ $a_0 = 0.3635819, a_1 = 0.4891775, a_2 = 0.1365995, a_3 = 0.0106411$
11	BLACKMAN HARRIS	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right) - a_3 \cos\left(\frac{6\pi n}{N - 1}\right)$ $a_0 = 0.35875, a_1 = 0.48829, a_2 = 0.14128, a_3 = 0.01168$
12	FLAT TOP	$w(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N - 1}\right) + a_2 \cos\left(\frac{4\pi n}{N - 1}\right) - a_3 \cos\left(\frac{6\pi n}{N - 1}\right) + a_4 \cos\left(\frac{8\pi n}{N - 1}\right)$ $a_0 = 0.21557895, a_1 = 0.41663158, a_2 = 0.277263158,$ $a_3 = 0.083578947, a_4 = 0.006947368$

13	COSINE	$w(n) = \cos\left(\frac{\pi n}{N-1} - \frac{\pi}{2}\right)$
14	POWER OF COSINE	$w(n) = \left(\cos\left(\frac{\pi n}{N-1} - \frac{\pi}{2}\right)\right)^x$
15	GAUSSIAN	$w(n) = e^{-\frac{1}{2}\left(\frac{n-M}{\sigma M}\right)^2}$ $\sigma \leq 0.5$
16	TUKEY	$w(n) = \frac{1}{2} \left[1 + \cos\left(\pi \left(\frac{2n}{\alpha(N-1)} - 1\right)\right) \right] \text{ for } 0 \leq n \leq \frac{\alpha(N-1)}{2}$ $w(n) = 1 \text{ for } \frac{\alpha(N-1)}{2} \leq n \leq (N-1) \left(1 - \frac{\alpha}{2}\right)$ $w(n) = \frac{1}{2} \left[1 + \cos\left(\pi \left(\frac{2n}{\alpha(N-1)} - \frac{2}{\alpha} + 1\right)\right) \right] \text{ for } (N-1) \left(1 - \frac{\alpha}{2}\right) \leq n \leq (N-1)$ $0 \leq \alpha \leq 1$
17	PLANK TAPER	$w(n) = \frac{1}{e^{(Z_a(n))} + 1} \text{ for } 0 \leq n \leq \epsilon(N-1)$ $w(n) = 1 \text{ for } \epsilon(N-1) \leq n \leq (1-\epsilon)(N-1)$ $w(n) = \frac{1}{e^{(Z_b(n))} + 1} \text{ for } (1-\epsilon)(N-1) \leq n \leq (N-1)$ $w(n) = 0 \text{ otherwise}$ $Z_a(n) = \epsilon(N-1) \left(\frac{1}{n} + \frac{1}{n - \epsilon(N-1)} \right)$ $Z_b(n) = \epsilon(N-1) \left(\frac{1}{N-1-n} + \frac{1}{(1-\epsilon)(N-1)-n} \right)$ $0 < \epsilon \leq 0.5$

Many of these windows are represented by sums of weighted cosines and the filter response of the overall filter is dependent on but a few variables: the window length, the window type, the filter type and the cut-off frequencies. The sampling frequency does not affect the filter coefficient values since the cut-off frequencies are specified in terms of normalized frequencies. Depending on the filter type, two cut-off frequencies may need to be specified such as in the case of band pass and band stop filters. The maximum value of a cut-off frequency is 0.5 which corresponds to half the sampling frequency in order to agree with the Nyquist theorem. The application of these filters to the signals entailed multiplying the series of values produced by the previous window equations with those generated by the manipulation of sinc functions used to create the desired response, e.g. low pass filter, and convolving the resulting series of values with an equal length signal segment.

The primary reason why so many filter and windowing options were provided was mainly due to the unknown behavior of the IR sensors prior to development of the filter module. However, once the ground work for the filter module had been established by incorporating the functionality required to handle the key values mentioned previously, such as the window length and cut-off frequencies, the addition of new filtering options was rather straightforward by simply programming the individual equations used to generate the desired coefficients. This led to a very versatile filter module which could perform very accurate filtering of all kinds in a quantifiable manner. This meant that in the event that specific noise sources were identified, they could possibly be attenuated.

5.3 Kinematic Formulations

The physical design of the proposed compliant wrist provides for a simple kinematic representation of the device with 3 DOFs, namely two rotational DOFs and one translational DOF. As mentioned previously, the device employs two independent sets of four IR sensors. Both sets of sensors operate in the same fashion and are capable of generating similar distance information from their respective anchor points. However, the way in which the distance information is interpreted is dependent on the sensory layer considered as well as the intended application. The internal sensors are used for measuring the deflection of the movable contact plate while the external sensors are charged with the detection of objects in the environment and estimating the relative pose of those objects with respect to the compliant wrist. For the internal sensors, since the surface of the movable plate is assumed to be uniformly planar (by design), the representation involves only two rotations and one translation to completely describe the detected movement. Unfortunately this assumption of planarity cannot be applied when dealing with the external sensor array as any surface shape can be encountered in general; therefore special considerations were made in order to provide as much meaningful information as possible for maximized versatility. These came in the form of normal vectors meant to describe the surface characteristics of the encountered objects. It should be noted that although certain kinematic calculations are more useful for a particular set of sensors, the implemented algorithms allow for any type of calculations to be carried out using distance information from either set of sensors, internal or external.

Figure 4.10 shows how both sets of sensors are organized with respect to the assigned reference frame, i.e. for both sets of sensors, sensor 1 is located on the negative side of the x axis and the sensors are numbered in a counter clockwise fashion thereafter. The reference frame associated with the compliant wrist has its origin located in the center of the sliding shaft and stationary plate,

corresponding to the intersection of the dashed lines with which the sensors are aligned, and is oriented with its axes as shown in the bottom right corner of the image. The extraction process of the rotation and translation parameters and of the normal vectors relies solely on distance measurements obtained from the IR sensors and the position of the sensors on the device relative to the assigned origin.

5.3.1 Normals

Although a specific application had already been thought up for the compliant wrist, there was still a desire to maximize the utility of the device beyond this initial application. With the IR sensors providing multiple depth measurements at various points on a surface, which in the case of the external sensors could potentially come from a non-planar surface, steps were taken to perform additional computations in order to generate multiple descriptors for the planes which could be perceived by these sensors.

A plane can be described in several ways: a normal vector to the plane, a group of three points which lie on the plane, or similarly, two vectors which lie on the plane. Each of these concepts is used to generate four normal vectors corresponding to four distinct planes in three dimensional space. Given that there are four sensors in the external sensory layer, four points in three dimensions are obtained. Since only three points are required for describing a plane, four separate three-point groupings can be formed, which describe four possibly different planes each with its own normal.

Referring again to Figure 4.10, the four possible combinations of three sensors are (S4, S1, S2), (S1, S2, S3), (S2, S3, S4) and (S3, S4, S1), where each sensor, S#, corresponds to a point in space, and where the X and Y components of the points correspond to the known (by construction) X and Y coordinates of the sensor on the reference plane (bottom fixed plate), and the Z component corresponds to the respective measured distances by the sensor. The next step towards obtaining the normal vectors describing each potential plane on a distant object is to take the cross product of the two vectors obtained from the vector differences between two sensor pairs. In the general form, this corresponds to:

$$\vec{N}_n = \vec{S_n S_{n+1}} \times \vec{S_n S_{n-1}} \quad (5.1)$$

where S_n corresponds to any of the four external sensors, S_{n+1} corresponds to the next sensor in the group, and S_{n-1} corresponds to the previous sensor, each assembly being selected among the four groups

of three sensors listed above. Note that the sensors are physically arranged in a circular pattern on the compliant wrist such that S_{n+1} when n is equal to 4, corresponds S_1 and S_{n-1} when n is equal to 1 corresponds to S_4 . Combining the resulting four normal vectors with the original distance measurements of the sensors allows the estimation of the overall surface orientation and curvature to be refined by creating multi-faceted representations of detected objects.

This is very similar to the process in which triangular meshes are made from point clouds in order to generate a three dimensional model of a surface. Calculating this onboard the compliant wrist allows for the possibility of using the external sensor layer for gross surface mapping in the event that information pertaining to the description of the area in front of the robot in question was not previously acquired either due to lack of sensor data, limited resolution, or possible occlusion of the workspace.

5.3.2 Rotations

As mentioned previously, the compliant wrist has 3 DOFs, two of which are rotational. Each of these rotation angles is calculated from the distance measurements of two IR sensors aligned along a particular axis. The rotation about the X axis (R_x) is extracted from the distances measured by the two sensors aligned along the Y axis, and the rotation about the Y axis (R_y) is extracted from the distances measured by the two sensors aligned along the X axis. The measured distances extracted from the sensors correspond to the Z component of the vectors associated with each sensor. Under the assumption that all IR sensors measure along parallel directions in 3D space, which is imposed by construction, taking the arctangent of a right angle triangle whose vertical side is the difference in distance measurements of the two sensors on that axis with a base whose length is equal to the distance that separates the two sensors, the desired angle is obtained. An example of how the rotation angle about the Y axis is calculated, using the distances measured from two sensors aligned along the X axis, is given in Figure 5.6, assuming an in-between sensor distance W .

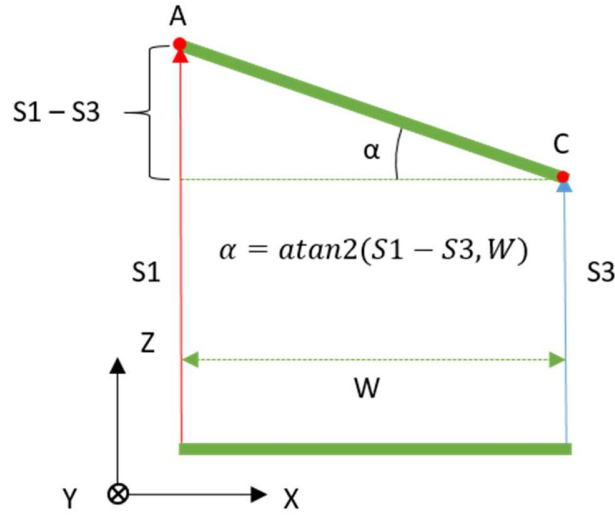


Figure 5.6 : Rotation Calculation Example

Both of the rotations can be calculated according to the equations below where $S_{\#(Z)}$ indicates the Z component of a sensor's associated vector which is essentially the distance measured by that sensor. These equations are valid regardless of which sensors are being used, either the internal set of sensors or the external, the only difference being that W will take on different values depending on the physical locations of the sensors with respect to the reference frame. The direction of the rotations are given by the right hand rule such that the direction of the fingers indicates a positive rotation.

$$R_X = \beta = \text{atan2}(S_{4(Z)} - S_{2(Z)}, W) \quad (5.2)$$

$$R_Y = \alpha = \text{atan2}(S_{1(Z)} - S_{3(Z)}, W) \quad (5.3)$$

5.3.3 Translation

The third DOF of the compliant wrist structure is translational in nature and occurs along the Z axis. This translation along the Z axis (T_z) can also be obtained from the distance measurements generated by the IR sensors by taking the average of the 4 distances reported by the sensors. In the case of the internal sensors, this average distance value corresponds to the distance between the centers of the upper and lower plates, the upper plate being the movable contact plate. For the external sensors, this calculation provides a rough estimate of the distance of a detected object from the compliant wrist. This estimate increases in accuracy with the planarity of the detected objects. The calculation is carried out as stated in equation 5.4

$$T_Z = (S1_{(Z)} + S2_{(Z)} + S3_{(Z)} + S4_{(Z)})/4 \quad (5.4)$$

where $S\#_{(Z)}$ is the Z component of the vector associated to the sensors according to the sensor numbers given in Figure 4.10.

Prior to the implementation of the algorithm responsible for calculating the normal vectors from the distance estimates of the sensors, an attempt was made at providing an efficient means of detecting planarity of the detected surfaces by the external sensors. Since the translation was being calculated from the average of four distance measurements coming from sensors arranged in a symmetric pattern, geometry allowed for the reuse of the calculations through some assumptions regarding the nature of the encountered objects.

Working backwards from the assumption that a detected object's surface is planar, it was possible to obtain an estimate of the translation using a single pair of sensors aligned along either axis. This is possible due to the symmetry of the sensor placement with each sensor being positioned at equal distances on either side of the origin of their respective axes. The following equations define how the translations are estimated using the distances measured from two opposite sensors:

$$T_{Z1} = \frac{S1_{(Z)} + S3_{(Z)}}{2} \quad (5.5)$$

$$T_{Z2} = \frac{S2_{(Z)} + S4_{(Z)}}{2} \quad (5.6)$$

The logic behind this calculation is visible in Figure 5.7 for T_{Z2} .

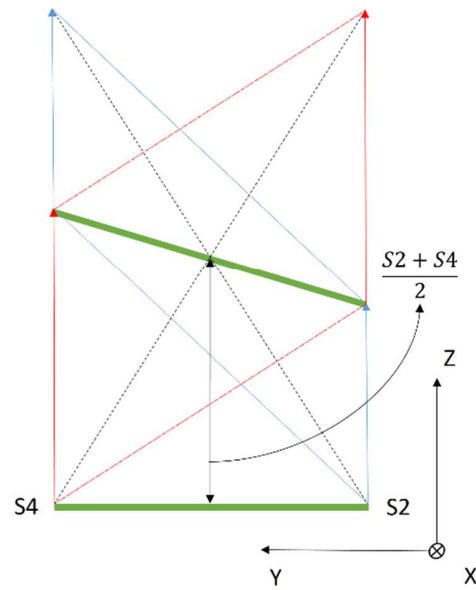


Figure 5.7 : Translation Distance Calculation Example

The result of these two calculations will only be the same for both pairs if the surface is planar as seen by all four sensors in the set. It should be noted that in reality, it is entirely possible for a surface to appear planar to the sensors but actually have large deformities which go undetected, however this should only be a concern for the external sensors as the assumption of planarity holds for the internal sensors. By comparing the two translation distances calculated by this equation, it is possible to set a threshold on the difference allowed between the two which results in the determination of whether or not the surface is planar.

Initially, the goal was to make use of these calculations to determine if a surface detected by the external sensors was planar; however, since there exists cases where the assumption would not hold, the use of this planarity detection method should be used with caution for the external sensors. Fortunately, this planarity detection algorithm has since been applied to a different problem.

As mentioned earlier, the sensor responses are non-linear, particularly in cases where objects become too close to the sensors which cause the output to erroneously indicate significantly larger distances. Since there were no physical stops preventing the moveable contact plate from coming too close to the internal sensors, by applying this algorithm to the distance measurements, such events could be detected as these would result in a non-planar surface representation, a fact which should not occur

under normal operation as the moveable contact plate is itself quite planar in reality. For this reason, the calculations of both of these translation estimates are carried out by the compliant wrist and are made available to external sources to be used in robot control algorithms along with the normal vectors which have become more useful in the case of the external sensors.

5.3.4 Transformation Matrix

A transformation matrix is a convenient mathematical representation of relative positions in Cartesian space. In robotics they are used to describe movements to be performed or to generate a description of a kinematic chain of links in a manipulator robot. The compliant wrist effectively acts as an additional link to such robots and can therefore make use of these to relate its physical pose to a robot controller. Figure 5.8 offers a rudimentary representation which depicts two cases of the compliant wrist's possible placement of its two plates and their respective physical reference frames. In both cases, the two plates, and hence their reference frames, are separated by a particular translation and rotation.

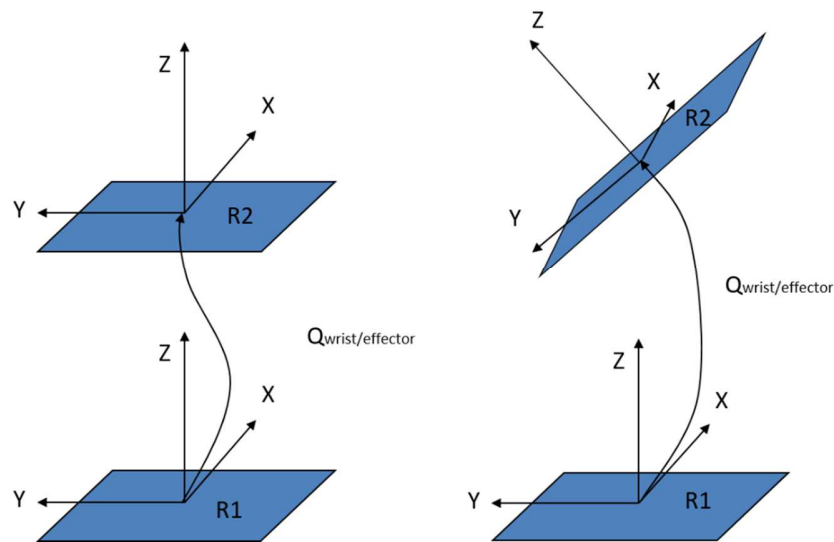


Figure 5.8 : Kinematic Transformation Graph

The relationship between the bottom plate, which serves as a static reference frame from the point of view of the instrumented wrist, and the compliant upper plate can be represented by such a transformation matrix and in general, is referred to as a 3D homogeneous transformation matrix. In the first case (left), we can suppose that the transformation represents the “at rest” state where the transformation exhibits only a translation and no rotation, while the second case (right) represents a

situation where external forces have been applied to deflect the movable plate and the transformation exhibits both translation and rotation. In either case, a transformation matrix is able to describe these situations. The parameters of this matrix depend on the four internal distance measurements, represented as A, B, C, and D in Figure 5.9. This figure simultaneously illustrates both sets of sensors and their associated distance measurements where A, B, C and D correspond to distances recorded by the internal sensors, and E, F, G and H correspond to distances of objects in proximity to the compliant wrist recorded by the external sensors. As mentioned previously the external sensors will not necessarily be dealing with object surfaces that are devoid of curvature or deformations. In such cases the distances obtained can lead to a surface representation such as the one shown on the upper part of Figure 5.9, requiring the extraction of additional parameters to describe the surface. Each of the resulting four triangular planes will have their own surface normal. It is to these normal vectors that we refer to in section 5.3.1.

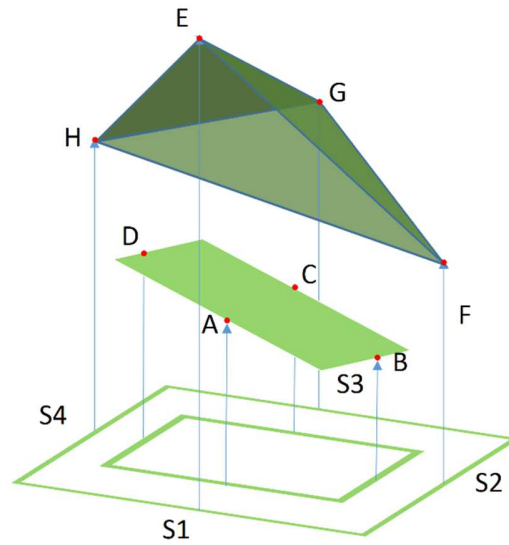


Figure 5.9 : Compliant Wrist Model Representation

In order to calculate the equivalent homogeneous transformation which describes the pose of the compliant wrist's moveable plate (which involves only the four internal IR sensors) with respect to the point of attachment onto the robotic platform, $Q_{wrist/effector}$, two matrices must be multiplied together. The first is the pure translation matrix in the Z direction which describes the offset between the point of attachment of the end effector and the origin of the compliant wrist set by the mounting position of the infrared sensors. The next is the matrix which describes the relative position of the

compliant wrist's moveable plate with respect to the infrared sensors. The equivalent matrix equation is given as follows:

$$Q_{wrist/effector} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & O_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \alpha & 0 & \sin \alpha & 0 \\ \sin \beta \sin \alpha & \cos \beta & -\sin \beta \cos \alpha & 0 \\ -\cos \beta \sin \alpha & \sin \beta & \cos \beta \cos \alpha & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.7)$$

where $\beta = \text{atan2}(D - B/W)$, $\alpha = \text{atan2}(A - C/W)$, O_z is the fixed offset distance between the origin of the reference frame associated with the sensors and the reference frame assigned to the robot's point of attachment, and T_z is defined in equation 5.4 where the letters A, B, C and D correspond to $S1_{(z)}$, $S2_{(z)}$, $S3_{(z)}$, and $S4_{(z)}$, respectively.

A similar equation can be obtained for the external sensors which describes rather the position of a perceived surface located away from the compliant wrist and captured by the four distance measurements from the external sensors with respect to the origin of the wrist's reference frame. This is done by replacing A, B, C and D by E, F, G and H, respectively for the estimate of T_z in equation 5.7 as well as providing a different value for the offset to account for the different position of the sensors relative to the robot's point of attachment. However care should be given to ensure that the obtained translation is truly representative of the surface's actual distance prior to contact with the compliant wrist since the surface itself could be quite irregular in shape.

5.4 Communications

The communications portion of the compliant wrist is yet another software implementation which allows the device to relay all of its collected and processed sensor information to be accessed by external sources such as robot controllers attempting to make use of the compliant wrist device for guiding the motion of a robot. The physical hardware required to achieve communications was presented previously. In this section, details of the software implementation required to provide this function are provided. The main components consist of a packet structure with a protocol describing the actions required to create packets by grouping the necessary information as well as for the extraction of data from these packets.

5.4.1 Packet Structure

In order to send and receive binary information to and from external sources requires knowledge of how to interpret each bit of data. Packets provide a very simple approach to describing and organizing the information being transferred between devices. Since the hardware performed data transfers using serial ports and its associated protocol, there were two initial choices on how to transmit data.

The first was to send all information as ASCII characters. This has the benefit of a simple transmission protocol since the number of possible characters which can be sent when dealing with numerical data is confined to a few characters allowing the use of specific characters to delimit, or frame, messages. The downside is that each ASCII character requires 8 bits of data in its binary representation and depending on the desired precision of numerical data, can lead to very inefficient data transfers in terms of data flow rates.

The second option was to use pure binary data to represent all of the information. This has the benefit that all numbers, on a 32-bit architecture, can be represented with great precision using only 32 bits. Compared to 32 bits being used to send 4 ASCII characters, this leads to significantly higher data transmission efficiency. Unfortunately, this method also has its own caveat, which is that all possible binary combinations are possible and no characters can be reserved for framing messages. This leads to the requirement of an additional protocol to deal with message delimiters in order for communications to function.

Despite the additional complexity of the second method, the data rate optimization was more than enough to justify its implementation especially when considering the limited resources available on the microcontroller. Longer messages also lead to longer delays and decreased reaction times when considering the effects of these in robot control situations. The protocol implementation requirements for the selected method are given in the following section. The packet structure and a description of its components are provided next.

Each packet is made up of a start of packet byte, a command byte, a source address byte, a destination address byte, a data length byte, a variable byte length payload, a four byte error control code and an end of packet byte. The start and end bytes are a specific binary combination of 8 bits

which is exclusively used to signal when new information is being transmitted and are discussed in section 5.4.2.

The command byte is used for identifying the type of information to be expected in the payload and allows the receiver to handle the data as outlined by the protocol. Depending on the type of command, when a packet is being sent to the microcontroller this byte will either instruct it to retrieve specific information available on the device which could either be sensor filter settings, sensor distance measurements or other similar information or it will instruct the microcontroller on how to handle the received information which could be new calibration settings to store in memory for example. It is essentially a method of pointing to a list of necessary actions required to be taken by the receiver of the packet.

The source address and destination address bytes are currently unimplemented, in the sense that the protocol makes no use of them, but are meant to simplify integration of multiple compliant wrist modules into a single network. By including these addresses, more complex networks of compliant wrists could be created where information could be broadcast by a single source to multiple compliant wrists for example or could be used to individually address each compliant wrist to update certain settings if multiple devices are being used by a single robot controller. The reason why this was not implemented is that the hardware used, namely the XBees, already provide this networking functionality. The software option allows less sophisticated hardware to be used should the need arise.

The data length byte is used as a method of flow control, indicating how many bytes are to be expected in a single packet and offers some additional error checking when trying to ensure payload integrity. All packets start with the same 4 bytes which means that all new packets will be handled similarly except for the payload section. Without a byte indicating how long a message is, there would be no way to control the length of the message reducing efficiency by requiring all messages to be a fixed length.

The variable length payload stores the useful data to be extracted from the packet which, in the case of the compliant wrist module, can consist of sensor voltage values, distances, rotation angles or a kinematic matrix to name a few examples. The protocol plays a significant role for this portion of the packet as the order of the information stored here is very important. The command byte is used to indicate what type of information to expect. However, to provide even greater flexibility over the packet contents, included in the payload of special commands are additional bytes of data describing the exact contents of the payload.

The error control code is a 32 bit cyclic redundancy check (CRC-32). These bytes are a result of a mathematical operation performed on all of the binary data contained in the packet excluding the start and end flags. This operation rarely produces the same result for different groupings of bits. By performing this calculation both before the packet is sent and once it is received provides a simple method of ensuring data integrity, i.e. making sure no errors were introduced into the message during transmission. Since transmissions are made using a wireless medium, message integrity can significantly deteriorate as the two communicating devices move away from each other or if there is an unusually large amount of noise introduced in the signal due to ambient interference.

Table 5.4 shows, in graphical form, the packet components and how they are organized in memory. The minimum packet length is therefore 10 bytes as the data section in many of the commands sent to the microcontroller, such as data requests, can be omitted since the command byte is sufficient instruction to discern which actions should be taken.

Table 5.4 : Packet Structure

Flag	Command	Address		Control	Information	Error Control	Flag
Start	Instruction	Source	Destination	Data Length	Data	CRC-32	End
8 bits	8 bits	8 bits	8 bits	8 bits	0 – 256 bits	32 bits	8 bits

5.4.2 Protocol

The following is intended to provide details of the implemented communications protocol for the compliant wrist module. The protocol used borrowed aspects from an existing protocol known as High-Level Data Link Control (HDLC) which was developed by the International Organization for Standardization (ISO). Information required to implement this particular protocol was obtained from [125].

This protocol is responsible for the transfer of packets between devices and as mentioned previously, requires special actions to be taken in order to allow unrestricted binary data transfers, i.e. all possible combinations of bits being allowed. The way this is done is by using a framing method. The fact that the hardware used for wireless communications makes use of serial ports makes the system well suited for the asynchronous framing method of HDLC.

This framing method uses frame boundary octets to delimit frames of data being transmitted. These are the start and end bytes found in the packet structure. The frame boundary octet is given as

'01111110', or 0x7E in hexadecimal. A control escape octet is also used and given as '01111101', or 0x7D in hexadecimal. If either of these two octets appears in the transmitted data, an escape octet is sent, followed by the original data octet with bit 5 inverted counting right to left starting at 0. For example, the data sequence "01111110" (7E hex) would be transmitted as "01111101 01011110" ("7D 5E" hex). This ensures that 0x7E will only appear in the data at the start and end of the frame while 0x7D will only appear in instances where the original data contained either of the special sequences.

On the receiving side, the process is reversed in order to recover the original message. Again, the 0x7E characters indicate the start and end of a packet which the protocol uses to determine when a new packet is being transmitted. Once the protocol has received the initial start byte it enters its packet forming routine which takes all new incoming bytes of data and appends them to the packet under the proper conditions, which is if the bytes received are neither of the special characters. For 0x7D, it will discard this byte but keep note of it so that on the next incoming byte, the 5th bit is again inverted in order to recover the original data, which is then appended to the packet. Another 0x7E byte signals the end of the byte. At this point the protocol will proceed to calculate the CRC and compare it with the one which was included in the packet. If the two are identical it is assumed that the packet was successfully transmitted.

Another section of the HDLC protocol is called the link configuration which essentially describes which devices are able to initiate a data transfer. For this application the link configuration which was implemented is described in the HDLC protocol as the Normal Response Mode (NRM), which is an unbalanced configuration in which only the primary terminal may initiate data transfer. The secondary terminal transmits data only in response to commands from the primary terminal. The primary terminal polls the secondary terminal(s) to determine whether they have data to transmit, and then selects one to transmit. In this application, the primary terminal is any external source capable of sending a packet over the wireless network on which the compliant wrist modules are capable of transmitting and the secondary terminals are the compliant wrist modules themselves. The polling in this case actually consists of data requests as the compliant wrist will always have data ready to transmit and is always actively listening for these data requests.

The combination of this protocol with the packet structure provides an efficient form of communications between the compliant wrist module and any external device looking to access the

information available while the CRC check of the packet structure increases the robustness of the system.

Chapter 6. Experimental Characterization and Validation

6.1 IR Sensor Characterization

Prior to the full integration of the compliant wrist module onto the selected manipulator robot, attempts at evaluating the performance of the IR sensors were made. The IR sensors needed to be characterized to determine whether or not they provided sufficiently accurate measurements for the control of a robotic arm. A protocol was established to achieve three separate goals. The first goal was for determining measurement accuracy, the second was to determine whether or not the calibration procedure that was developed was as effective as originally thought, and lastly, to examine the effects of filtering on the sensor data.

In order to enact the protocol, the same 1D motorized track used for calibration, and shown in Figure 5.4 and Figure 5.5, was also used to position a target planar object in front of the sensors during the data acquisition process. The track imposed certain physical constraints on the experiment which prevented the collection of data from all 8 sensors simultaneously and therefore data was collected from groups of 4 sensors at a time. Four sets of 4 sensors, 16 sensors in total, were evaluated in order to increase the overall amount of data collected for comparison purposes. The sensors were arranged in the same pattern as they would be placed on the actual compliant wrist, with the distance between opposing sensors equal to the distance separating the internal sensor positions on the compliant wrist. The latter choice was due to the fact that the shorter distance between sensors would produce the greatest (as in worst case) variations in rotational values since the rotations depend directly on this distance.

The protocol consisted of several steps, with the first being to record data from a group of 4 sensors at each calibration position along the linear track before performing the calibration procedure. This allowed for a more direct comparison between data collected before performing the sensor calibration and data collected after performing the calibration. This was repeated for multiple cases. The first case consisted of the sensor signals being unfiltered such that the output was simply the series of samples. The three other cases consisted of having the sensor signals filtered with moving average filters with varying window lengths, namely, window lengths of 7, 15 and 33. In every case, there were 18 calibration positions, the same as those used in the calibration procedure described previously, with data being recorded for 10 seconds at each of those positions.

The sampling rate of 50 Hz was used for acquiring the data for characterization of the IR sensors since this was the maximum sampling rate which could be achieved. This was not due to the speed of the microcontroller, which is capable of producing the sampling rate per channel stated in section 5.2.1, but rather to the bottleneck caused by writing speeds to the SD card that was used to record the data from the sensors. For each sample, the data recorded to the SD card consisted of multiple values including the raw voltage measurement, the output generated after filtering, the distance value corresponding to the filtered and calibrated output, as well as the X and Y rotations and the translations corresponding to the displacement of the center of the point between pairs of sensors aligned along either the X or Y axis.

The second step entailed having the motorized track move the target object a distance of 500 mm at three different speeds starting from the closest possible point to the sensors. This corresponded to approximately 11 mm from the sensors, which is well below the valid distances mentioned in the sensor data sheet. Speed control of the track could not directly be set in terms of mm/s due to the track control system being implemented using an Arduino microcontroller where motor speed was set based on a fixed setting using an arbitrary scale. In order to determine the movement speed of the track, the distance travelled was divided by the total time it took to complete the movement. Three different speed settings were chosen and the approximate speeds calculated were 11.11 mm/s (500 mm / 45 s), 18.52 mm/s (500 mm / 27 s) and 26.32 mm/s (500 mm / 19 s). The goal of this step was to determine if the sensors could indeed track moving objects without significant delays in their response as well as ensuring response uniformity across sensors.

The third step was the application of the calibration procedure. For this step, the track was again moved to each calibration position but this time data was not recorded and the sensors signals were now filtered with a moving average filter with window length 47. This was done to increase signal stability by having the mean value be more apparent during calibration when trying to adjust the sensor output to the desired position which should match that of the track position relative to the sensors. At each track position, all four sensors are made to produce as similar as possible of an output so that inter-sensor errors are minimized, leading to a more stable overall performance in terms of compliant wrist operation.

As part of the ongoing research regarding filtering, it was discovered that the moving average filter is actually the optimal solution when assuming that the noise present in the incoming signal is

random white noise [121] and therefore this is the type of filter that was used during almost every instance of characterization data acquisition. The few exceptions were the series of data collection completed using no filter. In hindsight, the development of the comprehensive filter module might not have been critical to the overall system's operation however, as mentioned previously, once the groundwork for the implementation of a single filter was completed, the extra filter options required very little work for the additional flexibility afforded.

The assumption of random white noise is a logical starting point since the noise coming from multiple sources could potentially all be uncorrelated and result in apparent random noise when it is compounded. The contributions of noise begin at the source, inside the IR sensor which processes the signal coming from the PSD chip to create a voltage signal, and continue on through a long chain of conversions and calculations each contributing its own portion of the overall noise. For example, there is a great deal of quantization noise coming from the fact that the ADC has only 10 bits leading to the 3.3V range to be separated into 1024 discrete levels. The width of the registers in the microcontroller are of a fixed width and therefore produce small precision errors during every calculation that takes place which could have adverse effects, particularly during the generation of filter coefficients since these are being performed using floating point numbers. The effects of external light sources were also considered however no signs of major interference were detected when operating the sensors in a variety of lighting conditions. A full error analysis in this case however, is not necessarily warranted if the desired signal characteristics are obtained from simple filtering as suggested from the statistical analysis results found in [126] which hint at the possibility of a normally distributed output from similar sensors.

For the envisioned application of controlling a robot's motion, the time domain characteristics of the signal were of utmost importance, with the stability of the distance measurements being key to smooth and accurate motion. Windowed-sinc filters are better suited to frequency domain applications where signal data information is encoded primarily in the frequency domain rather than the time domain as is the case with the IR sensors. These types of filters produce a greater amount of signal distortion than is desired in the form of overshoot and ringing observed from the well-known step responses. This was another factor that was considered during the selection of the moving average filter for the collection of the characterisation data.

In an attempt to perform a proper analysis of the collected sensor data, several features were sought out, both qualitative and quantitative in nature. For the sensor data in question, namely voltage

measurements taken periodically over time with the assumption that the underlying process, i.e. the relationship of that voltage measurement to a distance, is stationary (which is the case where the track was kept at a fixed distance from the sensors for the duration of the measurements), two of the most representative statistics are the mean and standard deviation. These two statistics, in conjunction with knowledge of the ground truth, are a quantitative approach at determining the precision and accuracy of each sensor. Qualitative data features, trends and outliers for example, can best be found using visual representations of the data and so several charts and graphs were produced for each data stream collected from all of the sensors. These included simple data charts graphing the signal amplitudes over time, graphs depicting the frequency content of these signals as well as histograms.

As mentioned previously, although each sensor only recorded a single signal, i.e. a voltage, additional information was obtained via onboard signal processing which produced a multitude of information for each set of sensors which were recorded during data collection. This resulted in a plot of each sensor's raw voltage signal as well as a plot of the sensor's signal after the selected filter had been applied. Plots of the distance values associated with each sensor's voltage signal were also produced. Due to the way in which the conversion process is performed on the compliant wrist module, the effects of the calibration process are applied only after having performed filtering of the voltage signal and are shown in these distance estimate plots. Plots of the rotations about the X and Y axes as well as of the mean distance between the pairs of sensors used to produce those rotations were also generated.

Figure 6.1 shows an example of a voltage measurement collected over a period of 10 seconds during which the sensors were pointed towards a static planar surface. This data was obtained from a sensor without any filtration applied. The mean value of the signal is shown as an overlay in the plot. The title of the plot refers to the third external sensor in the first set of 8 sensors needed to instrument a compliant wrist module. Figure 6.2 shows filtered voltage measurement corresponding to the signal of Figure 6.1. This particular signal has been filtered with a moving average filter with a window length of 33. By keeping the scales of each graph the same, we can easily notice the effects of the filter on the signal which is to remove the larger variations and bring the actual signal's output closer to the mean value.

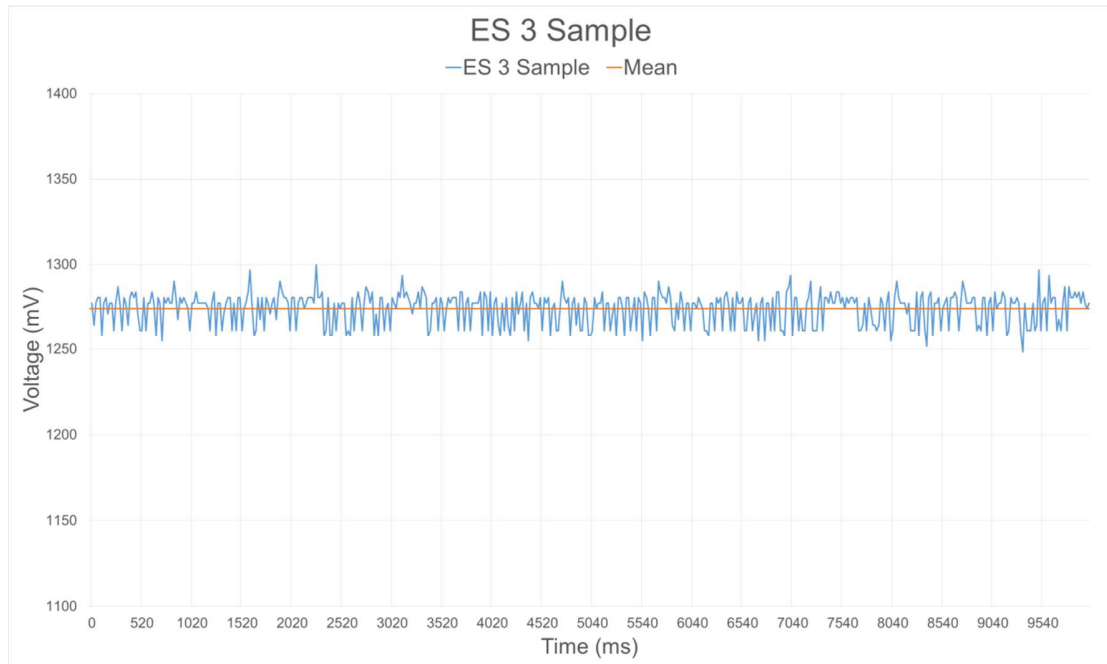


Figure 6.1 : Raw Voltage Signal

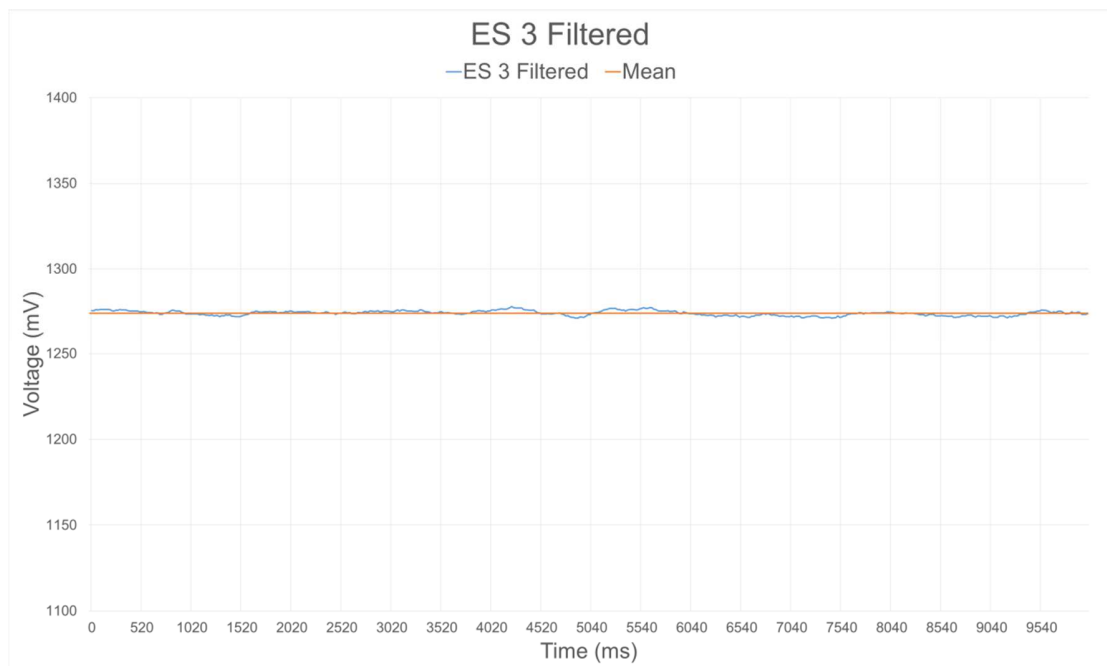


Figure 6.2 : Filtered Voltage Signal

Instead of moving on and displaying a graph of the distance corresponding to this signal, a comparison of this particular sensor's signal with those of the other sensors in the set is beneficial. Figure 6.3, again using the same scale, shows how each sensor's raw voltage output differs from the others. Sensor 1 and Sensor 3 appear to have similar outputs in terms of voltage amplitude also with

similar variations in their signals; however sensors 2 and 4 produce largely different voltage amplitudes while also aiming at the same surface located at the same physical distance. This is the problem that was identified during preliminary sensor tests and why a calibration procedure was developed since these outputs would result in different estimated distances being reported by each sensor for the same physical distance. Figure 6.4 again highlights the effects of the filter after it has been applied to each signal bringing each signal again closer to its mean value over time but having no effect on the disparities between sensors.

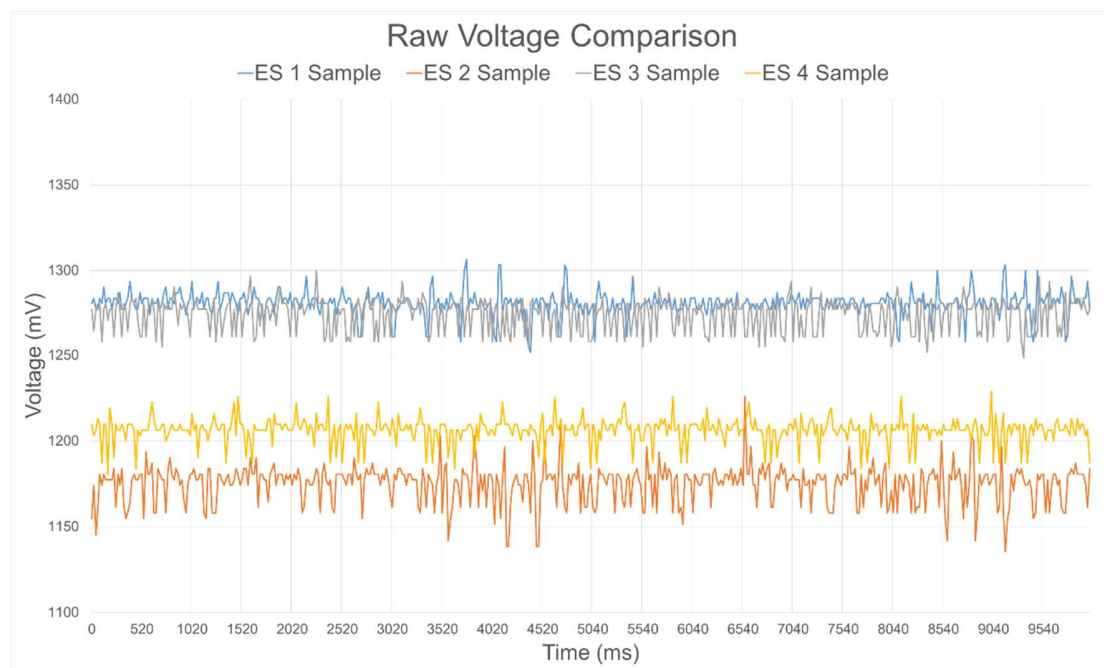


Figure 6.3 : Raw Voltage Signal Comparison

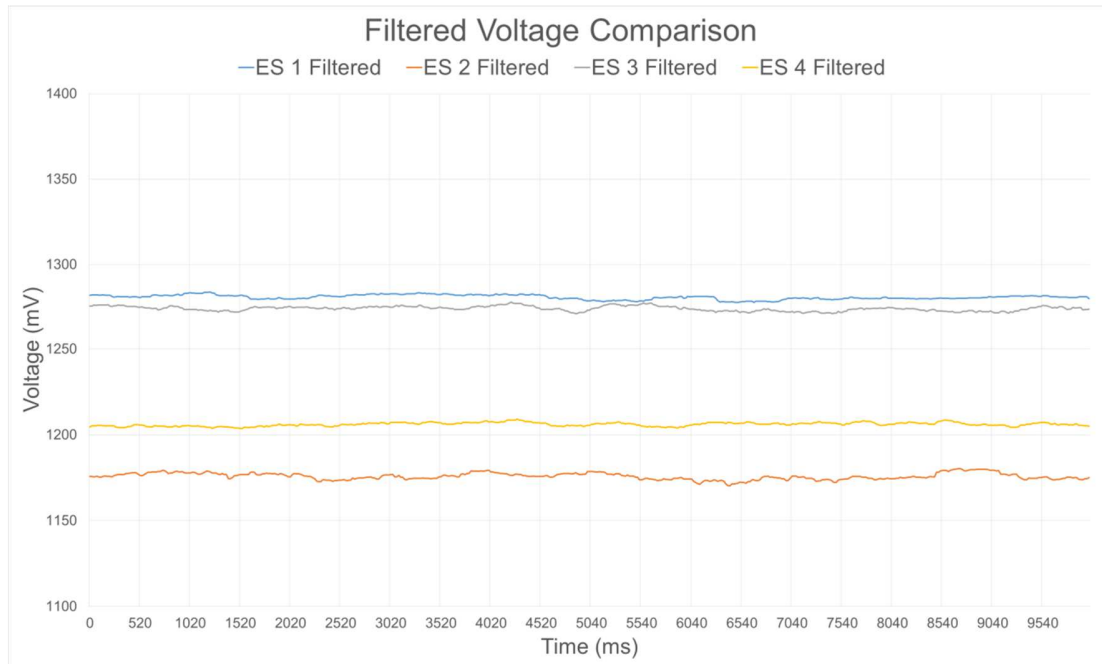


Figure 6.4 : Filtered Voltage Signal Comparison

In order to understand the importance of the calibration procedure, the distance estimates from the sensors prior to calibration and those after calibration are compared. Thus far, all of the previous plots have been representative of a single position of the motorized track, namely a physical distance of 90 mm from the sensors, corresponding to the 8th calibration point from the list given in Table 5.2. The data plotted in Figure 6.5 resulted in a mean distance of 99.97 ± 0.13 mm being reported by that particular sensor (3rd external sensor) which is a discrepancy of approximately 11% in this scenario. After having applied the calibration procedure to the sensor, we can see that the output is adjusted with the mean value being much closer, 89.98 ± 0.10 mm to be precise, to the desired set point as shown in Figure 6.6.

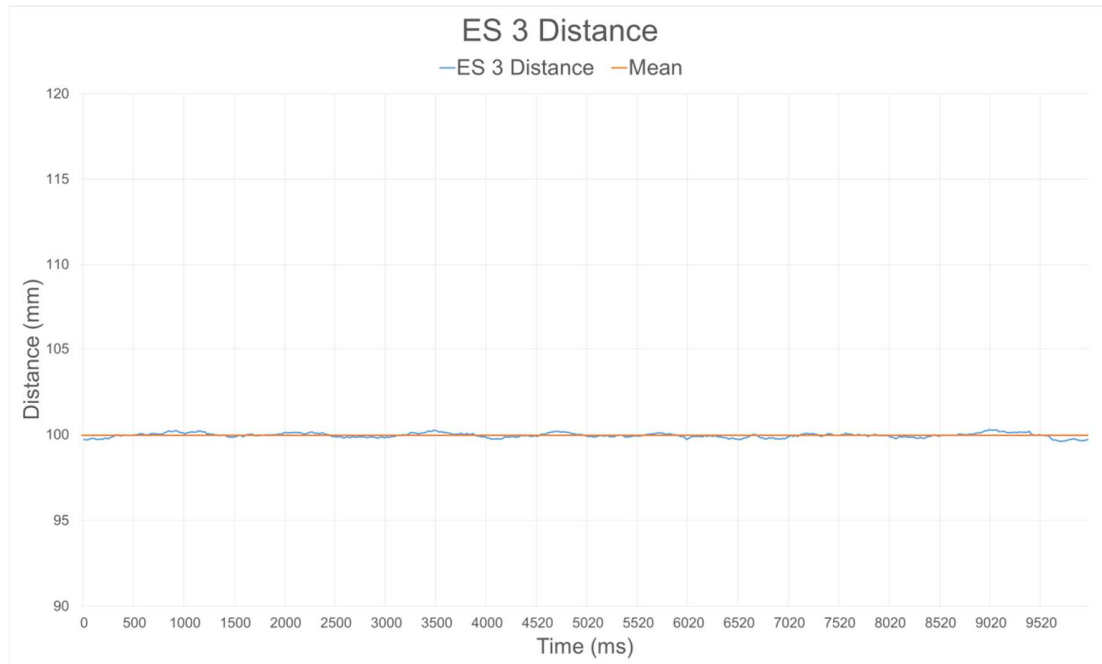


Figure 6.5 : Uncalibrated Distance Estimate

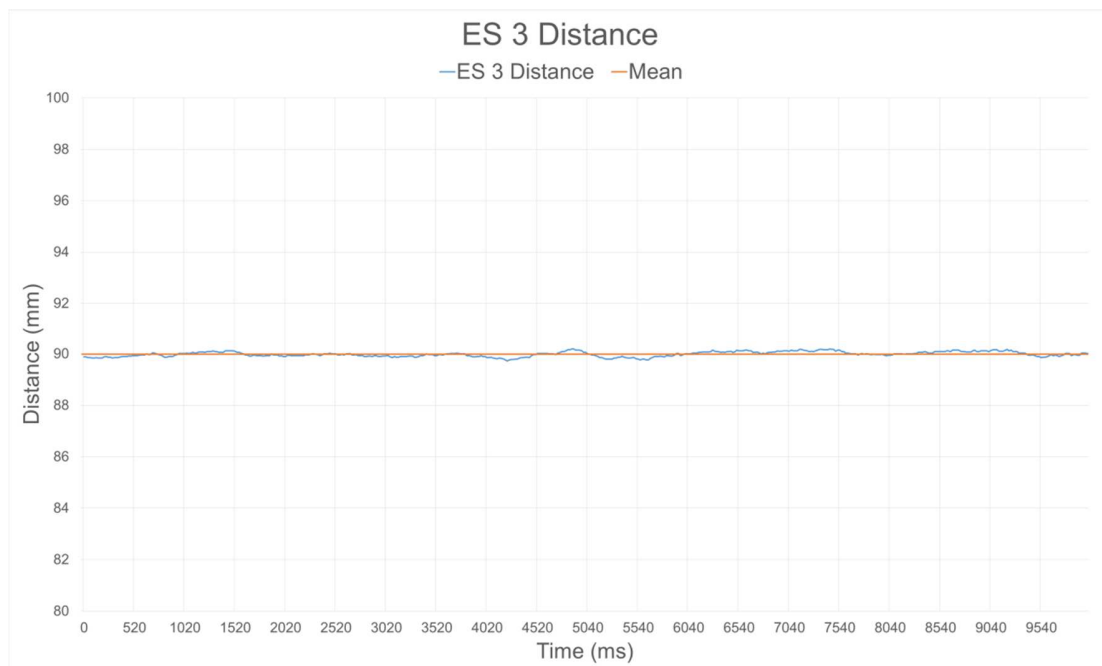


Figure 6.6 : Calibrated Distance Estimate

Again, it is important to note that this adjustment was not merely a simple voltage shift applied to the incoming voltage samples and that not all sensors require the same adjustments. In the case of the 14th calibration point, the true physical distance was set to 200 mm and the same uncalibrated sensor which has been under examination reported a distance of 252.04 ± 2.03 mm, an error of just over

25%. Again, calibration was able to reduce this error by providing the necessary adjustment, resulting in a distance estimate of 200.39 ± 1.27 mm.

Figure 6.7 illustrates the large variations in estimated distances from multiple sensors for the same physical distance of 90 mm, with each of these providing estimates that resulted in greater distances than expected. Once the calibration procedure has been applied, all of the sensors tend to produce a much better estimate of the true physical distance with Figure 6.8 showing clearly that this is the case for the 8th calibration point at a track distance of 90 mm.

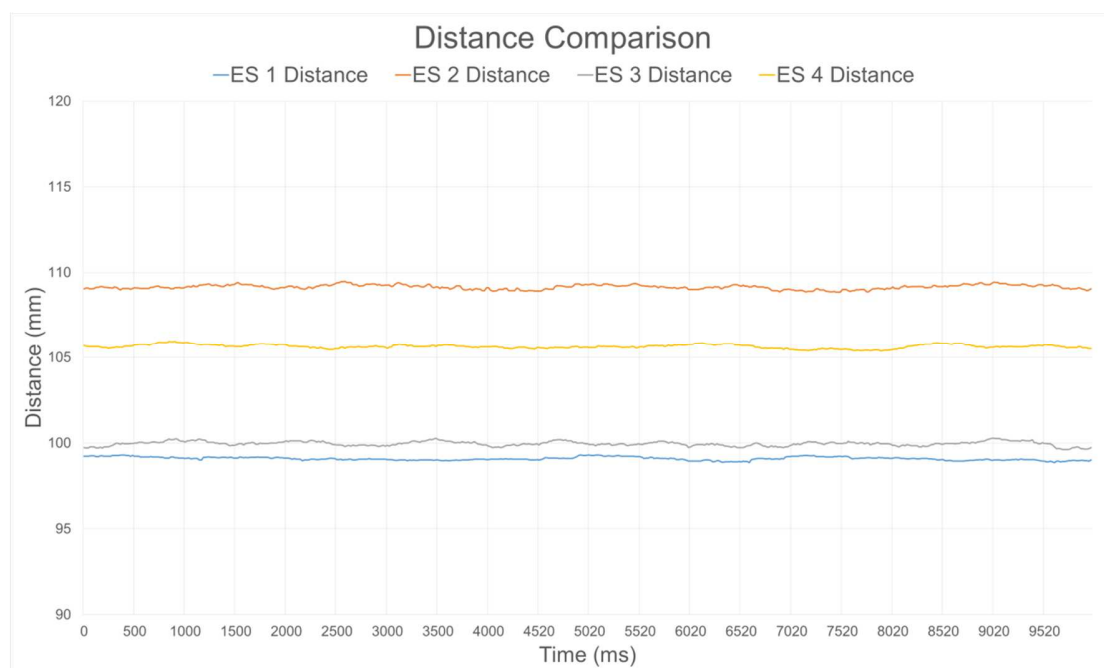


Figure 6.7 : Uncalibrated Distance Estimate Comparison

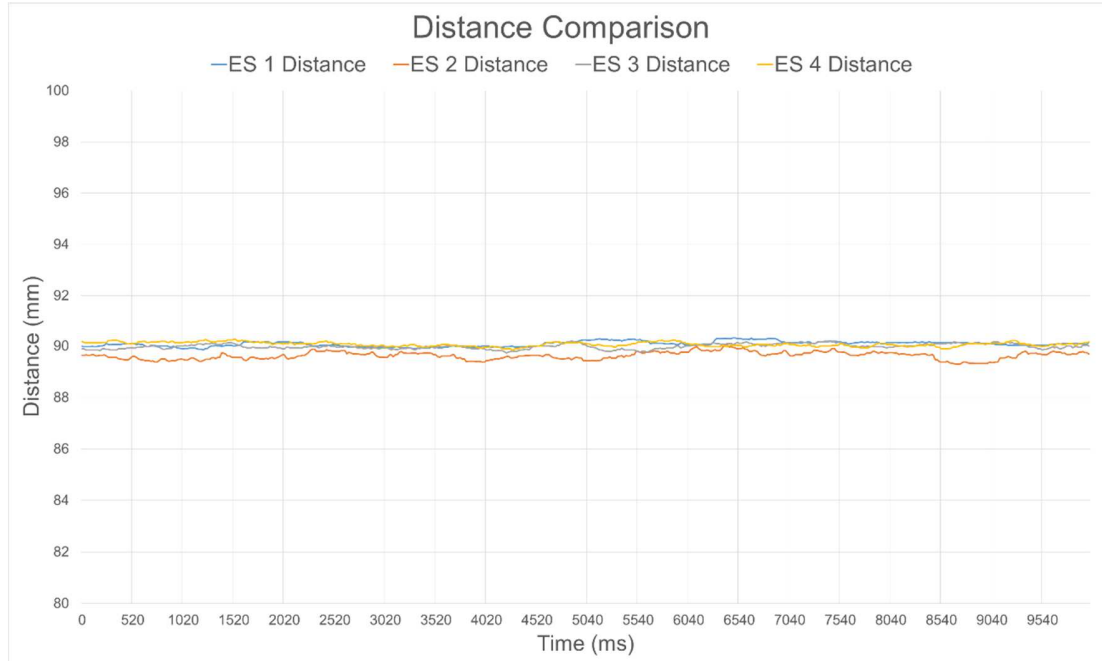


Figure 6.8 : Calibrated Distance Estimate Comparison

By ensuring that all of the sensors are producing accurate distance outputs, we greatly improve the rotation estimates of the system as well. Calibration attempts to remove the inter-sensor biases which are normally present in uncalibrated sensors leading to false rotational readings. Since the calibration procedure is performed by inspection of a live plot and a continuously varying numerical display, attaining a perfect calibration, i.e. one free of any errors, such that the mean values of readings are exactly equal to the desired set point, is quite unlikely. This is visible in Figure 6.8, where the distance estimates for sensor 2 sit slightly below the desired 90 mm mark when compared to the other three sensors. The respective distance estimate mean values, in millimeters, for each sensor after calibration for sensors 1, 2, 3 and 4, were 90.08 ± 0.10 , 89.62 ± 0.15 , 89.98 ± 0.10 , and 90.07 ± 0.08 ; a significant improvement from the uncalibrated values of 99.09 ± 0.10 , 109.15 ± 0.13 , 99.97 ± 0.13 , 105.65 ± 0.12 .

In the case of the 8th calibration point, sensors 1 and 3, which are used to calculate the rotation about the Y axis, were already producing similar outputs thereby having a small rotational bias regardless of the fact that their distance estimates were incorrect. Sensors 2 and 4 on the other hand generated largely different distance estimates resulting in a significant rotational bias about the X axis. Since the target planar surface was placed parallel to the sensor mounting plane, the expected rotation about either axis should be very close to 0 degree. Figure 6.9 and Figure 6.10 show how such bias is

greatly reduced, but not completely eliminated, when the sensors have been calibrated. The mean value for rotation estimates, in degrees, about the x and y axes go from -2.17 ± 0.09 to 0.27 ± 0.11 and -0.54 ± 0.10 to 0.06 ± 0.08 , respectively. Rotation estimates tend to be slightly more variable than the distance estimates due to the propagation of error which arises from the taking the difference of two such distance estimates. Earlier it was mentioned that the center distances of sensor pairs to the target were also obtained from the compliant wrist during data collection; plots of these for the uncalibrated and calibrated cases are provided in Figure A.2 and Figure A.3 of Appendix A, respectively, as the information they present is somewhat redundant since the results can be inferred with the help of Figure 6.7 and Figure 6.8.

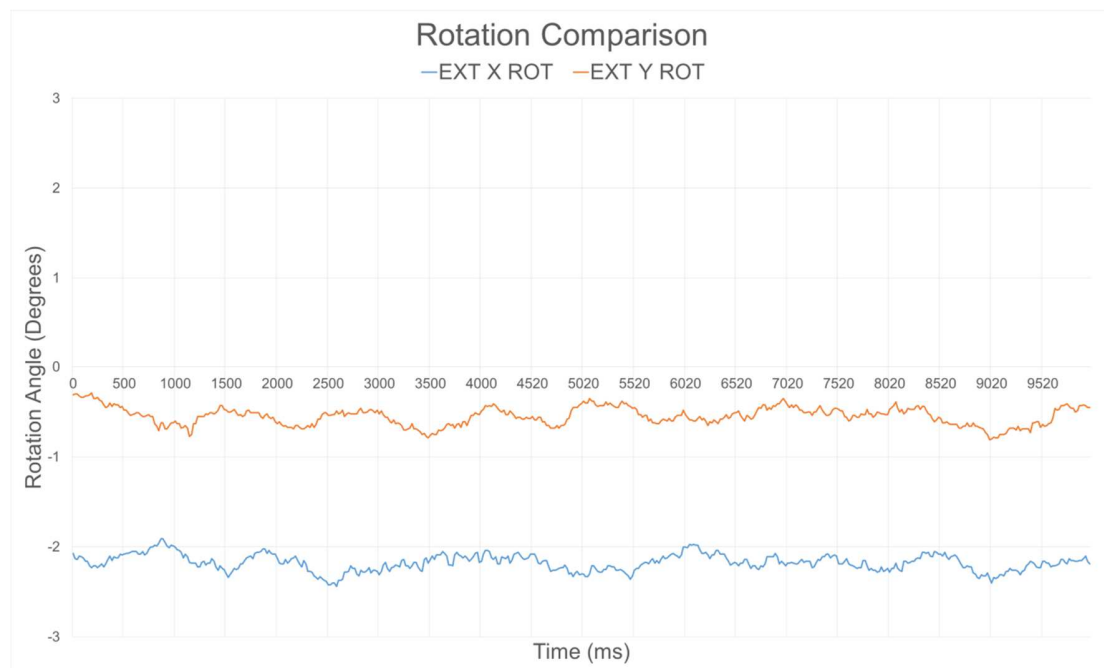


Figure 6.9 : Uncalibrated Rotation Estimate Comparison

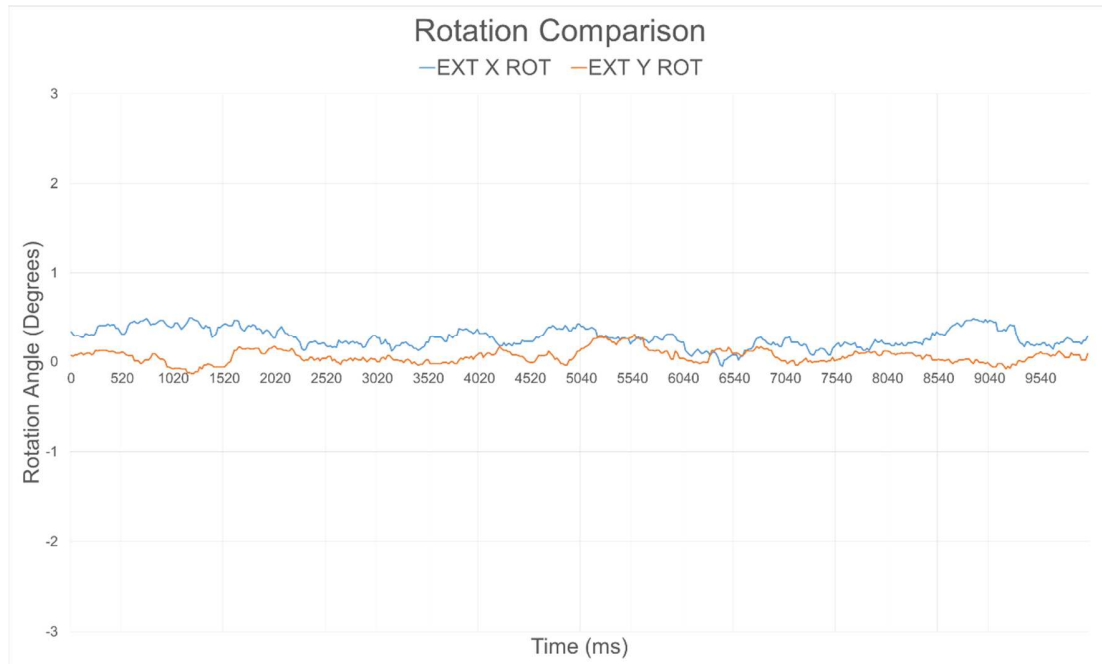


Figure 6.10 : Calibrated Rotation Estimate Comparison

The previous series of plots focused primarily on a single position of the track corresponding to a specific calibration point. This was useful to highlight the beneficial effects of both the filtering and calibration operations as they are applied to the sensor signals. The following plots provide aggregated results for all of the individual calibration positions. For example in Figure 6.11 the sensor voltage, for the same sensor presented previously, is plotted with respect to each of the 18 calibration positions. In this case, the mean voltage values shown have not yet been filtered nor calibrated; the calibration positions refer to the actual distances used to record the data. The values plotted are the mean values calculated from the data recorded at each of these positions. It should be noted that these plots do not represent the actual response curve of the sensors since the method for plotting shown here uses straight lines to join each marker whereas the effective response curve of the actual sensor is obtained through Catmul-Rom spline interpolation which generates the values between the markers as mentioned in section 5.1.1. Also shown in the graphs are error bars for each of the plotted points. These error bars represent the standard deviation associated with each mean value. They are difficult to discern for most points both due to a large span on the vertical axis as well as being quite small in value. They are most visible for the furthest track distances as the sensor output tends to fluctuate to a greater degree as distance increases.

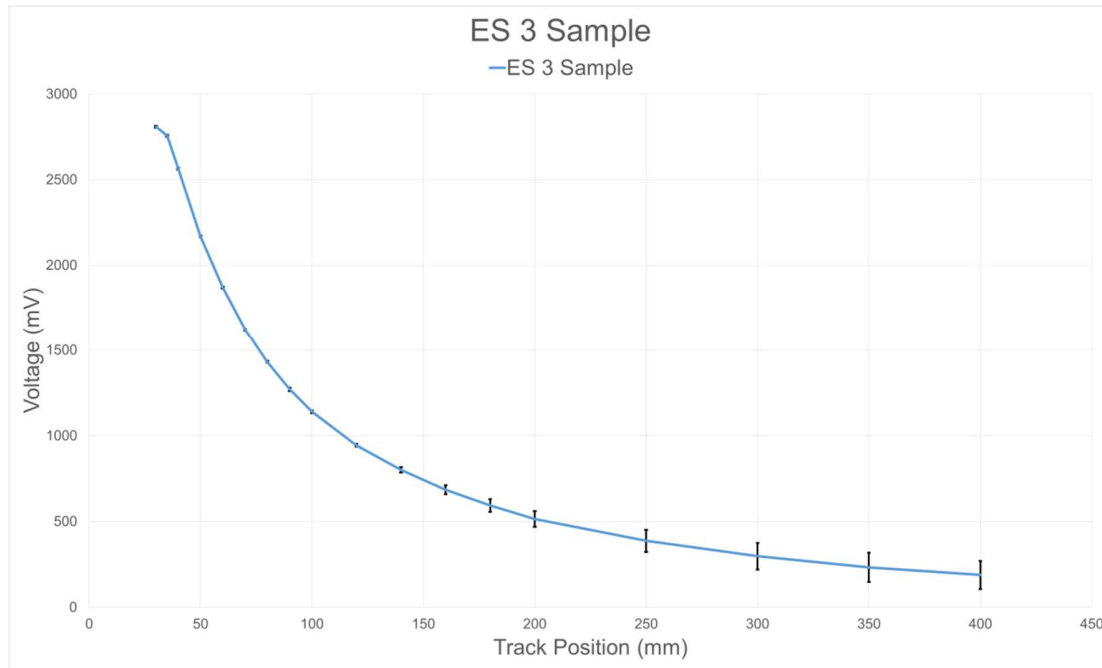


Figure 6.11 : Sensor Voltage Response Curve

When looking at the voltage response curve of Figure 6.11, it is evident that there is a greater degree of precision available for the shorter distances when objects are nearest to the sensors. This is because a larger variation in voltage is required to produce the same change in distance at a shorter distance than is required at longer distances. This fact also contributes to the larger errors at longer distances since the compliant wrist's ADC has a uniform scale throughout the range of voltage values.

The ADC onboard the microcontroller provides a 10-bit resolution and therefore 1024 discrete voltage levels between 0 and 3.3V which is the default operating voltage range of the IR sensor device. This means that the smallest voltage change which can be detected, and therefore the maximum sensitivity of any sensor is approximately 3.2 mV. Due to the shape of the characteristic voltage/distance curve provided in Figure 6.11 and the nonlinear relationship obtained, this leads to varying distance resolutions over the operational range of the sensor.

Considering the pairs of data points found in Table 5.2 the theoretical expected resolutions in the given ranges of distance is established by calculating the slope in between adjacent data (voltage versus distance) as follows:

$$Resolution = \left| \frac{p_{d2} - p_{d1}}{p_{v2} - p_{v1}} \right| \quad (6.1)$$

where the subscripts v and d represent voltage and distance values, respectively.

Toward the maximum range of operation, a distance variation from 40 cm to 35 cm corresponds to 70 mV change, representing 714.3 mm/V. Combining this value with the ADC sensitivity the actual distance resolution in that region is approximately 2.3 mm. At the other end of the valid distance range, going from 5 cm to 4 cm, the theoretical resolution is 26.3mm/V which results in an approximate distance resolution of 0.085 mm. The current prototype has the internal sensors separated by a distance, W , of 91.8 mm (external sensors are separated by a distance of 263 mm) leading to a worst possible angular sensitivity of 1.435 degree over the largest distances for the compliant plate (0.5 degree for external surfaces). In comparison, [64] reports worst-case accuracies of 0.6 mm for translation and 0.0099 radians (0.57°) for rotation. Resolutions are omitted in [76] for both the distance and rotation, stating only the operating ranges of $\pm 10^\circ$ for rotation about the X and Y axes, and a 10 mm travel of the upper plate's center point with respect to the lower plate's center point. In comparison, the latest prototype for the presented compliant wrist provides a translation range of -25 mm to +10 mm with minimum rotation ranges for both axes of $\pm 40^\circ$. The sliding shaft which houses the compression spring allows for the 10 mm of extension, however this type of translation would only be experienced in certain scenarios, such as when contact was made with an adhesive surface which, when the compliant wrist would be pulled away from the surface, an external pulling force would be applied to the device.

Figure 6.12 shows a comparison of the uncalibrated voltage response curves for the four sensors for which data was collected simultaneously while Figure 6.13 shows the corresponding distance response curves.

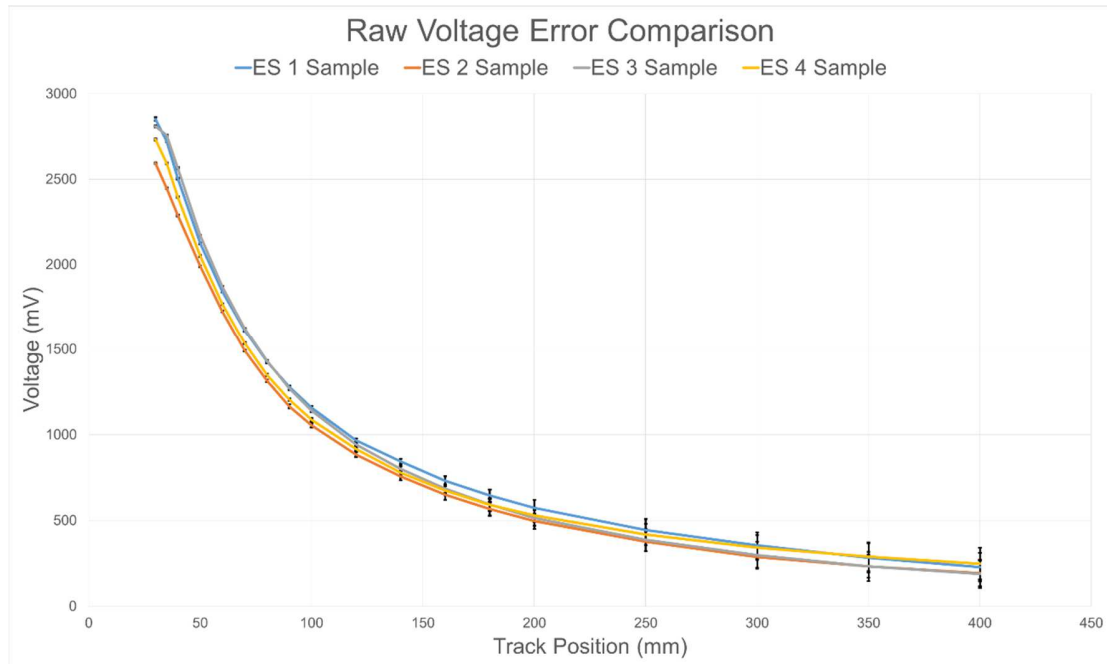


Figure 6.12 : Comparison of Uncalibrated Sensor Voltage Response Curves

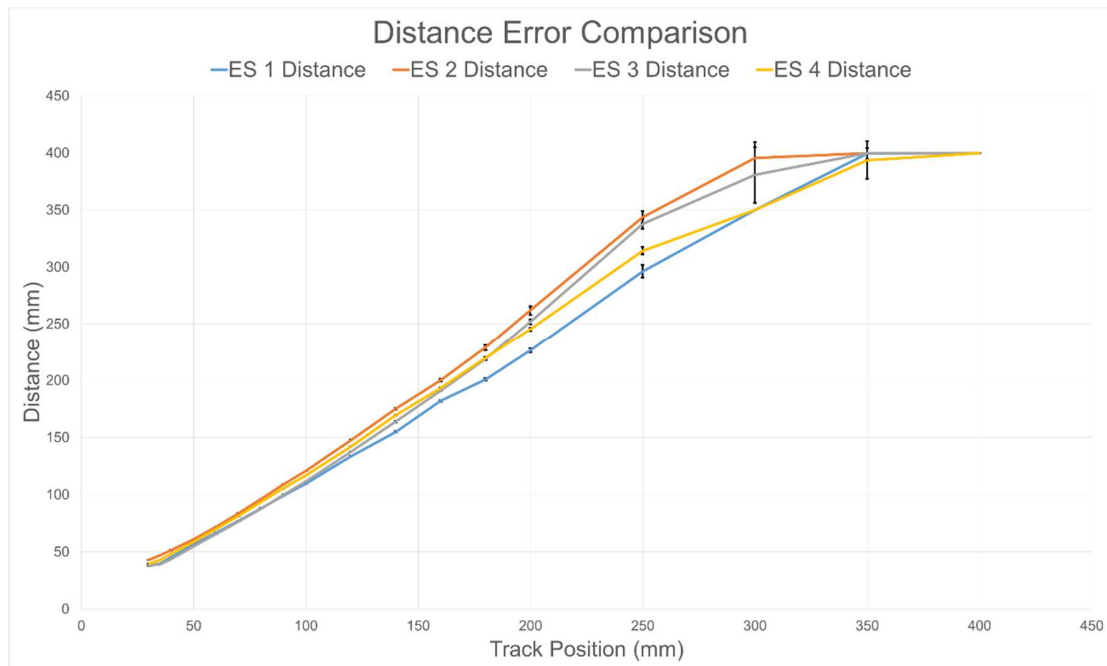


Figure 6.13 : Comparison of Uncalibrated Sensor Distance Response Curves

In their uncalibrated state, the distance response curves produced by the sensors are both nonlinear and stray significantly from each other as the distance increases. Due to the interpolation method, the mean values and errors associated with the two first points and the two last points on the curve should not be taken as reliable information since these act as the anchor points of the method. All

voltage values between the ranges set by these pairs of points will result in a conversion to either of those two points without any distance values in between being possible. This fact tends to skew the data at the extremities of the plot such as an error of 0 mm at a distance of 400 mm.

The ideal distance response curve is a straight line passing through all points having equal values for both the track position and sensor distance. The curves plotted in Figure 6.14 show how these ideal curves are nearly achieved through the proposed calibration scheme with the exception of the final point which varies slightly. This discrepancy is also due to the interpolation technique which has the effect of making the calibration procedure somewhat more difficult for the extremities of the curve. Despite the few adverse effects of this interpolation method, it does however provide the benefit of having a maximum distance which is very useful for the detection of nearby objects while ignoring those outside the desired range.



Figure 6.14 : Comparison of Calibrated Sensor Distance Response Curves

As a final point to highlight the importance of having properly calibrated instruments, plots of the rotational bias with respect to track position of the uncalibrated sensors as well as the calibrated sensors are provided in Figure 6.15 and Figure 6.16, respectively.

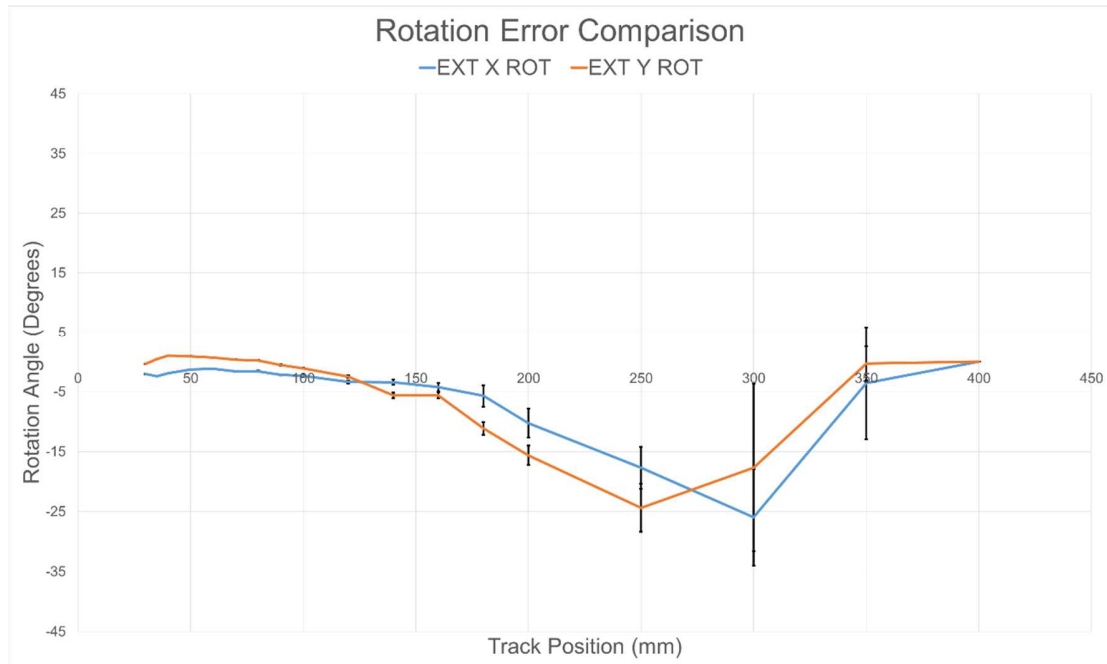


Figure 6.15 : Comparison of Uncalibrated Rotational Bias

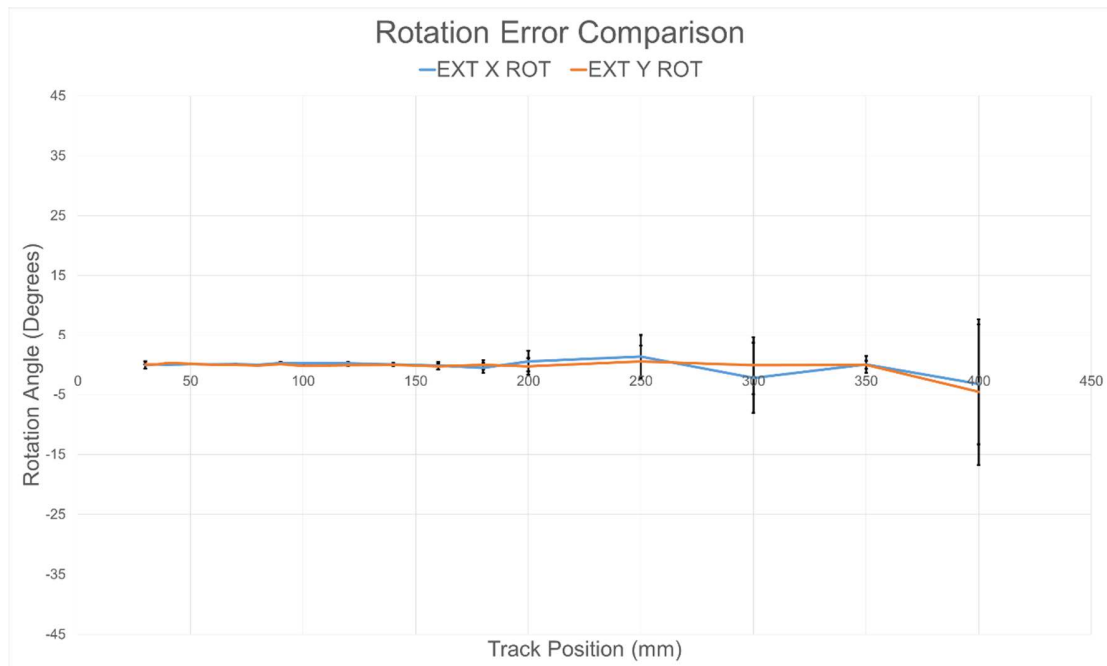


Figure 6.16 : Comparison of Calibrated Rotational Bias

Thus far, only the time domain characteristics of the sensor outputs have been discussed, with emphasis on the particular case of using a moving average filter of window length 33. The same analysis was performed for 3 additional cases, namely the unfiltered case and two cases where the window length of the moving average filter was set to 7 and 15. Results for the unfiltered case were essentially

captured in the comparison of voltage amplitudes both before and after being filtered in the case previously presented while the cases of the moving average filters of window lengths 7 and 15 led to the conclusion that the shorter window lengths simply provided less smoothing of the time domain signals which essentially resulted in poorer overall system performance due to larger variations in the signals.

Evidence of periodic noise was found to be embedded in some of the sensor voltage signals such as the one shown in Figure 6.17. The underlying signal appears to be modulated by multiple sinusoidal signals at different frequencies which was not in line with the assumption that all of the noise in the signal was random (white) noise. These occurrences appeared as the gap between the object from the sensors reached a large enough distance and increased in severity as the distance increased further. The obvious patterns in the noise begin to appear at an approximate distance of 100 mm and grow from there. The graphs in the following spectral analysis are for the 12th calibration position corresponding to 160 mm for the second external sensor. It should also be noted that the data is the unfiltered raw voltage signal from a calibrated sensor. This patterned noise prompted a more in-depth investigation of the frequency domain characteristics of the sensors.

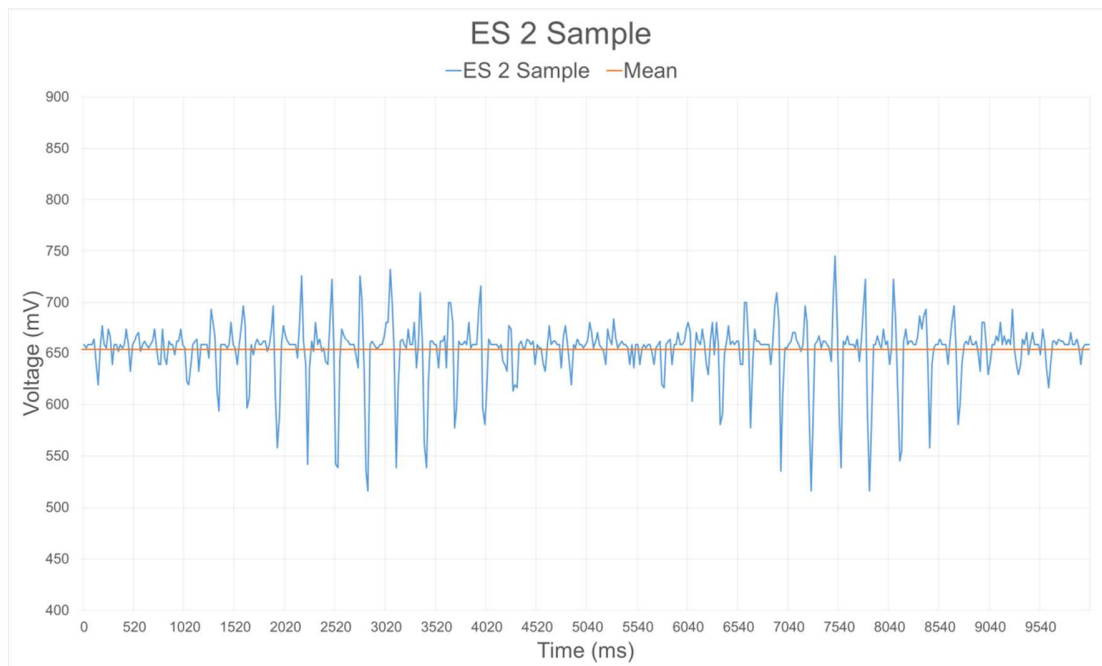


Figure 6.17 : Voltage Signal with Periodic Noise

The frequency spectrums of the signals were obtained using the Fourier analysis function found in the Data Analysis Toolpak add-in for excel. The input signal was approximately 500 points and zero padded to obtain the necessary 512 point signal required by the function. The returned values from the function are the complex numbers corresponding to a 512 point discrete Fourier transform (DFT) generated by a fast Fourier transform operation (FFT). From this computed data, two other representations of the information were generated, namely the magnitude of these complex numbers and the power spectrum which was obtained via the following formula for calculating power spectral density (PSD):

$$PSD_j = 10 \log_{10} \left(\frac{1}{F_s \cdot \#Samples} \cdot |DFT_j|^2 \right) \quad (6.2)$$

where F_s is the sampling frequency and j is the index of the current data point.

When looking at the power spectrum in the frequency domain shown in Figure 6.18 corresponding to the voltage signal of Figure 6.17, it is possible to identify an underlying structure consisting of a main lobe with multiple side lobes; a commonly occurring feature in the frequency domain of multiple window signals. It is speculated that this is most likely caused by the signal preprocessing that is believed to be performed by the sensor's internal circuitry acting as a pre-filter of sorts. The shape of the power distribution would explain the periodic noise which is essentially resulting from the sharp cut-off points and raised lobes present in the frequency domain.

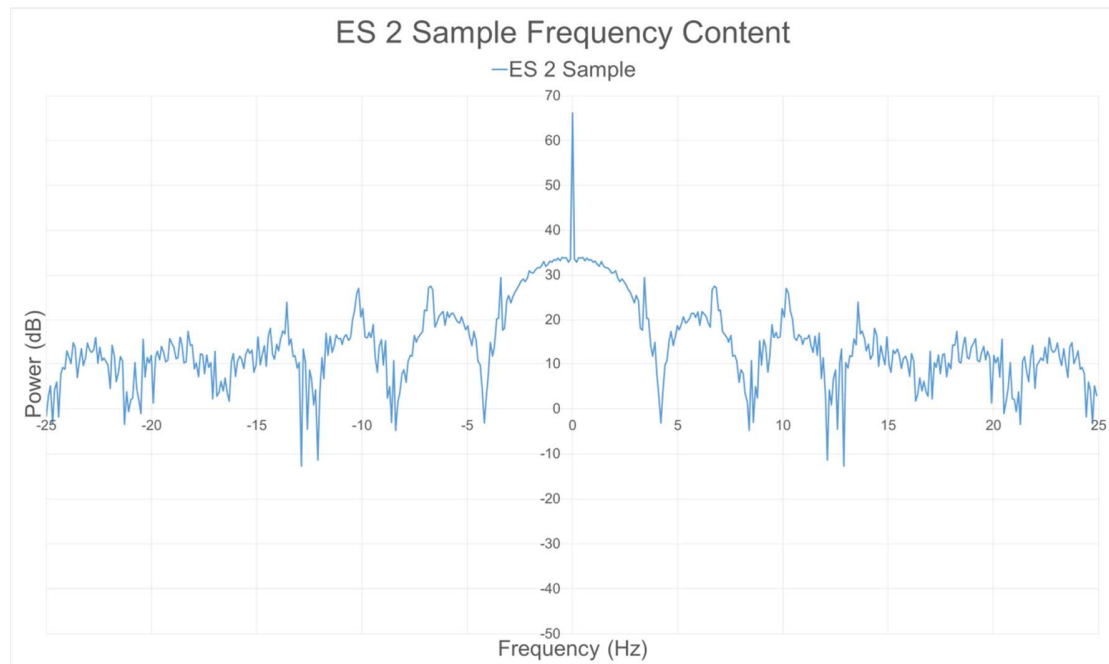


Figure 6.18 : Power Spectrum of Raw Voltage Signal

A mean value in the time domain can be represented as a constant value and corresponds to an impulse signal in the frequency domain at the DC (zero frequency) point. In Figure 6.18 we can see that the frequency content present in the recorded signal has a large spike at the DC point which illustrates this fact. The energy that is concentrated at this point is quite large relative to the frequency content at other frequencies and so the mean value is still representative of the desired value. Superimposed onto the side lobes of the frequency spectrum of the signal are several spikes which were suspected to be the culprits of the aberrations found in the time domain signal. A logarithmic scale is very useful in displaying information that spans a large range of values but isn't always the best choice when trying to extract or isolate meaningful information. When looking at the magnitude of the signal, the picture becomes even less clear however, due to the overwhelming peak at DC although the peaks that were evident in Figure 6.18 are still slightly visible in Figure 6.19.

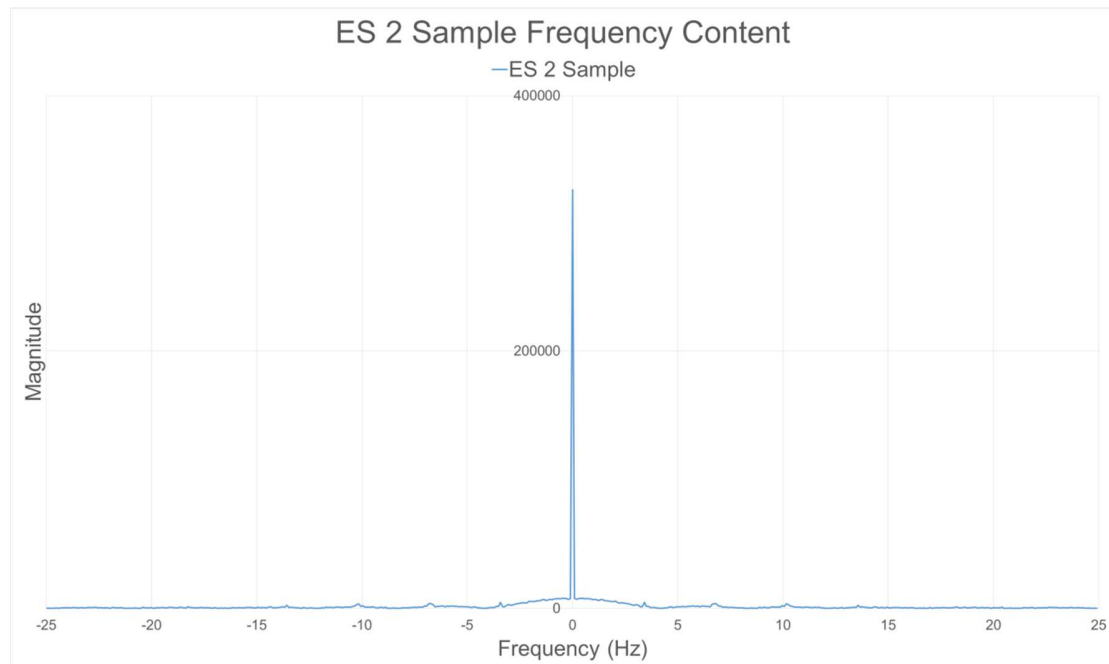


Figure 6.19 : Magnitude Spectrum of Raw Voltage Signal

In order to obtain a better picture of the frequency content, additional data processing was performed post collection. The mean of the signal was calculated from the available data and removed from the signal by subtracting the mean value from every data point of the original signal. This resulted in a modified signal which was now varying around a zero value. This had the effect of removing nearly all of the energy coming from the desired part of the signal, namely the mean, and leaving essentially the noise which was superimposed onto the signal. Due to linearity, by removing a mean value from a signal in the time domain, the resulting frequency content is also representative of the modified signal. The power spectrum of this modified signal is given in Figure 6.20. Having removed the mean value from the signal has resulted in an energy content approaching zero indicated by the large negative peak at the DC point as well as the removal of large amount of energy across the entire spectrum. The lobe structure which was embedded in the sensor's signal has now also been removed leaving only the undesirable noise present with the peaks still very much present. This power spectrum is also now better tailored for examination with a magnitude scale.

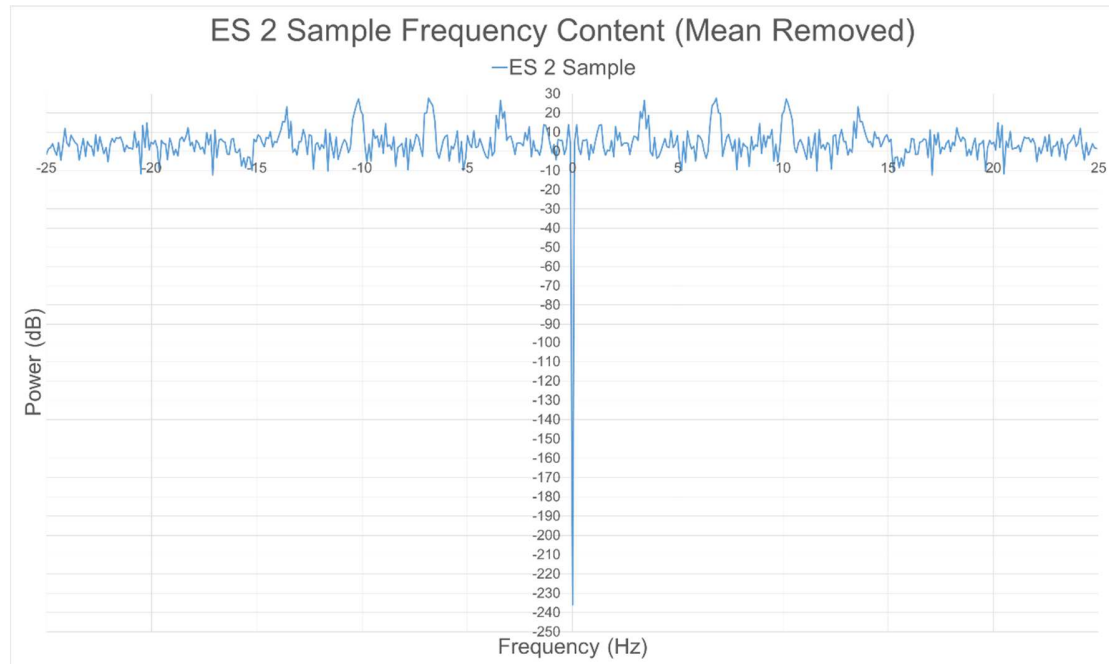


Figure 6.20 : Power Spectrum of Modified Voltage Signal

Figure 6.21 shows the pure magnitude of the frequency response of the voltage signal whose mean has been removed. What this graph represents now are the undesired characteristics of our sensor signals. At this point, we can clearly see the sinusoids in the frequency domain which are represented by pairs of impulses at multiple frequency points amidst additional, less prominent, seemingly random noise. Since the object placed in front of the sensors remained stationary, such large, patterned noise, was unexpected and it had to be verified as to whether or not the filtering strategy employed was able to properly handle this scenario. A shorter window length in the time domain corresponds to a wider main lobe in the frequency domain and vice versa due to the duality of the two domains. Therefore by adjusting the window length, it is possible to tailor our frequency domain frequency rejection range to the desired width.

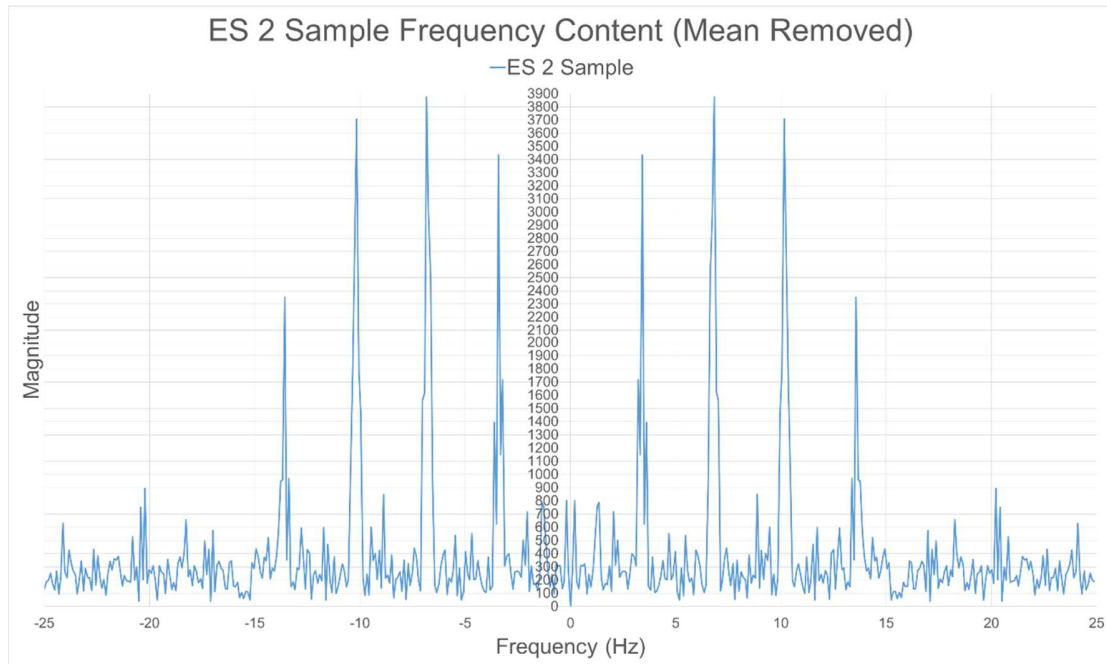


Figure 6.21 : Magnitude Spectrum of Modified Voltage Signal

Since it was not known a priori that this periodic noise was a factor to be considered during the filter length selection process, it could not be guaranteed that the noise would be fully rejected. The effect that window length for the filtering process has on noise is evident when comparing the frequency content coming from the same sensor with two different window lengths. Shown in Figure 6.22 is the frequency content contained in the signal generated by the second external sensor after it has been filtered by a moving average filter with window length 7. The peaks found above a frequency of 2 hertz are each diminished to a greater degree as the frequency increases; however, the first largest peak found at approximately 3 Hz is still much larger than those found near the DC point indicating that they could still interfere with a signal produced by a stationary object. Through a process of experimentation with different window lengths and their effects on the noise content, it was found that the longer window length of 33 samples was able to reduce the size of those peaks to a point below those found in the desired range of frequencies as seen in Figure 6.23. This result suggests that a window length of 33 samples, in the case of a sampling frequency of 50 Hz, was an adequate choice for ensuring a relatively stable output.

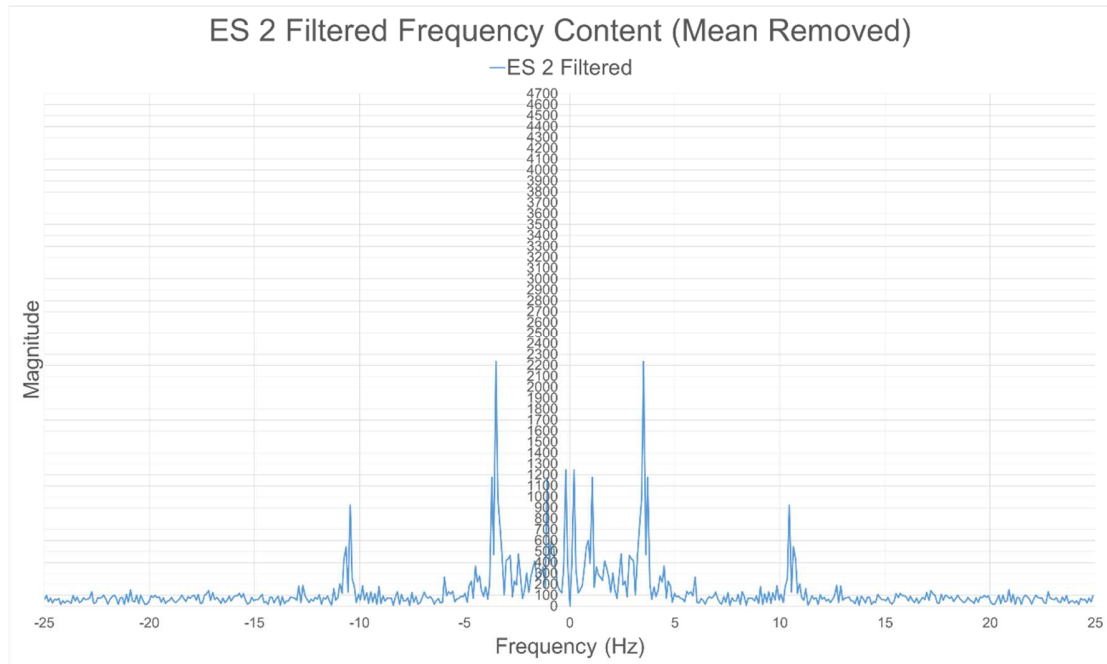


Figure 6.22 : Magnitude Spectrum of Modified Signal with Filter Applied (Window Length 7)

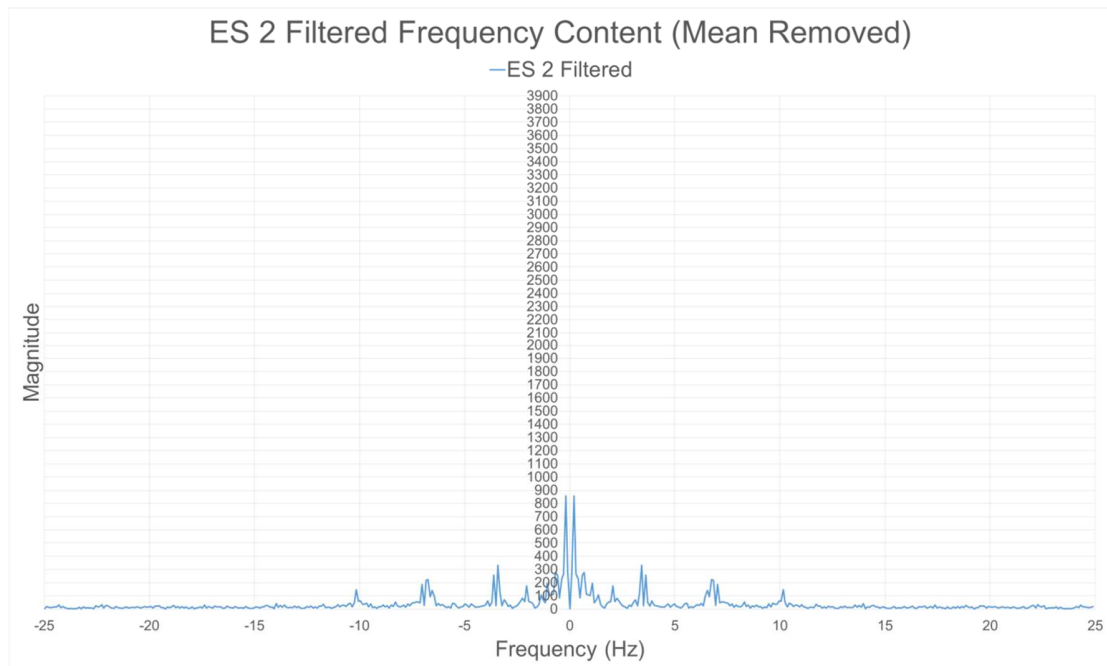


Figure 6.23 : Magnitude Spectrum of Modified Signal with Filter Applied (Window Length 33)

The source of this noise has yet to be determined, since as mentioned previously, the possible sources of noise are numerous. It is suspected that the quantization that occurs in the ADC, which converts an analog signal by mapping certain values to a set of discrete digitally represented values, creates an illusion of periodicity in the signal since this varies in discrete, repeating steps over time. This

could potentially still be of significance even after the filtering. Another aspect of this noise which makes it even more conspicuous is that the patterns are different for each sensor. Sensors 1 and 2 in Figure 6.24 both seem to be plagued by noise in the lower frequencies while sensors 3 and 4 tend to have noise present in the higher frequencies. Regardless of these differences seen, filtering with a moving average filter with window length 33 does appear to rectify the problem to a certain degree as shown in Figure 6.25.

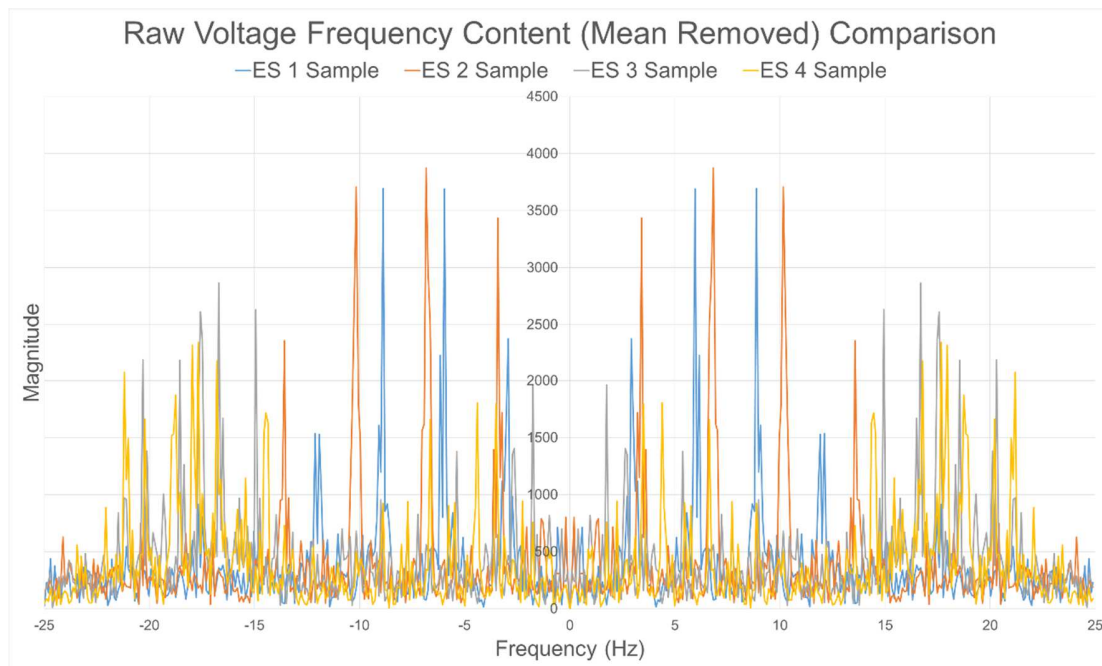


Figure 6.24 : Comparison of Magnitude Spectrums of Modified Unfiltered Signals

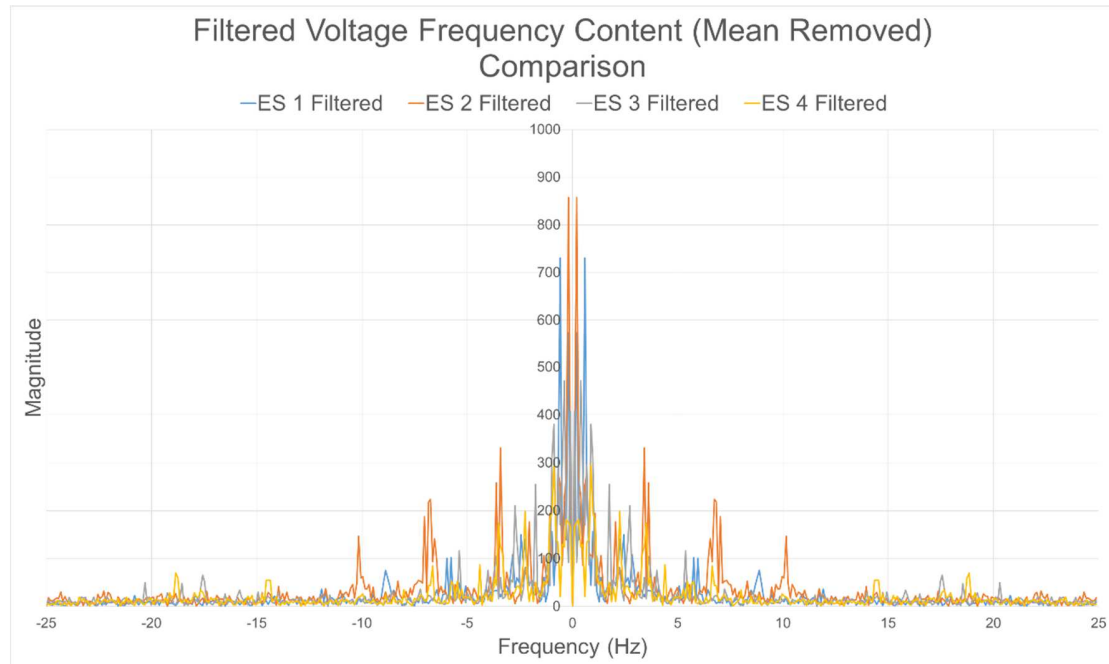


Figure 6.25 : Comparison of Magnitude Spectrums of Modified Signals with Filters Applied (Window Length 33)

An additional step was taken to gain additional insight into the behavior of these signals by plotting the recorded sample values in histograms. Histograms provide a straightforward method of visualizing the variability of signals by illustrating the frequency of each measurement, or in the case of continuously varying signals, determining how often a signal takes on values found between specified ranges. This kind of information is useful in order to assess whether or not the current assumptions of a Gaussian, or normal, distribution exists for our current data. If this is the case then it is possible to more easily characterize and predict the performance of the overall system.

Histograms do present one problem however; the selection of the adequate number of bins is something that is somewhat difficult to do. The bins represent the discrete ranges of values that will be used when individual values are counted for each range. Normally the full range of values for the measured signal is divided equally by the number of bins to obtain multiple smaller ranges of values. The clarity of the information contained in this type of graph is directly dependent on the number of bins. In some cases, when there are too few bins, the true nature of the signal becomes hidden by being too grossly grouped. Similarly, too many bins and all intelligible information becomes too diluted to draw any meaningful conclusions.

Figure 6.26 provides an example of the latter case where the number of bins chosen is slightly larger than needed leading to several empty bins. The histogram was produced from sensor readings

where the target surface was placed at a distance of 40 mm. As mentioned previously, ADC voltage samples produce discrete values at this stage in the system which account for the gaps as not all values in the range are possible due to the ADC's resolution being larger than the bin size of 2.08 mV in this particular instance. The number of bins and the range that values can take must allow for a bin size which is at least greater than the ADC's resolution in order to minimize gaps in the histograms. For example, the range of values in Figure 6.27 is 229.03 compared to 35.48 in Figure 6.26. Dividing both of these values by the number of bins minus one, 17, gives bin sizes of 13.47 mV and 2.09 mV, respectively. It can be seen that in Figure 6.27, there is only a single gap in the data, which is most likely due to the lack of data points falling within that range when considering the distribution of values. Due to the large amount of data collected, processing of the information needed to be automated and since the range of values could not be known prior to the analysis, rather than selecting a fixed bin size for every scenario histograms were generated using several different bin sizes, namely 8, 10, 14 and 18.

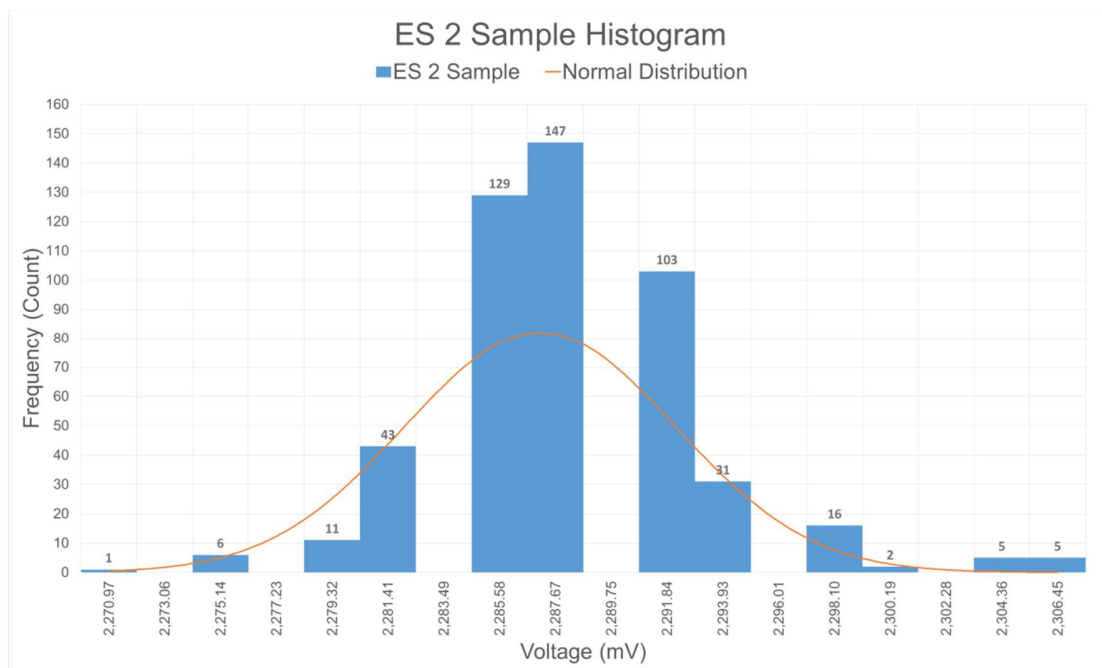


Figure 6.26 : Raw Voltage Histogram with 18 Bins (Set Distance = 40 mm)

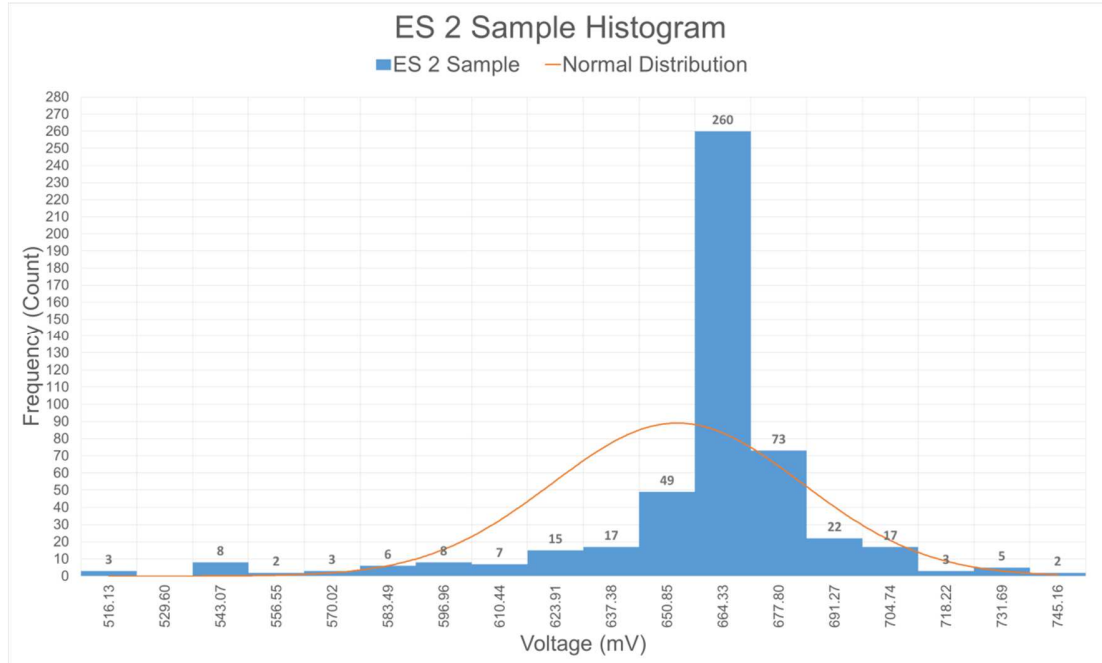


Figure 6.27 : Raw Voltage Histogram with 18 Bins (Set Distance = 160 mm)

It should be noted that all of the histograms are produced using 500 samples and that the numbers above each bar represents the total count of those samples that fall within the range represented by the bin. Overlaid over the histograms are normal distribution curves plotted using the Gaussian function:

$$f(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (6.3)$$

where μ and σ represent the mean and standard deviation, respectively. These parameters were also calculated using the 500 samples available. Having the normal distribution in the same graph allows for direct comparison as to how the actual samples of the signal are behaving. In order to make this comparison fairly, the actual distribution function must be scaled properly in order to obtain the correct area under the curve to match the total area present in the histogram. This is done by multiplying the width of the bins by the total number of samples to obtain the necessary scaling factor.

When looking at Figure 6.28, with a smaller number of bins, the graph seems to offer a more adequate picture of the sample values. Having the majority of samples being concentrated near the center indicates an accurate measurement with low variability; however, the shape of the curve is not enough to guarantee that this is what's truly happening. The signal shown has yet to be filtered and

therefore does not reflect the final result obtained from the system. The full range of the signal varies approximately by 229 mV at a physical distance of 160 mm. Comparing this to the filtered signal plotted in Figure 6.29 we can see how much of an effect filtering has on the variability, reducing the range to just over 19 mV. Filtering also has a smoothing effect leading to a signal distribution which resembles much more that of a normal distribution in the process.

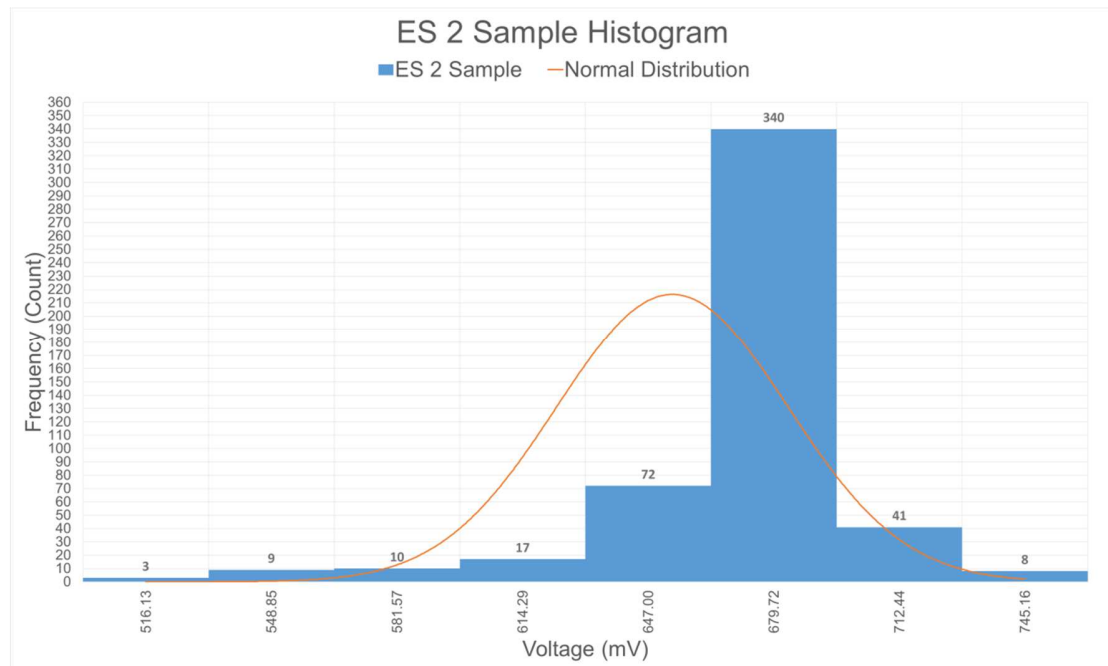


Figure 6.28 : Raw Voltage Histogram with 8 Bins (Set Distance = 160 mm)

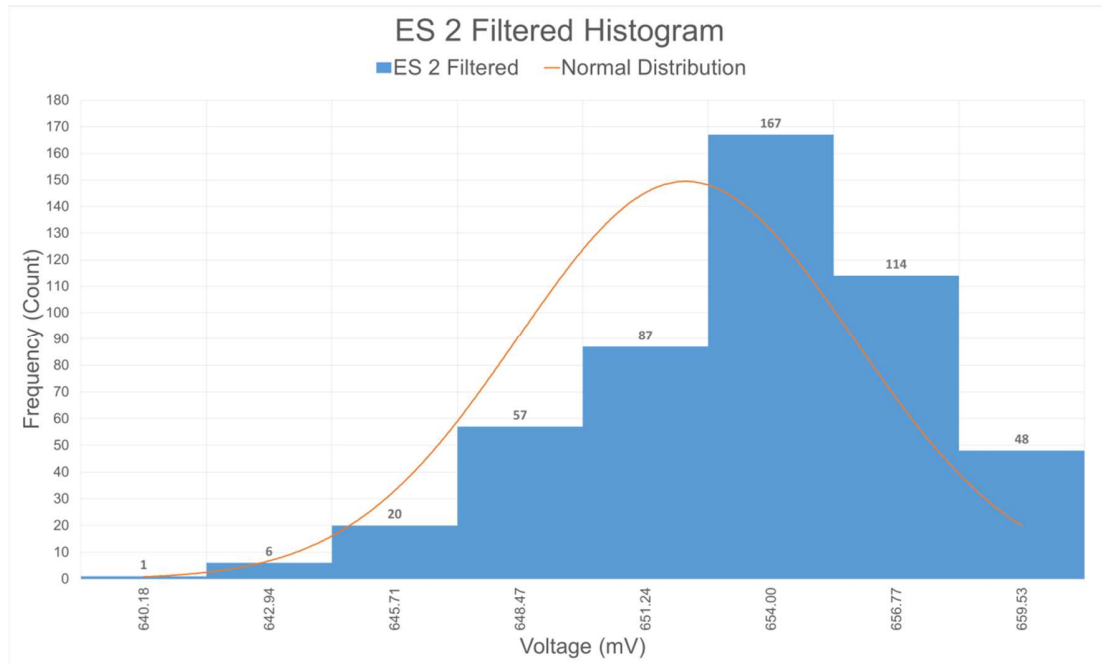


Figure 6.29 : Filtered Voltage Histogram with 8 Bins (Set Distance = 160 mm)

Moving over to the histogram representing the converted distance estimates in Figure 6.30 we see that the number of bins required to represent the signal is much lower due to the miniscule range of variation. The converted distance estimates had a range of 0.17 mm. The corresponding means and standard deviations for the raw voltage, filtered voltage and distance estimates were 2287.09 ± 5.07 mV, 2287.27 ± 1.13 mV, and 40.48 ± 0.04 mm, respectively. It should be noted that these values represent best case scenarios with variability increasing accordingly as distance increases from the target objects due to lower resolution. By comparison, in Figure 6.31, for a distance estimate signal we obtain a full range of approximately 4.5 mm at a physical distance of 160 mm, representing approximately 3% of the desired signal, up from 0.4% at 40 mm. At 160 mm, we can also compare means and standard deviations for all three signals which are 653.30 ± 30.17 mV, 652.12 ± 3.69 mV, and 160.42 ± 0.82 mm. In all cases, it is evident that filtering is an essential part of this system, greatly increasing accuracy by decreasing variability.

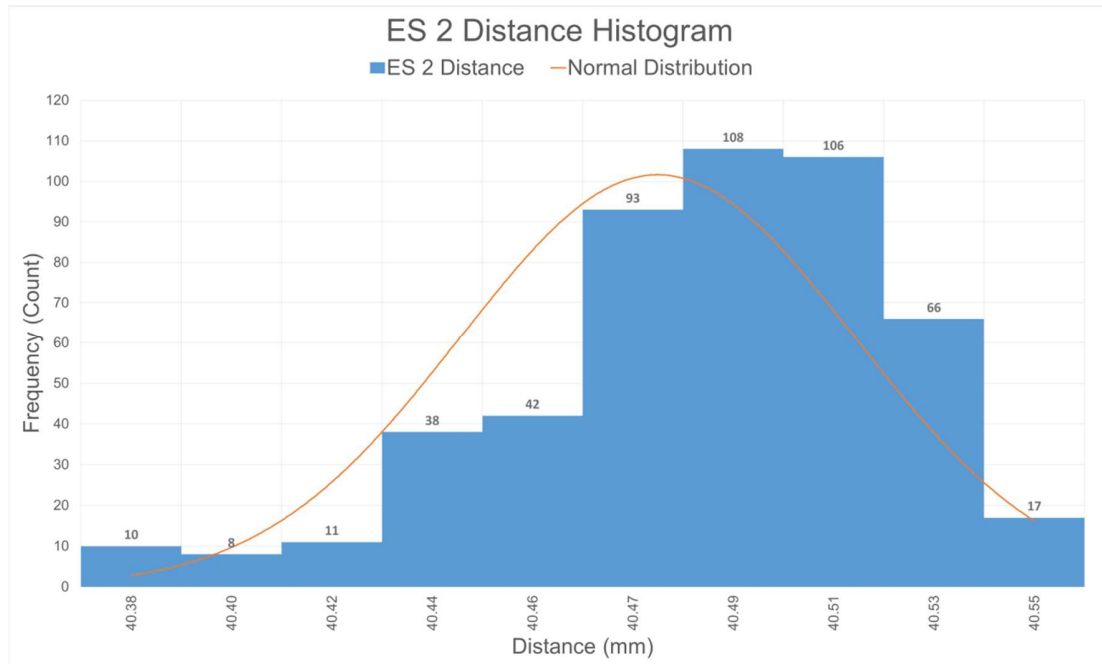


Figure 6.30 : Distance Histogram with 10 Bins (Set Distance = 40 mm)

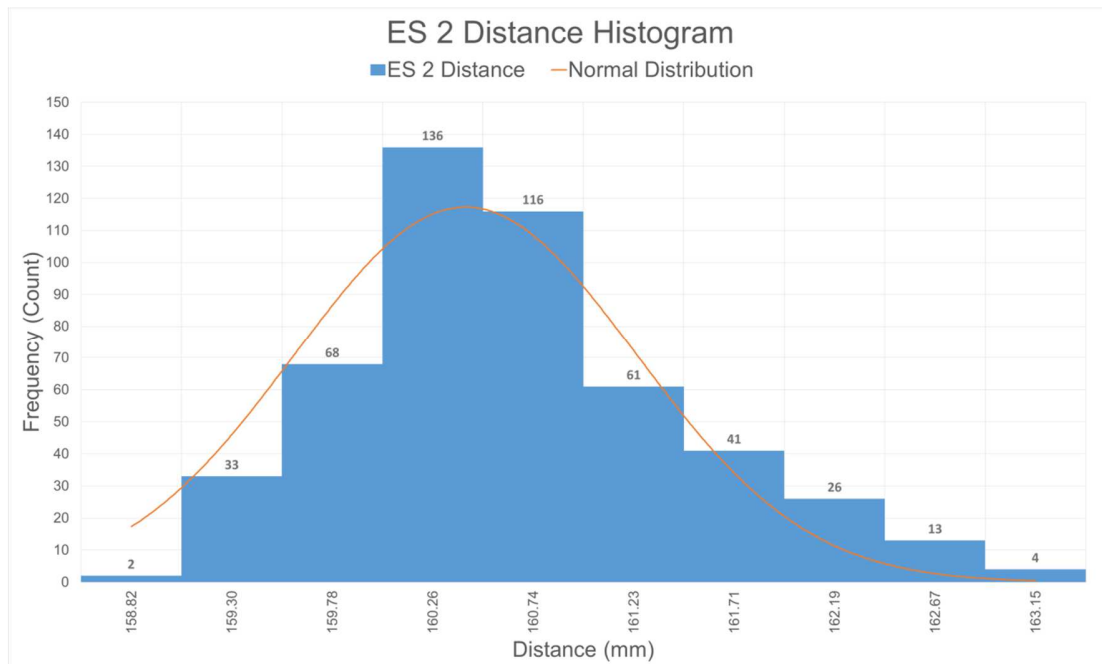


Figure 6.31 : Distance Histogram with 10 Bins (Set Distance = 160 mm)

A final investigation into the characteristics of the signal involved the comparison of the dynamic response rate of all the sensors. By moving the target object in a continuous fashion, starting from the closest possible point to the sensors out to a distance exceeding the maximum rated distance, it was possible to determine if all sensors had similar response times. This is important for the simple

fact that all kinematic information calculated for the compliant wrist, i.e. the rotations and translation parameters of the transformation matrices, involve multiple sensor readings which, if the sensors have different response times, can directly induce errors into those calculations by not having the most current information from all sensors simultaneously.

Figure 6.32 shows the raw voltage signals of four sensors mounted to the motorized track allowing for the measurements of continuous motion for an object. There are a few points of note which indicate that the sensors are in fact reacting in unison to the changes made to the distance of the object. For one, the peaks following the sharp rise on the left of the image appear to all line up at the same instance in time, with successive peaks and valleys also following in turn. The separation of alignment once the signals begin to diminish in value after the last peak is simply due to the uncalibrated state of the signals being recorded since as mentioned previously, calibration effects appear after conversions are made to distance estimates. Also visible here is the increasing noise as the object reaches the furthest point away from the sensors.

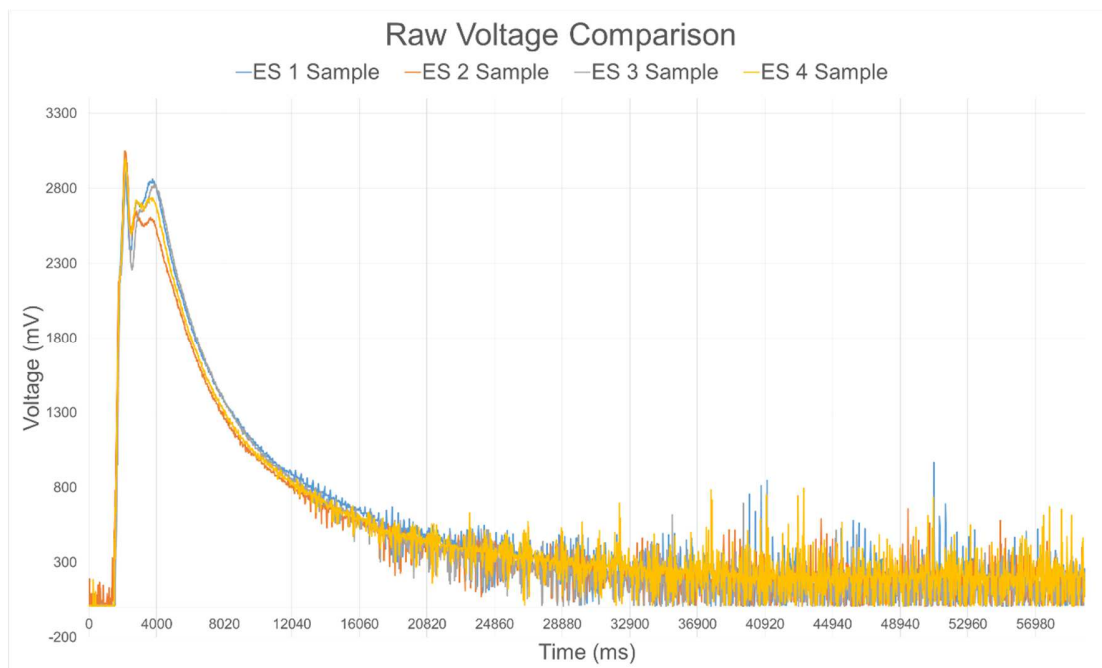


Figure 6.32 : Raw Voltage Dynamic Response Comparison

Once filtering is applied in Figure 6.33, we see that the shape of the curves changes drastically. The first peak following the sharp rise has been attenuated due to the low pass characteristic of the moving average filter removing the high frequency components. Also noticeable is the significant

reduction of oscillations noise at the extremities. This again shows that a window length of 33 samples has the desired effect on the signals.

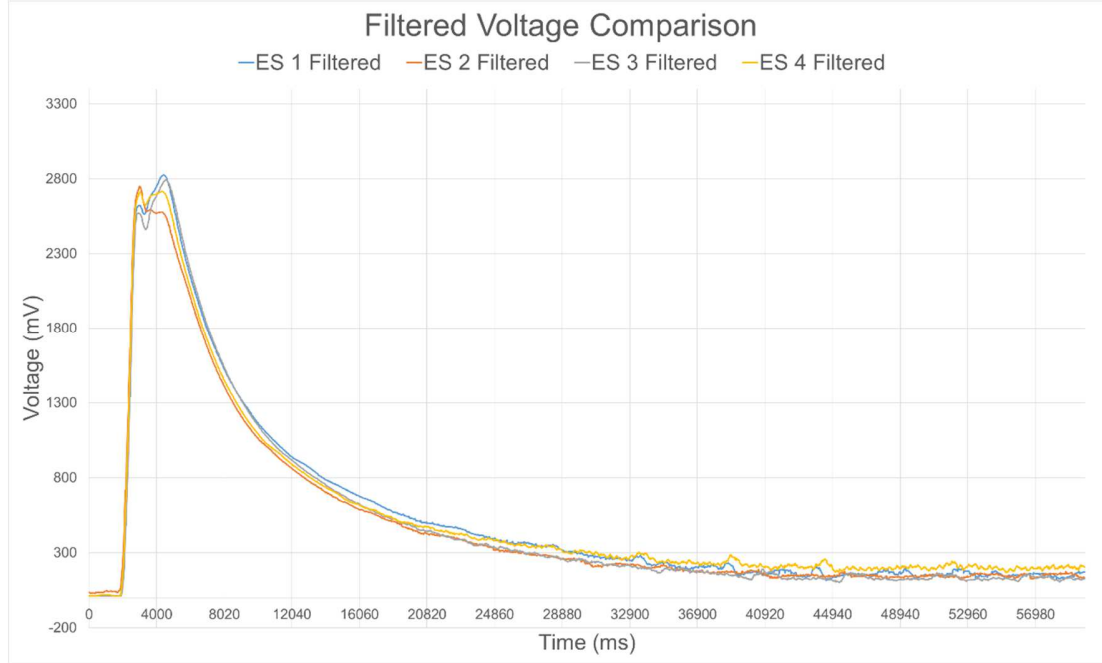


Figure 6.33 : Filtered Voltage Dynamic Response Comparison

Also previously mentioned was the fact that any type of filtering action applied to a signal introduces time delays into a system. The traditional definition for filter delay is the group delay which is defined as the derivative of the phase response of the filter. Since an FIR filter is being used, it is known that the filter has linear phase and therefore constant group delay, meaning that all frequencies contained in the signal will be delayed by a constant amount when passing through the system. This simplifies the result and is obtained using the following equation:

$$D = \frac{(N-1)}{(2 \cdot F_s)} \quad (6.4)$$

where D is the delay, N is the number of taps in the filter or in our case the window length used in calculation of the average, and F_s is the sampling frequency. Since the filter used here was an averaging filter with a window length of 33 samples applied to a signal sampled at a rate of 50 Hz, in this case we should expect to see delays on the order 320 ms from the above equation.

In order to determine if this delay introduced into the system due to filtering was close to the expected value, in Figure 6.34 the signal from a sensor prior to filtering is compared temporally to the

signal from that same sensor after having passed through the filter. Labels were added to data points at two different locations on the plot where the voltage values available were as close to each other as possible in order to compare the time at which each of the signals, raw and filtered, reached those values. In the first instance, the raw voltage signal reached a value of 14.17 mV after 1300 ms while the filtered voltage signal reached a value of 15.74 mV after 1840 ms resulting in an approximate delay of 540 ms. For the second instance, again comparing similar voltage values, the resulting delay was 740 ms.

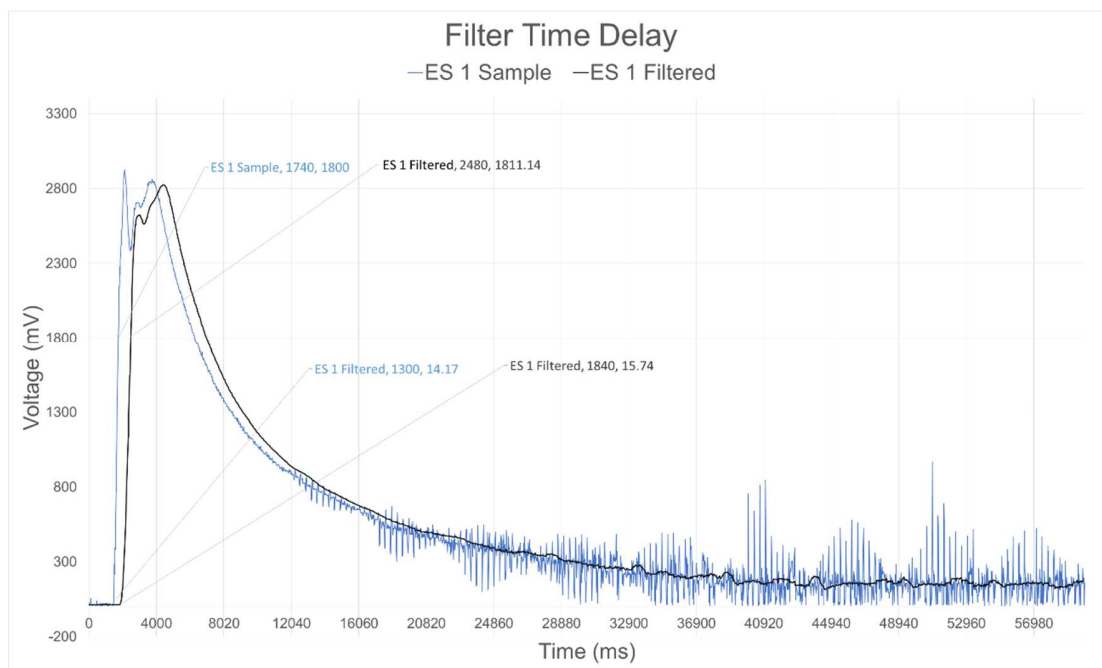


Figure 6.34 : Filter Time Delay Effect

The reason that these values are much larger than the expected value given by the group delay is that the group delay fails to account for other factors present in the system. When thinking of the filter and how it is applied to a signal, a more intuitive method of measuring delay would be to allow for the filtered signal to be completely overlapped by the filter in order to produce a resulting value which takes into account as much of the signal's information as possible, namely the full length of the window. Using this estimate a value of 33/50 or 660 ms is obtained.

If thinking of the filter in terms of a system, there are additional statistics that are used to characterize the response time. For example, rise time and settling time measured during application of a step input reveal key information on the behavior of the system. This seems to apply in our case since the larger delays occur when the input signal is rapidly changing, an effect analogous to the slew rate of physical systems.

Figure 6.35 again confirms the findings of the sensors having uniform response times with calibration offering very closely related distance estimates. The section of the plot which shows direct jumps in value between 350 mm and 400 mm shows the effect of the interpolation technique used which prevents intermediate values between these two anchor points to be calculated. Also apparent is the fact that the effective distance for which these particular sensors should be used, to prevent unwantedly large signal variations would be less than 200 mm.

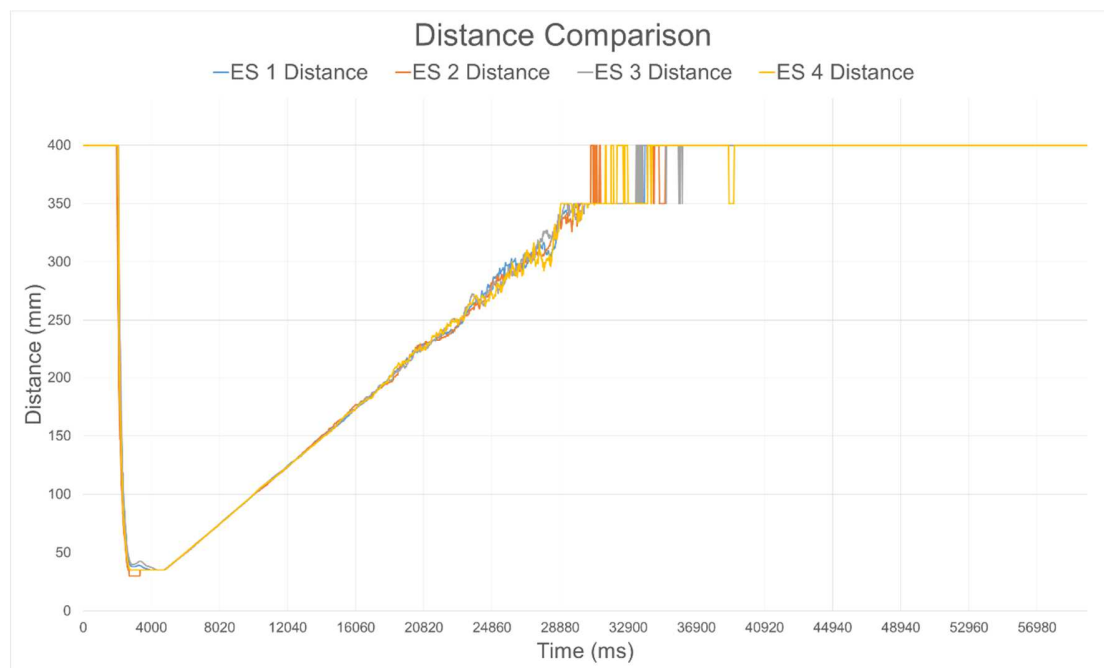


Figure 6.35 : Distance Dynamic Response Comparison

The rotations in Figure 6.36 seem to have the greater rate of error increase compared to all other signals as distance to the object increases, which also limits the effective useful range of these particular sensors. This is most likely the result of compounding errors since these values are obtained using two independent distance signals. A similar complete analysis of sensors having different specified operating ranges would possibly be of merit in order to tailor the operating range to the current device possibly allowing it to function at longer distances than currently available. The original design for this device called for a much shorter center spring housing shaft and the current sensors were selected based on those specifications. Once it was realized that the amount of translational distance was somewhat limited, the shaft length was increased however new sensors were not acquired taking into consideration these modifications.

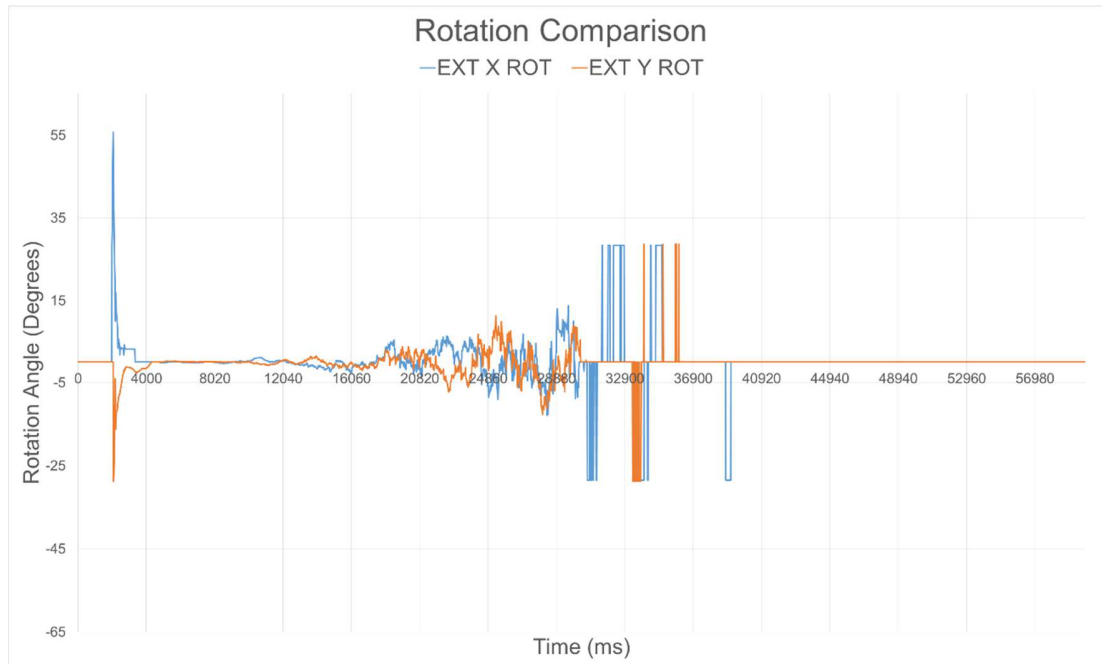


Figure 6.36 : Rotation Dynamic Response Comparison

With all of the information gathered and the calculated statistical data it has been deduced that the individual sensor performance is adequate for the task at hand keeping in mind that the effective operational range of the sensors is slightly diminished. Further use of the compliant wrist in control algorithm implementations would require taking this into consideration in order to monitor signal integrity using additional limits or confidence intervals. Despite all of the noise sources, the signals behaved as expected and should not pose significant problems in system operation since error rates are easily quantified.

6.2 Compliant Wrist Performance

After completing the analysis of the individual sensors these were then mounted onto the designed compliant wrist in order to collect further data to determine whether or not the overall system, namely one that includes a robot manipulator and corresponding controller, could perform adequately. The sensor analysis indicated that it should be possible to effectively use the distance estimates to accurately control the position of a robotic manipulator's end-effector when taking the results into consideration.

The protocol for this data collection consisted of mounting the compliant wrist device onto a CRS-F3 6 degrees-of-freedom manipulator robot so that it may interact with a planar surface, both at a

distance and while in contact, thereby determining the accuracy of the overall system. The manipulator robot is shown in Figure 6.37 with the compliant wrist acting as its end-effector. The robot assembly is comprised of a base which sits on a motorized track meant to increase its effective workspace as well as 6 rotational joints for controlling the position of the end-effector with respect to the base.



Figure 6.37 : Compliant Wrist Mounted on the CRS-F3 Manipulator to Act as its End-Effector

A special mount was fabricated to securely hold a planar surface in a desired orientation while the robotic manipulator, equipped with the compliant wrist, could effectively come into contact with the surface without it experiencing deflections from the desired, previously chosen position and orientation. The device is shown in Figure 6.38, maintaining the planar surface parallel to the compliant wrist's contacting surface. The mounting device incorporates 2 rotational joints behind the planar surface allowing for the rotation of the planar surface about the X and Y axes. The joints, shown in Figure 6.39, are locked into place by tightening nuts onto the bolts securing the pieces together. This mount, combined with the mobility of the manipulator, allows for the compliant wrist to be presented with a planar surface in a desired orientation in such a way that all external sensors are able to detect the surface simultaneously. An example of this is given in Figure 6.40 where, in this particular case, the compliant wrist is also making contact with the angled surface.

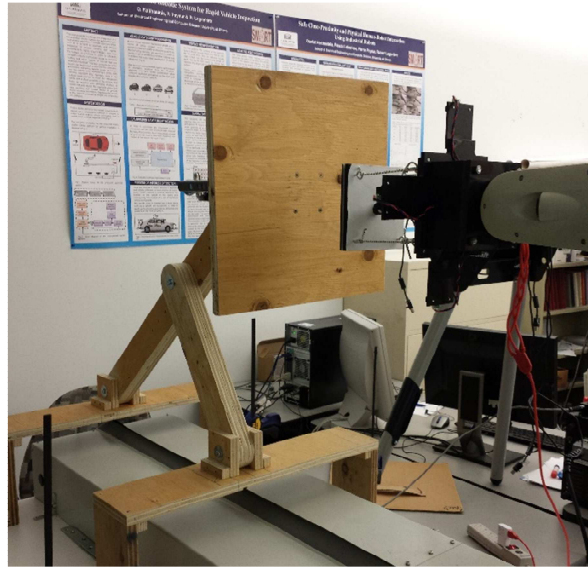


Figure 6.38 : Custom Planar Surface Mount

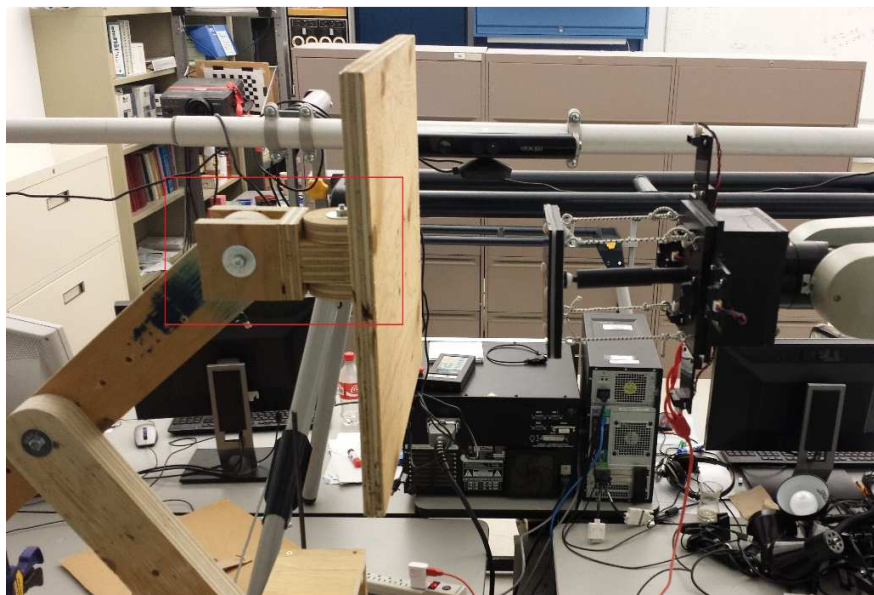


Figure 6.39 : Rotating Joints of Planar Surface Mount

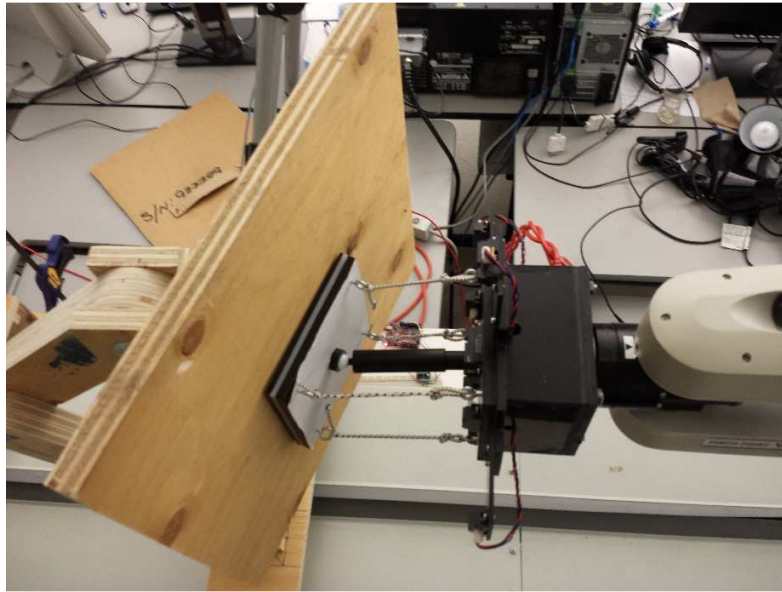


Figure 6.40 : Compliant Wrist in Contact with Angled Planar Surface

Four scenarios were examined using the mounted planar surface. The first scenario consisted of positioning the planar surface at a particular orientation and distance away from the compliant wrist while recording compliant wrist sensor data obtained via a PC making requests for the transformation matrix information calculated only from the external sensors of the wrist. This scenario is also represented by Figure 6.39, which shows the compliant wrist positioned at a set distance from the planar surface which, in this case, is positioned parallel to the contacting surface. The distance of the surface to the compliant wrist was set by taking distance measurements between the planar surface and the compliant wrist using a ruler to determine the ground truth distance. Multiple measurements such as the one illustrated in Figure 6.41, were taken depending on the orientation of the planar surface in order to obtain the distance from the center of the contacting plate to the surface. In order to measure the orientations of the surface, a protractor was used to measure the angles directly from the rotational joints of the mount.

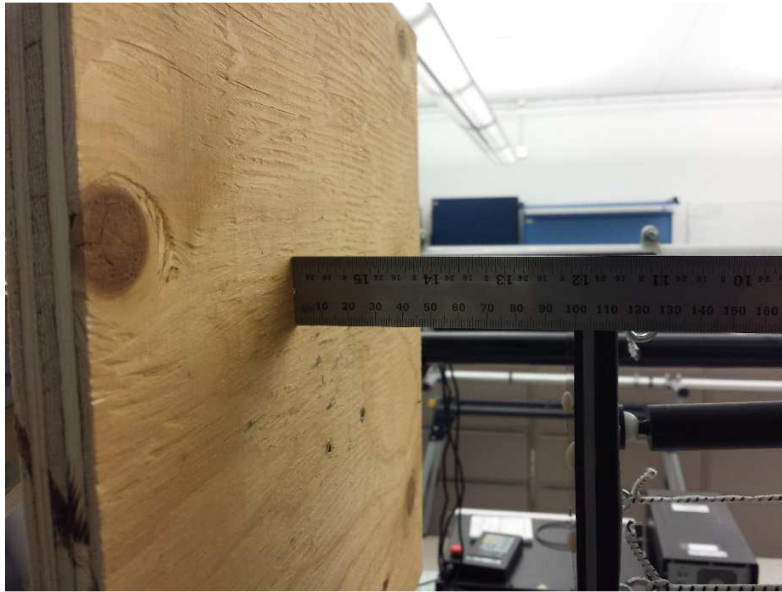


Figure 6.41 : Measurement of Distance between Compliant Wrist and Planar Surface

The second scenario consisted of repeating the previous scenario; however, information collected was instead obtained only from the internal sensors of the wrist. In order to make use of information coming from the internal sensors, the planar surface needed to be brought into contact with the compliant wrist. Also, rather than setting the surface at a fixed distance away from the compliant wrist, the compression distance needed to be evaluated and therefore the surface was set to a position which forced the center spring to compress by a desired amount and the moveable plate to be deflected about the axes of rotation.

The third and fourth scenarios consisted of making similar adjustments to the orientations of the surface; however, this time, an algorithm, whose pseudocode is provided in Appendix B, was enacted for controlling the manipulator robot so that it would act on the received information from the external sensors and internal sensors, respectively, in the form of continuously updated transformation matrices in an attempt to correct any deviations from the desired set points for both translation and rotations.

Results obtained from these scenarios provide useful insights on the performance of the sensors, the robotic manipulator and the overall system. Rather than attempt to collect data through an exhaustive set of combinations of distances and angles for both rotational axes, several test cases were selected in an attempt to evaluate the effects of varying the distance and rotational angles on the system's performance.

For the first scenario, Figure 6.42, Figure 6.43, and Figure 6.44 show the translation parameter extracted from the transformation matrix generated by the external sensors over time at three distinct distances away from the target, namely 50 mm, 75 mm and 100 mm, respectively. The orientation of the target about both axes in this particular case was set to 0 degree. Each plot includes the values of the parameter, represented by the undulating blue lines, the mean value of the parameter, represented by the horizontal orange line, the desired or expected value, represented by the grey dashed horizontal line, and finally, the two black dotted horizontal lines represent one standard deviation from the mean.

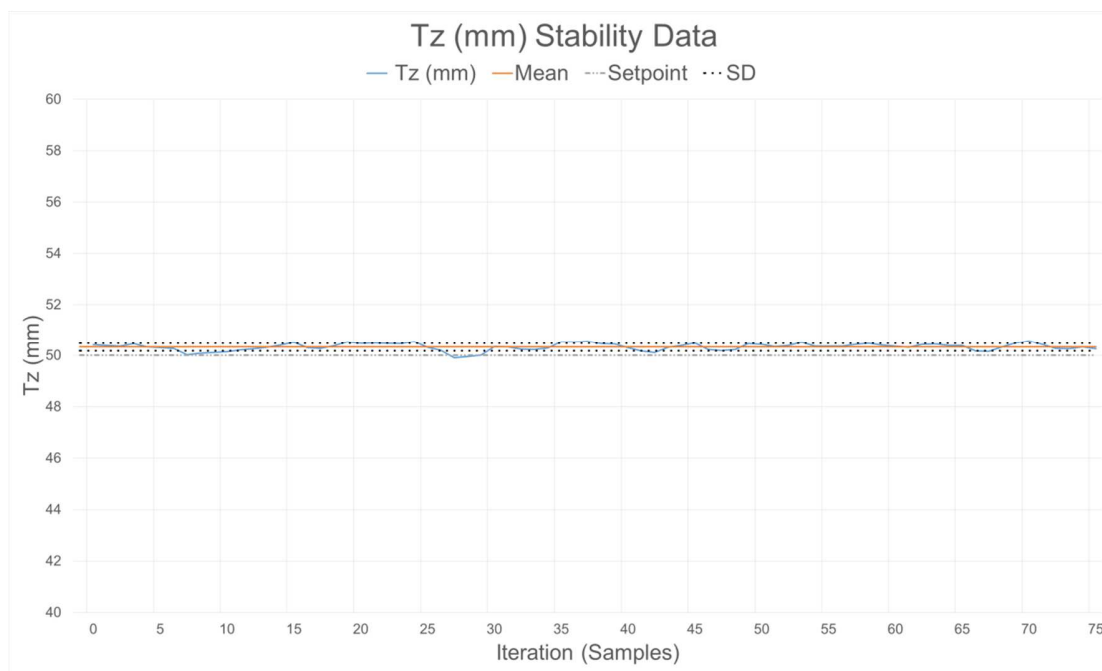


Figure 6.42 : External Sensor Stability Evaluation of Tz Parameter ($T_z = 50$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

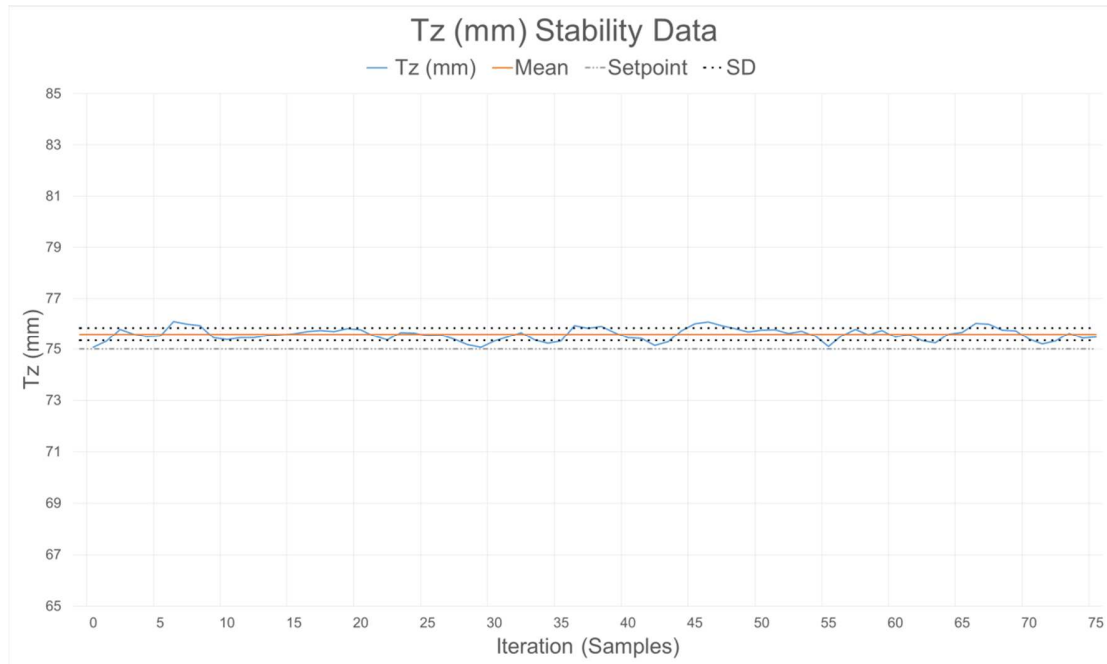


Figure 6.43 : External Sensor Stability Evaluation of Tz Parameter ($T_z = 75$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

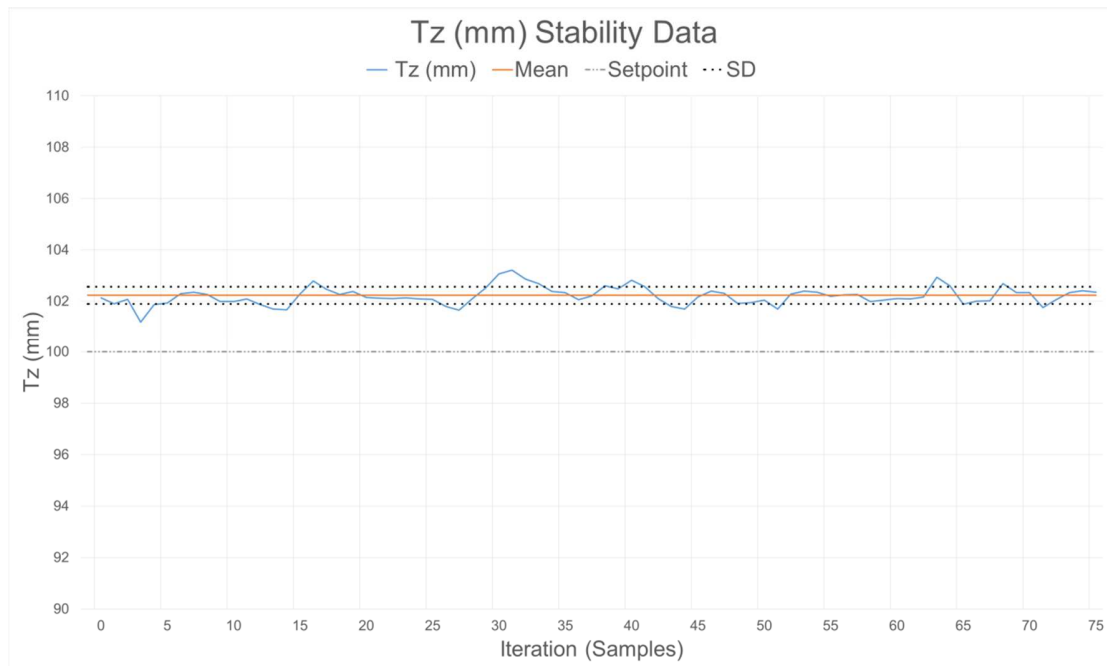


Figure 6.44 : External Sensor Stability Evaluation of Tz Parameter ($T_z = 100$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

It should be noted that although the graphs are presenting the distance between the compliant wrist's contacting surface and the target, which is the value reported by the compliant wrist, the actual distance from the target to the sensors was 135 mm greater due to the relative position of the sensors with respect to the wrist's contacting surface. For the collection of this data, the optional contacting

surface described in section 4.1 was mounted onto the compliant wrist thereby increasing the total distance between the contacting surface and the external sensors. This therefore places the target in an operating range of the sensors which is slightly more prone to signal variations as seen from the results of the sensor characterization performed in the previous section.

The results again confirm that signal variations increase as the distance between objects and the sensors increases. In this case, the mean values were 50.33 ± 0.15 , 75.59 ± 0.25 , and 102.23 ± 0.33 , respectively. The noticeable deviation of the mean from the set distance of 100 mm is a result of two compounding inaccuracies. The first resulting from the method used to make the ground truth distance measurements, namely a metric ruler with 1mm increments leading to a ± 1 mm error. The second factor is the possibility that the calibration for that particular distance was not properly executed leading to an offset in the reported values. Recall that since signal variations increase with distance, manual calibration therefore becomes increasingly challenging as well for the larger distances. Both of these factors affect all measurements to a certain extent, but with varying degrees of severity based on the distance being evaluated causing the mean values to deviate from the set point. Despite this inaccuracy present in the system, the precision of each measurement is quite good with the standard error for the three cases being a relatively constant factor with only 0.30%, 0.33% and 0.32% of the measured quantity, respectively.

The results shown in Figure 6.45, Figure 6.46, and Figure 6.47 depict the parameter corresponding to the rotation about the X axis for the same cases as above, namely at the distances of 50, 75, and 100 mm, respectively. The data again shows the characteristic increase in signal variation at greater target distances with mean values of -0.04 ± 0.06 , 0.19 ± 0.18 , and 0.25 ± 0.27 , in degrees. Rotation measurements were also plagued with ground truth measurement errors which can account for at least $\pm 1^\circ$ deviations from the desired rotation angles as a protractor with 1° graduations was used to position the rotational joints of the target surface mount. Similarly, results for the parameter corresponding to the rotation about the Y axis are shown in Figure 6.48, Figure 6.49, and Figure 6.50 where mean values of 0.01 ± 0.12 , 0.06 ± 0.24 , and -0.06 ± 0.22 , in degrees, were obtained.

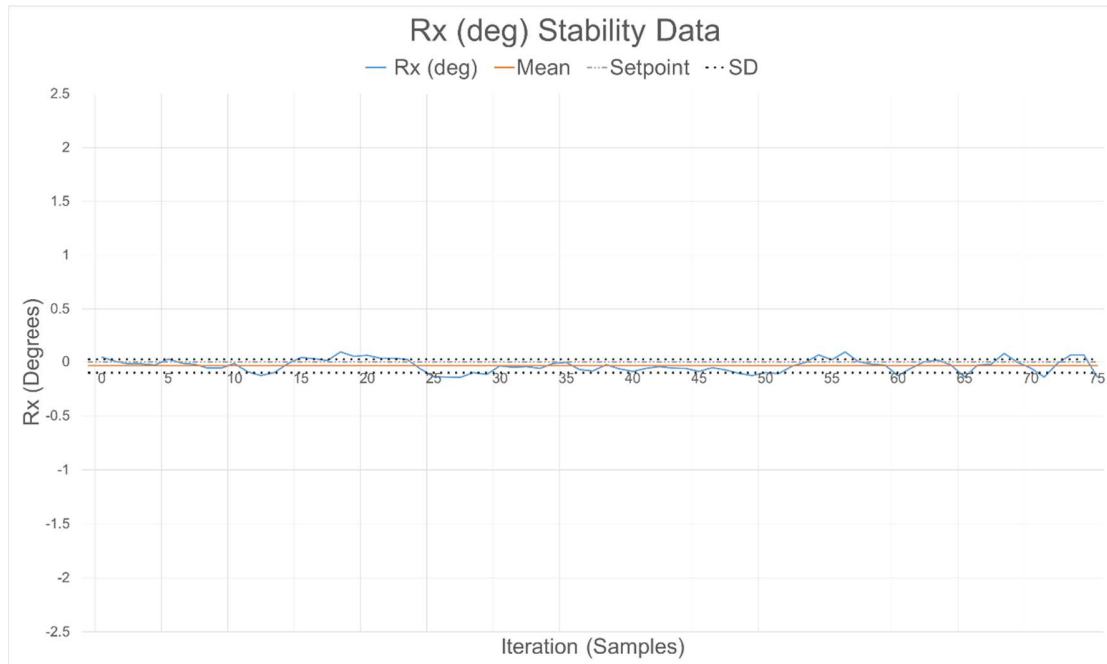


Figure 6.45 : External Sensor Stability Evaluation of Rx Parameter ($T_z = 50$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

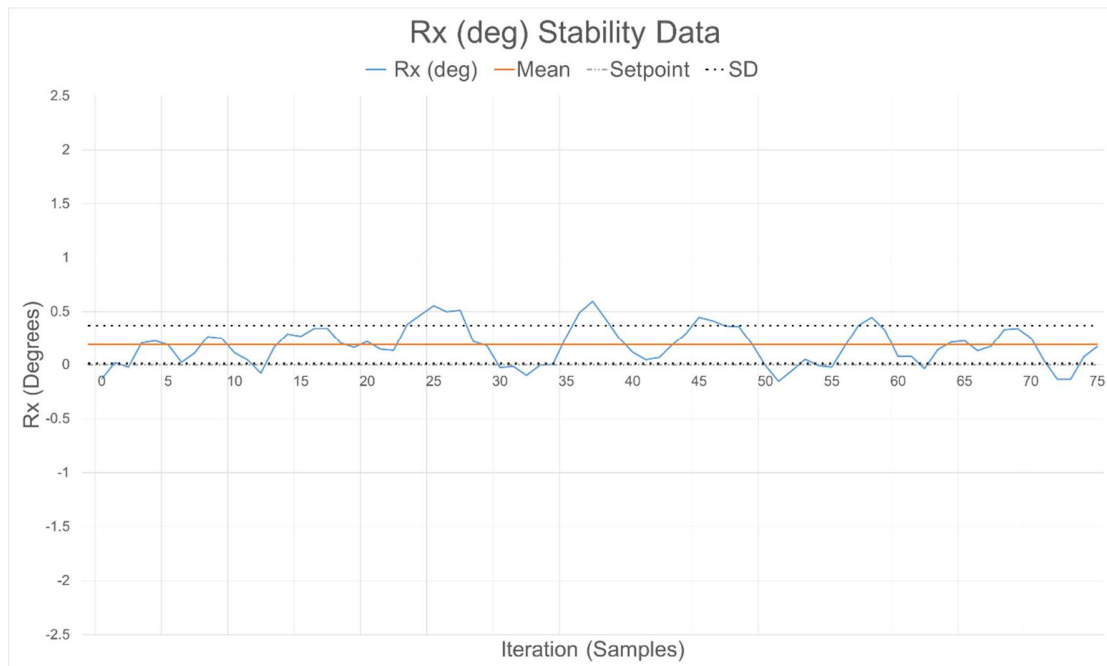


Figure 6.46 : External Sensor Stability Evaluation of Rx Parameter ($T_z = 75$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

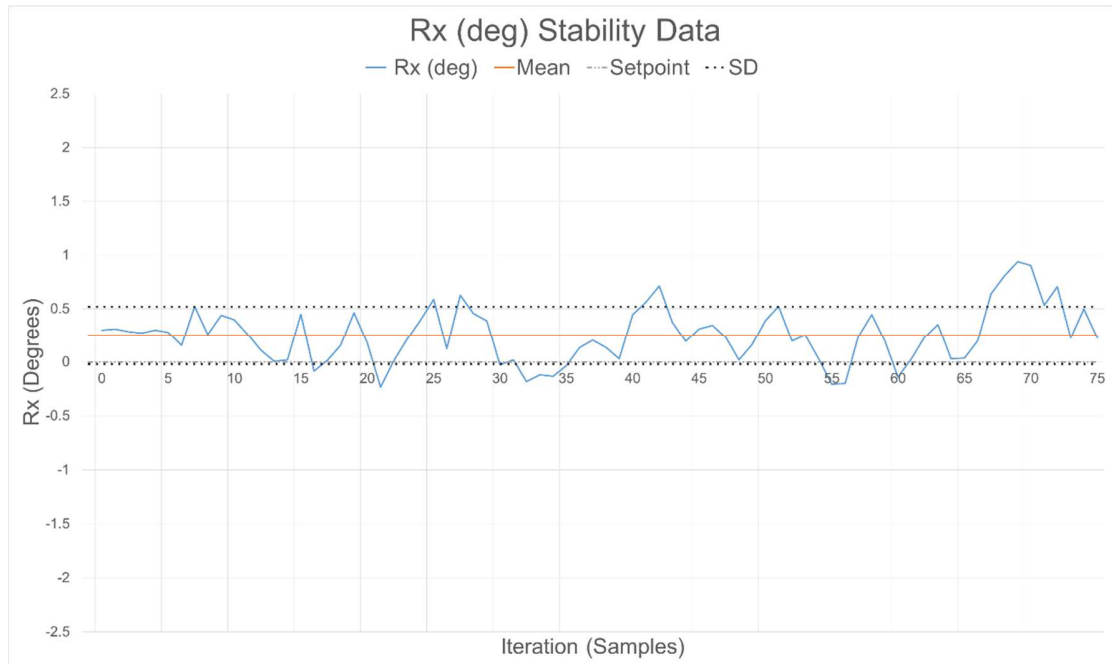


Figure 6.47 : External Sensor Stability Evaluation of Rx Parameter ($T_z = 100$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

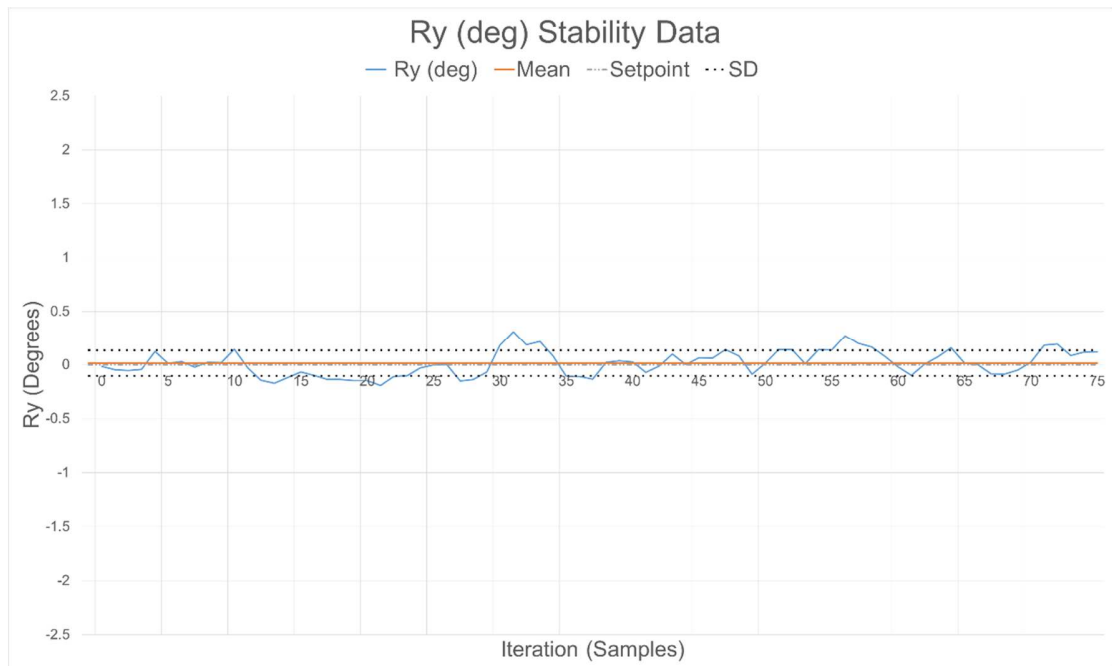


Figure 6.48 : External Sensor Stability Evaluation of Ry Parameter ($T_z = 50$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

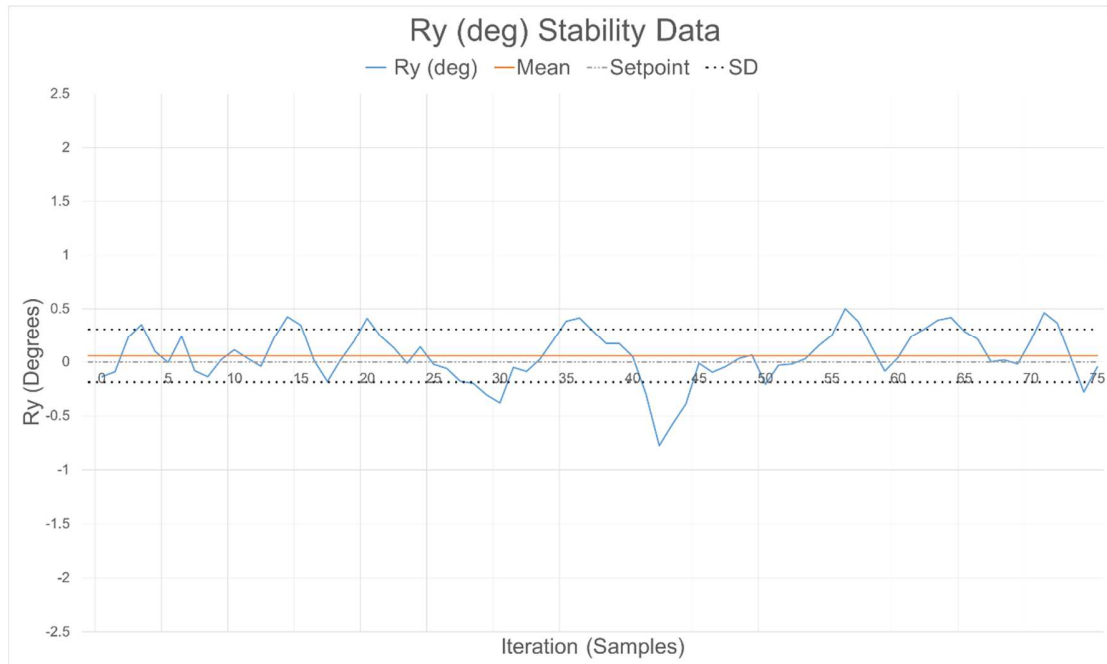


Figure 6.49 : External Sensor Stability Evaluation of Ry Parameter ($T_z = 75$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

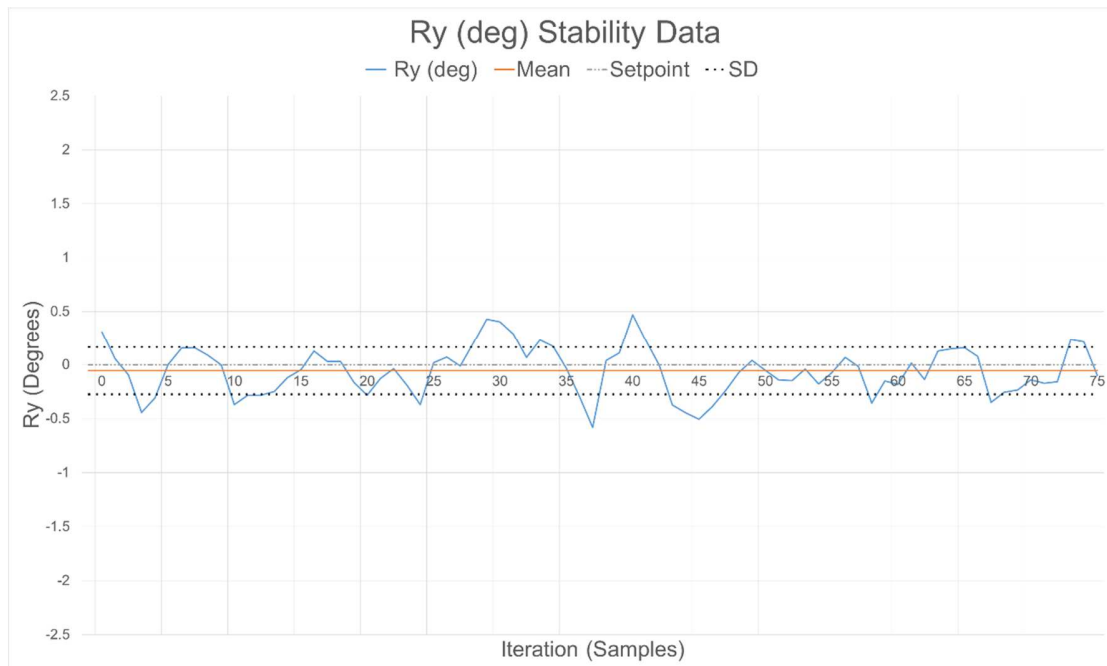


Figure 6.50 : External Sensor Stability Evaluation of Ry Parameter ($T_z = 100$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

In all of the previous plots and cases, it has been confirmed that accuracy and precision are both degraded as distance from the target increases. This should come as no surprise as the evidence of the sensor characterization had already indicated this fact. Due to the limitations of the device used for performing the data characterization and calibration protocols, namely the fixed surface which did not

allow for any rotation, a need to evaluate the effects of surface orientation with respect to the sensors remained.

Figure 6.51, Figure 6.52, and Figure 6.53 show the results for each of the three parameters extracted from the transformation matrices, generated again by the external sensors, for the particular case of a desired distance of 50 mm, a rotation about the X axis of -30° and a rotation about the Y axis of 0° . This data can be compared directly to all parameters previously presented for the 50 mm case as only a single parameter, namely the rotation about the X axis, has been changed. The mean values for the translation, X rotation and Y rotation parameters were 49.32 ± 0.49 mm, $-30.62 \pm 0.33^\circ$, and $-0.16 \pm 0.04^\circ$, respectively.

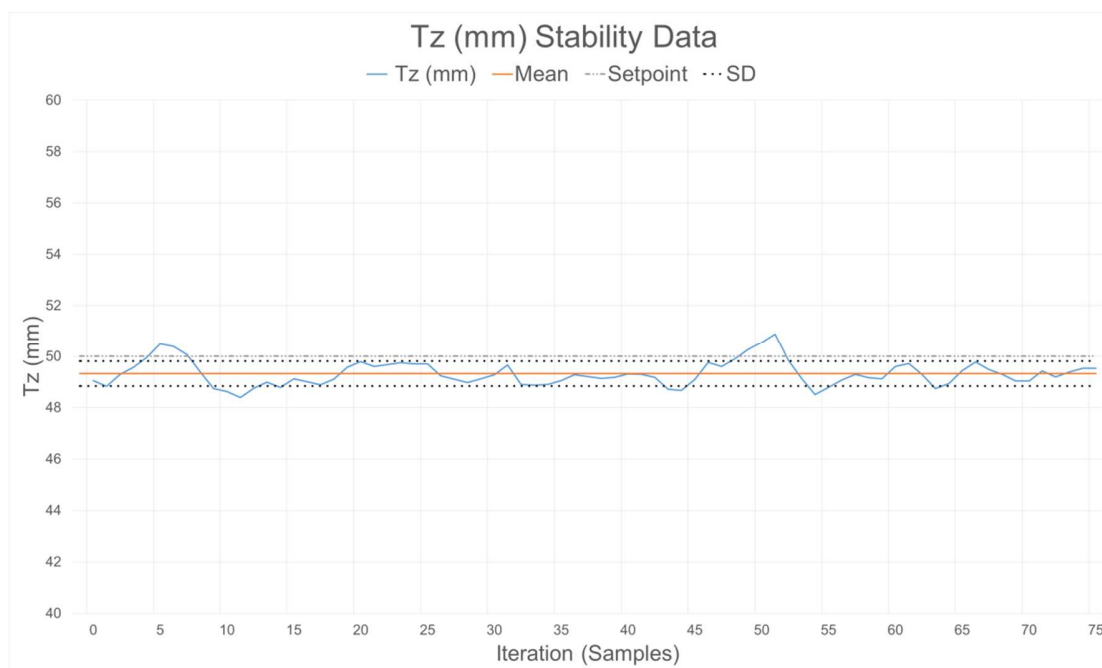


Figure 6.51 : External Sensor Stability Evaluation of Tz Parameter (Tz = 50 mm, Rx = -30° , Ry = 0°)

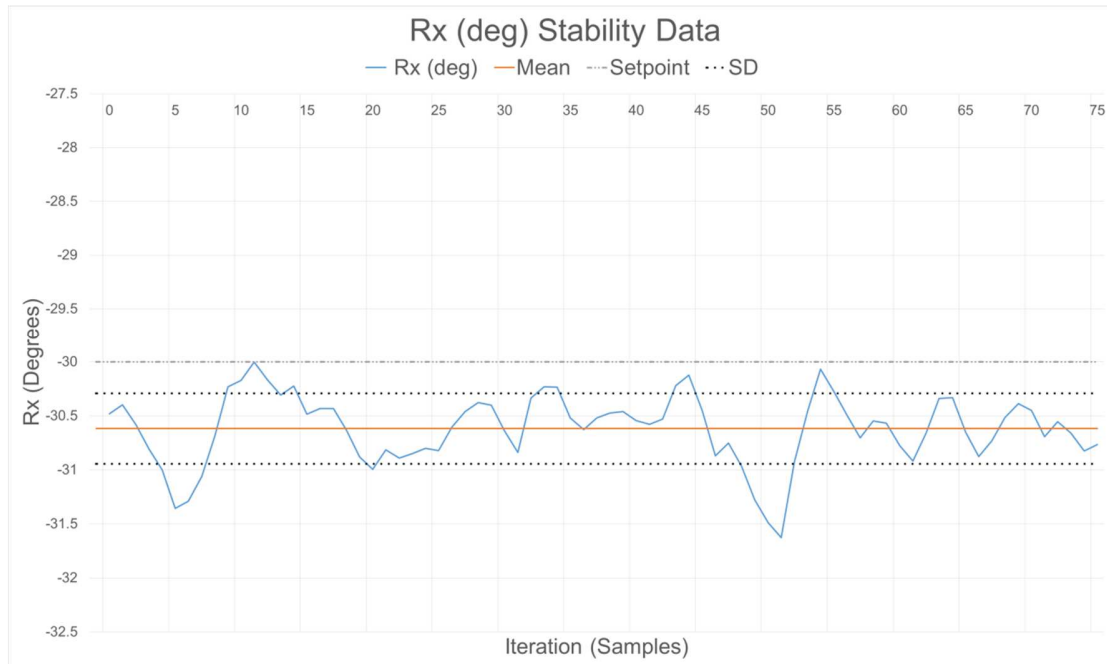


Figure 6.52 : External Sensor Stability Evaluation of Rx Parameter ($T_z = 50$ mm, $R_x = -30^\circ$, $R_y = 0^\circ$)

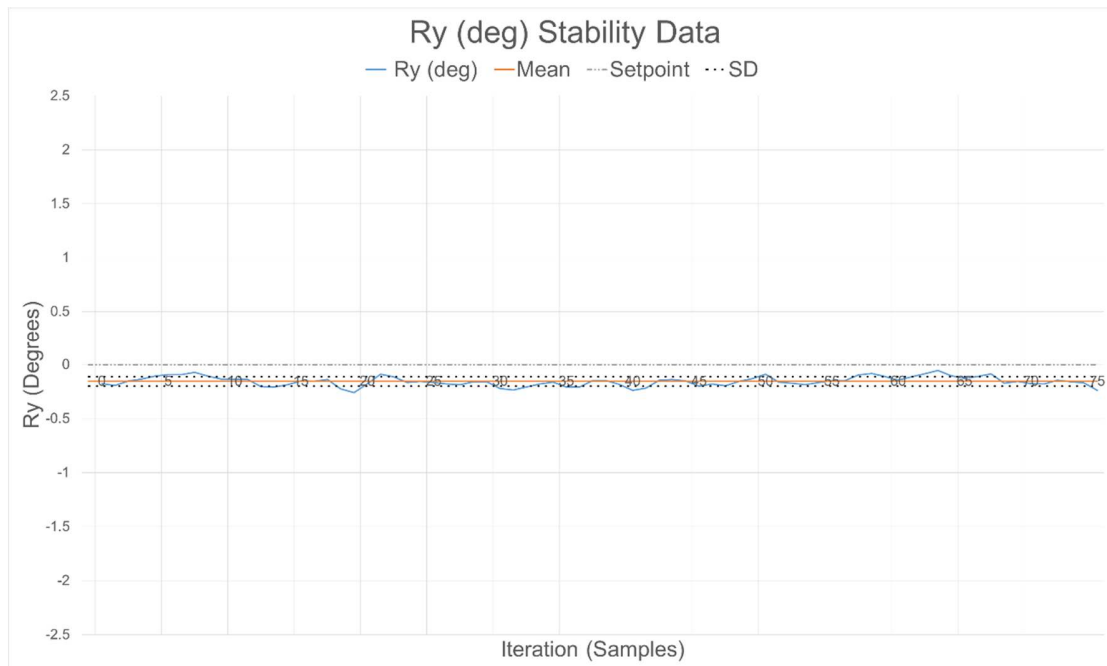


Figure 6.53 : External Sensor Stability Evaluation of Ry Parameter ($T_z = 50$ mm, $R_x = -30^\circ$, $R_y = 0^\circ$)

This reveals an increase in signal variation for both the translation and the rotation about the x axis, but a slight decrease for the rotation about the y axis. The increases in signal variations due to rotation can be explained by the nature of the sensor response curves. When the sensors are faced with an object which is closer to one sensor along an axis and further from the other sensor along that same

axis, this results in the detection of a rotation about the perpendicular axis in the same plane. The distance measurements used to calculate the rotation will be smaller for one sensor and greater for the other. The sensor with the greater distance experiences greater variations than the sensor with the shorter distance, but this increase in variation is non-linear and therefore the resulting increase in variations of the greater distance outweighs the decrease in variations of the shorter distance resulting in an overall increase in signal variation for both the translation and rotation parameters for the axis about which there is a rotation. Since there was no rotation about the Y axis, the distances used for the calculation of the rotation were similar and therefore no significant increase in signal variation was expected. It is speculated that perhaps the angle of rotation about the opposite axis could have favored the light reflection mechanism of one or both of the sensors, which could have accounted for the slight improvements in signal stability.

Table 6.1 provides a comparison of each parameter for variations in both distance and rotation. The rows of the table indicate at which distance the measurements taken from the target surface, going from 50 mm to 100 mm while the three pairs of columns allow for direct comparison between both rotations presented, namely 0° and -30° . The results show that in the case of 0° , variations increase with distance for all parameters while the results for the -30° show that variations increase with distance for both the Tz and Ry parameters but Rx appears to be somewhat constant although significantly increased due to the rotation itself.

Table 6.1 : External Transformation Parameter Comparisons during Stability Trials

Distance	Tz (Rx = 0°) (mm)	Tz (Rx = -30°) (mm)	Rx (Rx = 0°) ($^\circ$)	Rx (Rx = -30°) ($^\circ$)	Ry (Rx = 0°) ($^\circ$)	Ry (Rx = -30°) ($^\circ$)
Tz = 50 mm	50.33 $\pm$ 0.15	49.32 $\pm$ 0.49	-0.04 $\pm$ 0.06	-30.62 $\pm$ 0.33	0.01 $\pm$ 0.12	-0.16 $\pm$ 0.04
Tz = 75 mm	75.59 $\pm$ 0.25	75.47 $\pm$ 0.74	0.19 $\pm$ 0.18	-29.97 $\pm$ 0.40	0.06 $\pm$ 0.24	0.09 $\pm$ 0.19
Tz = 100 mm	102.23 $\pm$ 0.33	101.6 $\pm$ 0.62	0.25 $\pm$ 0.27	-30.47 $\pm$ 0.33	-0.06 $\pm$ 0.22	0.38 $\pm$ 0.22

For the second scenario, namely the scenario where data from the internal sensors was used, similar results were obtained. Figure 6.54, Figure 6.55, and Figure 6.56 show the data collected for the three parameters of interest for the particular case of the contact surface being compressed by 10 mm without any rotations about the X or Y axes. As mentioned previously for the external sensors, the

distance reported by the compliant wrist is not the true distance but a corrected distance for proper system operation. The physical distance between the contacting surface of the compliant wrist and the internal sensors when the device is at rest is 95 mm and the negative compression values indicate a distance less than this offset.

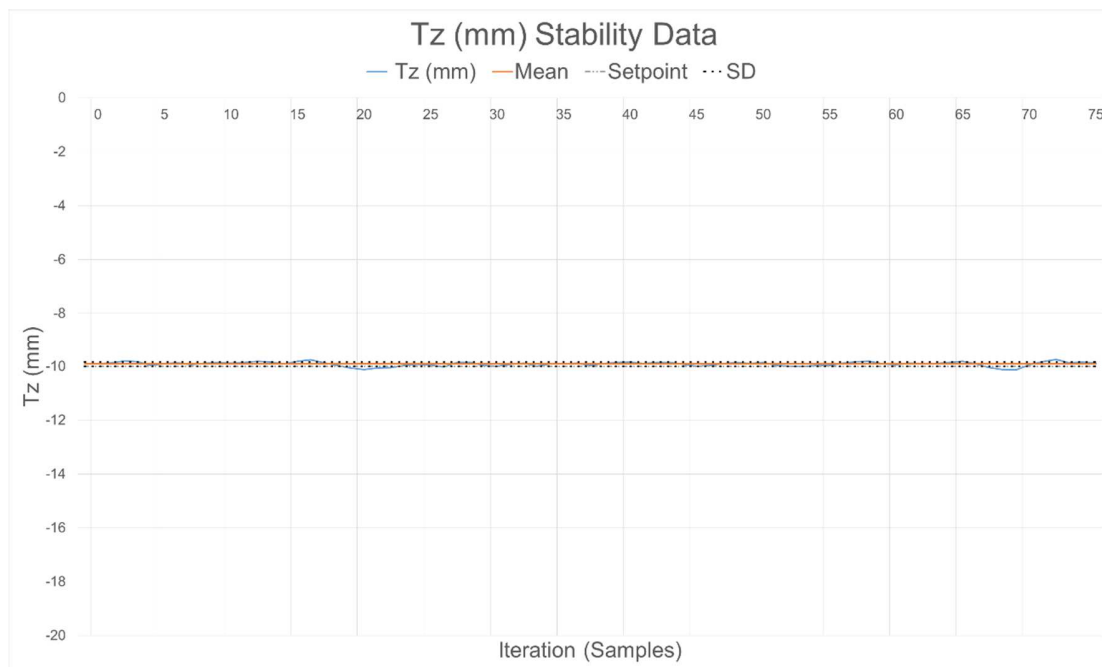


Figure 6.54 : Internal Sensor Stability Evaluation of Tz Parameter (Tz = -10 mm, Rx = 0°, Ry = 0°)

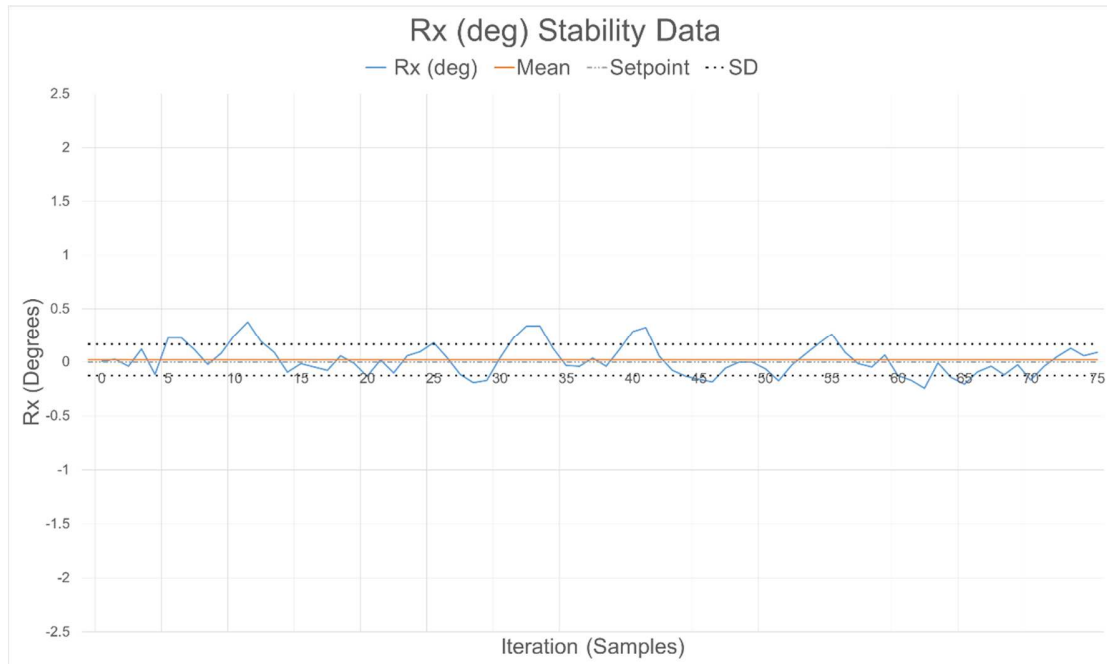


Figure 6.55 : Internal Sensor Stability Evaluation of Rx Parameter ($T_z = -10$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

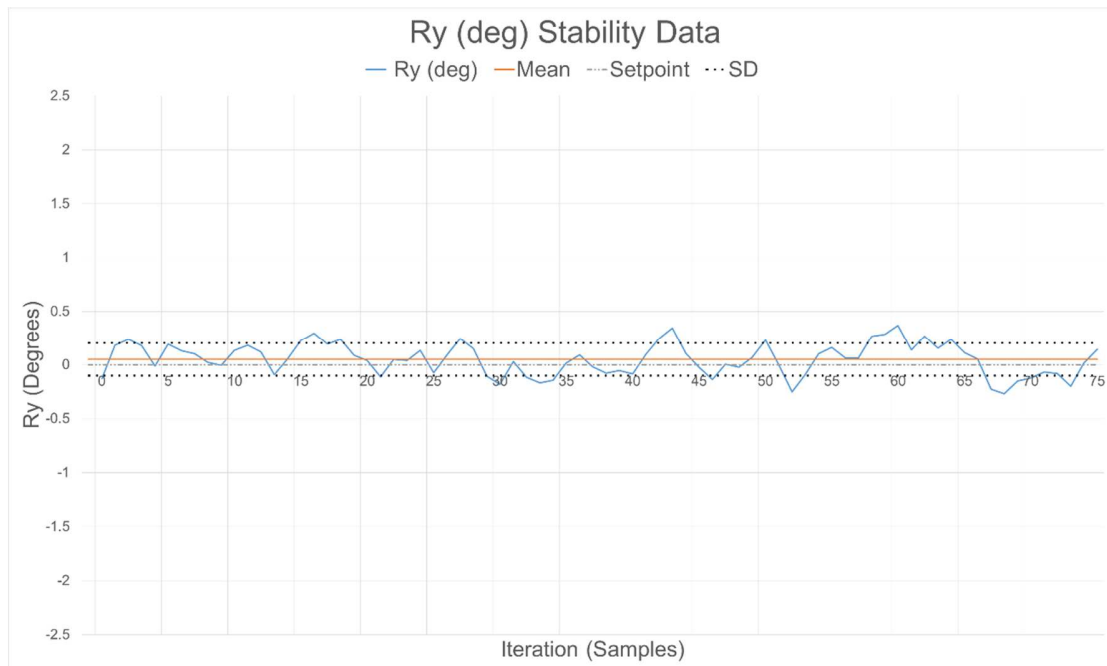


Figure 6.56 : Internal Sensor Stability Evaluation of Ry Parameter ($T_z = -10$ mm, $R_x = 0^\circ$, $R_y = 0^\circ$)

As expected, the signal variations for the translation parameter is reduced due to the decrease in distance between the detected object and the sensors resulting in a mean value of -9.91 ± 0.08 mm. For the rotation parameters, the signal variations did not decrease accordingly as predicted by the results of the external sensors. With mean values of $0.02 \pm 0.14^\circ$, $0.05 \pm 0.15^\circ$ for the X and Y rotation,

respectively, a slight increase in variation is observed when comparing to the shortest distance of the external sensors. However, it should be noted that when comparing results from the internal sensors to the external sensors the type of surface presented to the sensors differs which could explain the unexpected behavior. By comparing the results from two distances and rotations collected using the internal sensors it can be shown that signal variations for all parameters are indeed inversely proportional to distance, as shown in Table 6.2. The two distances were 10 mm and 20 mm compressions and the rotations were 0° and -10° about the X axis. Since the negative distance values indicate compression, a larger compression corresponds to a shorter physical distance between the compliant wrist's contacting surface and the internal sensors. The distance signal variations also shows a slight increase as the angle of rotation increased and results again from the sensor response curves. In this case, the smaller rotation change did not produce the expected signal variations in the rotation values as in the previous scenario. This time, the signal variations for the rotation about the Y axis appear to increase rather than decrease and the signal variations for the rotation about the X axis slightly increase in one case and slightly decrease in the other. The lack of trend in the rotation parameters at these distances could potentially indicate that the signal variations are indication of a lower limit to the errors associated with these parameters.

Table 6.2 : Internal Transformation Parameter Comparisons during Stability Trials

Distance	Tz (Rx = 0°) (mm)	Tz (Rx = -10°) (mm)	Rx (Rx = 0°) (°)	Rx (Rx = -10°) (°)	Ry (Rx = 0°) (°)	Ry (Rx = -10°) (°)
Tz = -20 mm	-19.91±0.07	-20.01±0.07	-0.08±0.08	-10.21±0.11	-0.01±0.08	0.13±0.14
Tz = -10 mm	-9.91±0.08	-9.88±0.09	0.02±0.14	-10.36±0.13	0.05±0.15	-0.10±0.19

The results obtained in the two previous stability scenarios were meant to gauge how accurate and precise the sensors were when kept at a desired pose with respect to an object's surface. What is seen in all three parameters are slight deviations of the mean from their respective set points. These errors are due in part by the amount of precision to which the calibration can effectively be performed as well as the difficulties faced when trying to obtain sub millimetre precision during the positioning of the planar surface. This results in a slightly reduced precision in the measurements although accuracy is still maintained evident by the narrow standard deviation boundaries indicating a stable signal. It should

be noted that the precision of the compliant wrist is directly dependent on the measurement devices used during calibration as well as the setup of the experiments, both of which were compounded in the results provided.

The last two scenarios, namely those where the implemented algorithms guide the pose adjustments for the robot in an attempt to compensate for the errors between the sensor readings and the desired values, were meant to gauge the accuracy and precision of the robotic manipulator when equipped with the instrumented compliant wrist. Ideally, the mean value of the signals should be aligned with the desired values.

Results for the compensation scenario using data from the external sensors are presented next. Figure 6.57, Figure 6.58, and Figure 6.59 show data collected for the three matrix parameters T_z , R_x and R_y , denoting the translation and rotations about the X and Y axes, respectively for a desired distance of 50 mm and desired rotations of -20° about the X axis and 0° about the Y axis. It should be noted that for the compensation scenarios, ground truth measurements were not taken as the goal was to determine whether or not the robot could make the necessary adjustments to compensate for the error between the desired parameter values and those reported by the sensors. Such measurements would also not have had much practical meaning as the actual orientation of the target object was of no consequence as the robot did not maintain its position as in the case of the stability scenarios.

The experiments for the compensation scenarios began with positioning the target surface in the approximate desired orientation but with an arbitrary distance away from the compliant wrist. This was done in order to determine if the robot could in fact make both large and small pose corrections to deal with the errors detected in the signals. The large pose corrections are illustrated in the figures by the sharp initial transitions. To remove the bias of these initial transitions from the mean value calculations the first 5 samples were omitted.

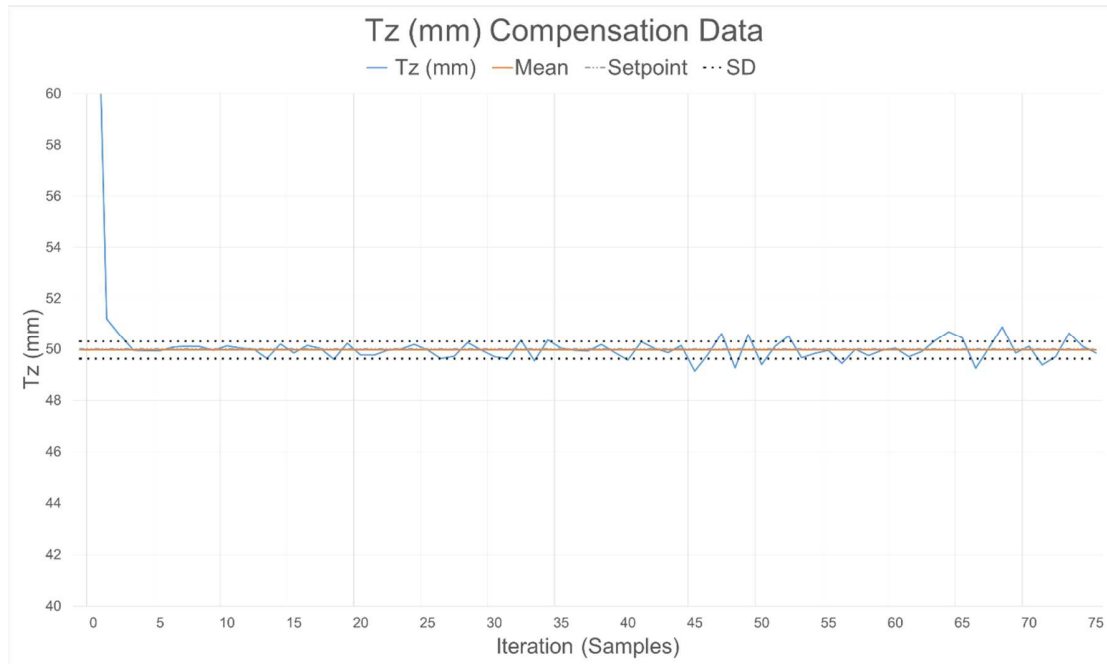


Figure 6.57 : External Sensor Compensation Evaluation of Tz Parameter (Tz = 50 mm, Rx = -20°, Ry = 0°)

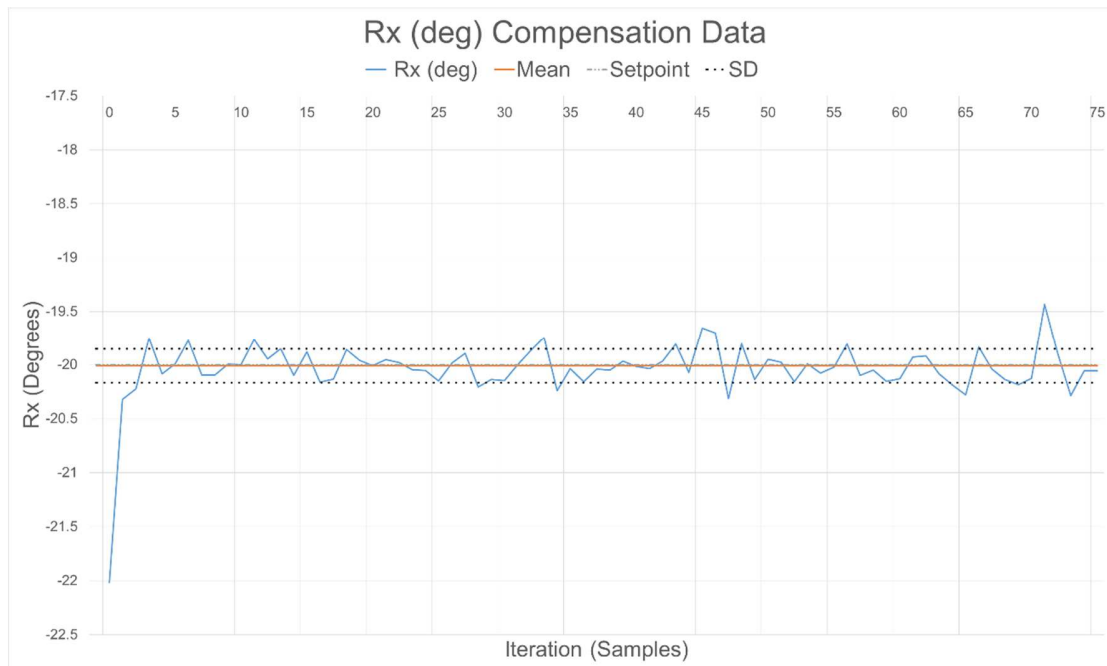


Figure 6.58 : External Sensor Compensation Evaluation of Rx Parameter (Tz = 50 mm, Rx = -20°, Ry = 0°)

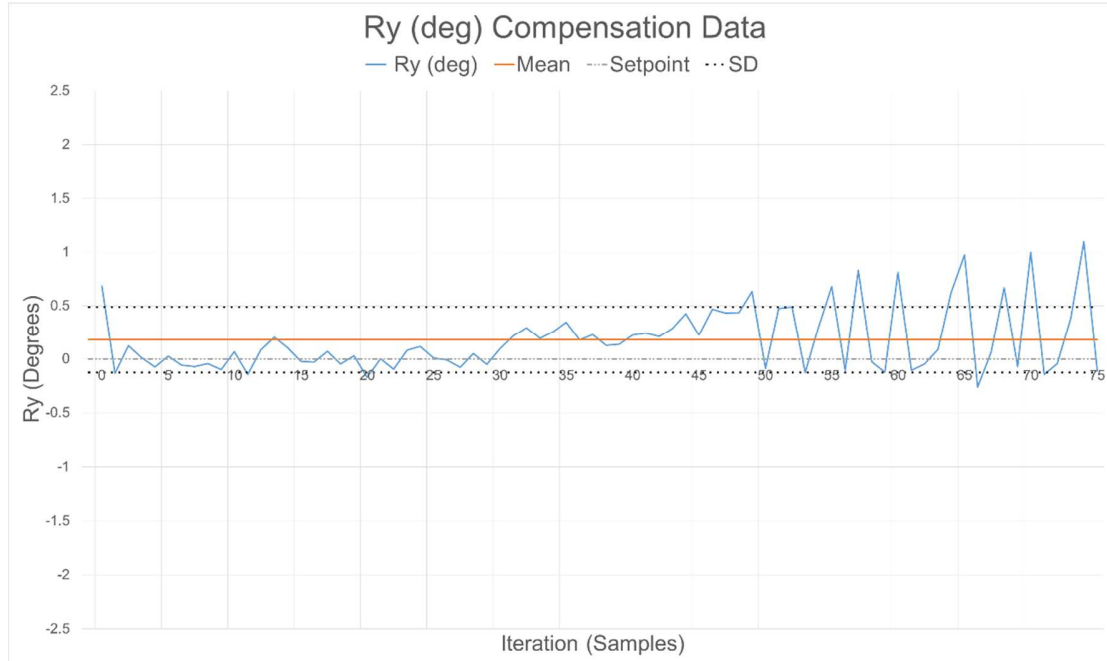


Figure 6.59 : External Sensor Compensation Evaluation of Ry Parameter ($T_z = 50$ mm, $R_x = -20^\circ$, $R_y = 0^\circ$)

A comparison of the mean values of the parameters for three distances is provided in Table 6.3. The results obtained during compensation are characterized by two primary points. The first is that the mean value for all of the parameters are generally brought closer to their desired set points, indicating an increase in precision. This appears to hold regardless of the actual distance or orientation. The second is that the motion produced by the manipulator tends to reduce accuracy as seen by the increased variations in all of the parameter values.

Table 6.3 : External Transformation Parameter Comparisons during Compensation Trials

Distance	T_z ($R_x = -20^\circ$) (mm)	R_x ($R_x = -20^\circ$) ($^\circ$)	R_y ($R_x = -20^\circ$) ($^\circ$)
$T_z = 50$ mm	49.97±0.34	-20.01±0.16	0.18±0.30
$T_z = 75$ mm	74.98±0.95	-19.96±0.43	0.20±0.41
$T_z = 100$ mm	100.01±0.99	-20.03±0.41	0.04±0.44

Upon further investigation it was discovered that, although the manipulator is capable of extremely fine movements, the inverse kinematic algorithm used for the calculation of the joint

positions introduced additional errors. The implemented algorithm employed an iterative search method for the determination of certain joints as the transformation matrix did not provide sufficient information for direct inference of all of the manipulator joints including the motorized track used to increase the size of the robot's workspace. In order to obtain faster calculation of the inverse kinematic solution, the implementation included a tolerance parameter permitting the user to relax the constraints on precision of the inverse kinematic solution. It is possible that the tolerance selected influenced how closely the algorithm could match the exact transformation matrix parameters obtained from the compliant wrist. This is also supported by the fact that the mean value remains close to the set point for the parameters indicating that the algorithm is attempting to compensate as closely as possible the desired value despite its inability to reach the desired precision leading to oscillations about the target value, particularly for the R_y parameter as seen at the end of the trial shown in Figure 6.59. These oscillations, although appearing to be increasing, did not grow without bound but merely continued with varying intensity with those shown being some of the larger variations experienced.

For the fourth and final scenario Figure 6.60, Figure 6.61, and Figure 6.62 show results for the case of a compression distance of 20 mm, a rotation about the X axis of -10° and a rotation about the Y axis of 0° , while Table 6.4 shows the comparison between the results depicted in those figures with those obtained for the case of a compression distances of 10 mm and the same rotation set points. Similar statistical characteristics are observed for the compensation scenarios when compared to the stability scenarios. The signal variations are reduced for each parameter due to the shorter effective distance between the sensors and the contacting surface of the compliant wrist. Also, due to the movements performed by the robot, variations in the signals increase for the compensation scenario relative to the stability scenario for the internal sensors while the mean values are brought closer to the desired values, indicating a trade-off between precision and accuracy depending on the type of task being performed, namely observing an object or interacting with an object. It should also be noted that part of increased signal stability and precision for the internal sensors might also be attributed to the fact that the contacting surface of the compliant wrist is made from the same material used to fabricate the target for the calibration procedure. This means that the internal sensor outputs were adjusted using similar reflectivity characteristics as the contacting surface whereas the external sensors were subjected to plywood surfaces during the collection of data and this material had a slightly rougher and duller surface which might have contributed to the greater variations seen in the results.

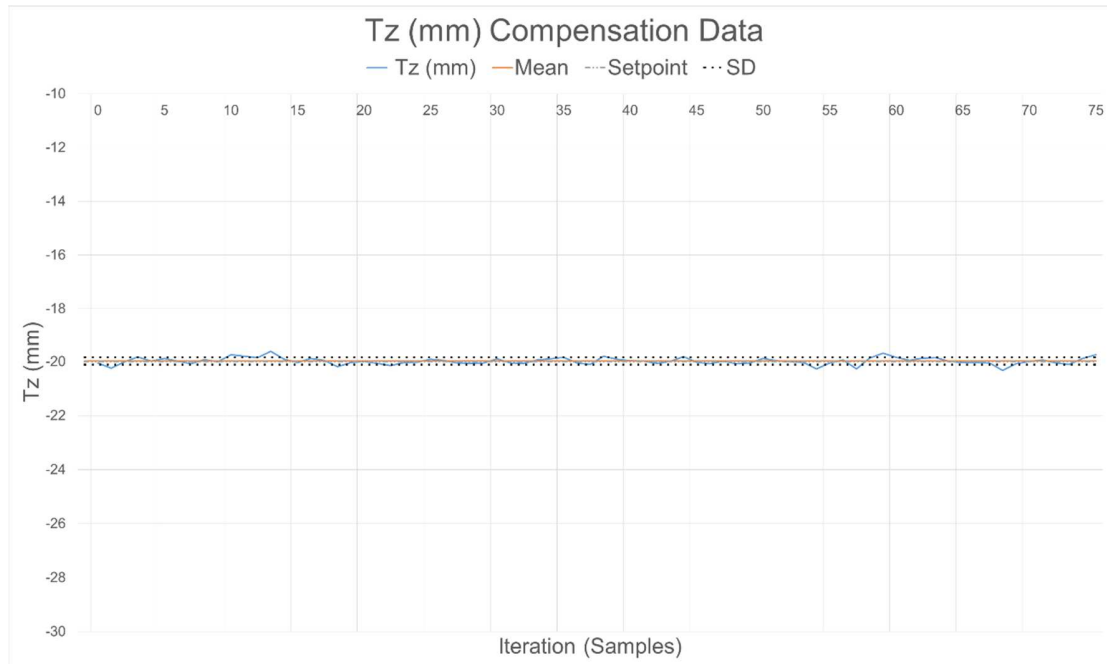


Figure 6.60 : Internal Sensor Compensation Evaluation of Tz Parameter (Tz = -20 mm, Rx = -10°, Ry = 0°)

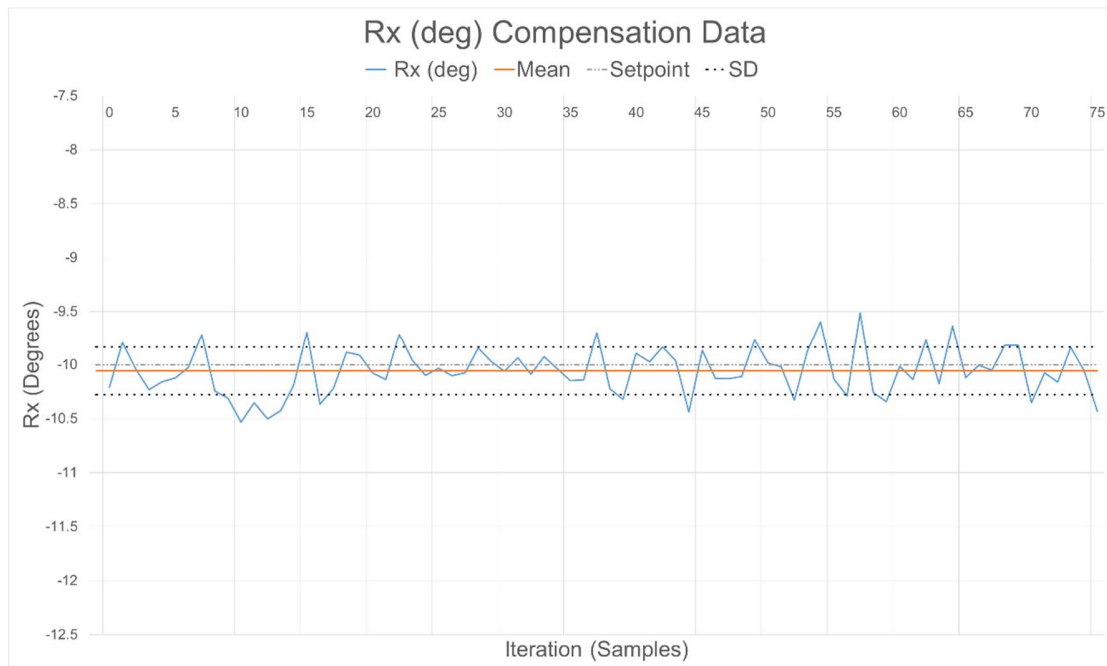


Figure 6.61 : Internal Sensor Compensation Evaluation of Rx Parameter (Tz = -20 mm, Rx = -10°, Ry = 0°)

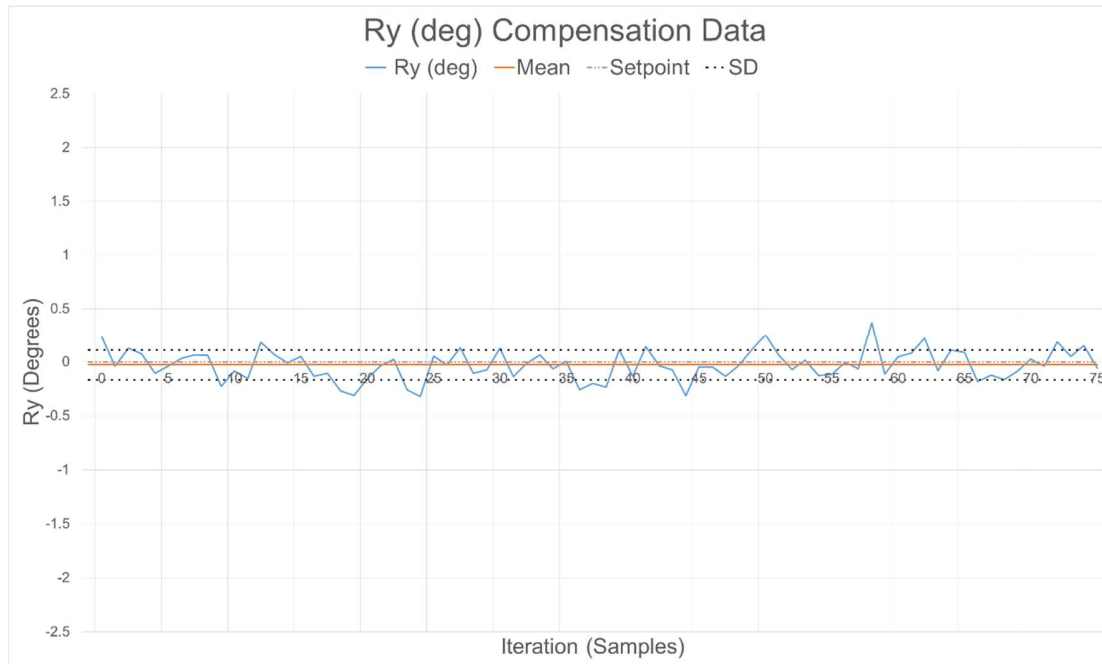


Figure 6.62 : Internal Sensor Compensation Evaluation of Ry Parameter ($T_z = -20$ mm, $R_x = -10^\circ$, $R_y = 0^\circ$)

Table 6.4 : Internal Transformation Parameter Comparisons during Compensation Trials

Distance	T_z ($R_x = -10^\circ$) (mm)	R_x ($R_x = -10^\circ$) ($^\circ$)	R_y ($R_x = -10^\circ$) ($^\circ$)
$T_z = -20$ mm	-19.98 ± 0.13	-10.06 ± 0.22	-0.03 ± 0.14
$T_z = -10$ mm	-9.99 ± 0.15	-10.01 ± 0.23	0.05 ± 0.31

When compiling results from all the scenarios, a few conclusions can be derived. The calibration procedure must be carefully performed in order to maximize the accuracy of the compliant wrist regardless of the intended purpose of the device. Although the robotic manipulator was capable of fine movements which compensated the deviation of the mean value of the signals from the desired values, this does not imply greater accuracy. The best way to ensure high accuracy is with the use of reliable ground truth distance measurements during the calibration procedure.

The precision of the compliant wrist system is dependent primarily on the sensor outputs themselves and any of the signal processing applied thereafter. Analysis of the data has shown that sub millimeter precision can be achieved with the sensors for distances which extend beyond the contacting

surface of the compliant wrist using a moving average filter with a window length of 33 samples. Precision also has a non-linear dependency on the distance between the target objects and the sensors such that accuracy decreases as distance increases.

The reduced precision experienced during the compensation scenarios shows that an additional dependency on the relative motion between the compliant wrist and objects exists. This can most likely be attributed to the fact that each sensor reading is the result of a moving average calculation which means that motion causes a measurement to be composed of samples that will experience a greater range of values beyond the normal random errors intrinsic to the sensors themselves.

It has been shown that precision increases as objects are brought closer to the sensors thereby improving the pose estimates generated by the compliant wrist to improve as it approaches objects. Assuming that the calibration procedure is able to produce sensor outputs whose accuracy are within acceptable tolerances for a given application, the compliance provided by the mechanical structure of the wrist affords a slight immunity to the reduced precision during motion. In the event that there exists unwanted discrepancies between the actual pose of the objects and the pose reported by the compliant wrist, the compliance allows for safe interaction with objects by protecting both the contacted object and the robot structure from sharp increases in contact forces through its own compression in order to conform with the shape of the objects.

6.3 Path Planning Algorithms

In order to provide a proof of concept for the operation of the compliant wrist, two simple algorithms for controlling the CRS-F3 manipulator robot's motion were devised. Although the findings for the experiments conducted using these algorithms are shown following the previous in-depth system operation analysis, the experiments themselves were carried out prior to collection of the previously presented data. The results shown here are of a more qualitative nature rather than quantitative as rigorous protocols were not adhered to when collecting data during these preliminary experiments with the compliant wrist. The methodology for the data collection of the previous section was developed based on observations of these experiments. The data is presented primarily as support material to visualize the execution of the algorithms as well as to provide simple use cases for the API which was developed previously.

6.3.1 Object Search

The first algorithm that was developed was named “Object Search”. The object search algorithm was devised to serve a dual purpose. The first was to demonstrate how the individual sensors could be used to detect the presence or absence of an object in its field of view and the second was to increase the effectiveness of the other algorithm that was developed, namely the “Pose Matching” algorithm which is described later. Due to the physical characteristics of the compliant wrist, specifically the distance between each of the sensors that make up the external array, the pose estimates generated by the compliant wrist are most accurate in terms of the orientation values when all four sensors in the array are able to detect a target. Therefore, whenever an object is not being detected by all of the sensors in the external array, it is beneficial to invoke this object search algorithm in the hopes of having the maximum possible number of data points describing the pose of the object.

This algorithm is meant to guide the robot in the direction that has the highest likelihood of allowing all of the four external sensors to return a valid distance measurement indicative of an object present in front of the end effector. The infrared sensors have a maximum range of detection which is approximately 400 mm and continuously return this value even when no object is present in front of the sensors. Therefore, in order to differentiate between the situation of having no object present and when an object is present, a distance value which is less than 400 mm must be measured to discriminate between the two cases. Distance measurements are deemed valid when they are below a desired value set in software which acts as a threshold for this particular algorithm. Based on the available sensory information, i.e. the number of sensors and the position of the sensors which are detecting an object, the robot moves by a specified increment in position in one of eight different directions. The directions are defined with respect to the end effector’s reference frame and can be either -X, -Y, +X, +Y or a specific combination of these.

Table 6.5 : Movement Rules of the Object Search Algorithm

Rules					
If	Then	Direction	If	Then	Direction
None		N/A	S3 , S4		+X & +Y
S1		-X	S4 , S1		+Y & -X
S2		-Y	S1, S2, S3		-Y
S3		+X	S2, S3, S4		+X
S4		+Y	S3, S4, S1		+Y
S1, S2		-X & -Y	S4, S1, S2		-X
S2 , S3		-Y & +X	S1, S2, S3, S4		N/A

As shown in Table 6.5, a set of If-Then rules are considered to decide in which direction to steer the robot. For example, if only the sensors S_1 and S_2 detect an object, the robot moves in the -X and -Y direction with respect to the wrist reference frame whose axes are by construction aligned with that of the compliant wrist. The motivation behind the selected directions of displacement is inferred from the respective location of the sensors mounted on the wrist, as defined in Figure 4.10.

In order to achieve this motion, since the robot can be in any pose when the object is detected, the target position is transformed to the robot base frame as shown in the following equation.

$${}^B P_T = Q_{BW} \cdot Q_{WE} \cdot {}^E P_T \quad (6.5)$$

where ${}^E P_T$ represents the target point with respect to the compliant wrist frame associated with the external sensors, Q_{BW} is the homogenous transformation between the robot base and the robot wrist, Q_{WE} is the homogenous transformation between the robot wrist and the reference frame associated with the external sensors of the compliant wrist end effector (essentially a pure translation) and ${}^B P_T$ is the target position with respect to the base frame. The target point information is extracted from the transformation matrix obtained directly from the compliant wrist's sensors.

In an attempt at validating the rules that were established for the search algorithm, a simple experiment was devised. The experiment consisted of triggering the search algorithm by introducing an object in the field of view of the sensors and allowing the robot to react according to the rules of the

algorithm. For this experiment the object was held in hand by a person attempting to maintain its pose to the best of their ability. The implementation of the search algorithm was the result of a collaboration with another party looking to incorporate a compliant wrist into path planning algorithms [127]

Figure 6.63 illustrates the experimental setup used for testing of the algorithm with an example of how the algorithm proceeds. In the first image on the left, we can see that one of the sensors has been blocked by the rectangular object, in this case it is the upper most external sensor (S3). This caused the sensor to detect the object and initiate the search algorithm which attempts to steer the robot in the direction which should allow more of the sensors to detect the object. Since the upper most sensor (S3) was detecting the object, the robot began moving upwards. After a few iterations of movement, the right most sensor (S2) then becomes obstructed by the target and also begins detecting the object's presence as shown in the center image. According to the rules of the algorithm, since two sensors (S2 & S3) can now detect the object, the following movements were upwards (+X) and to the right (-Y), simultaneously for each subsequent iteration. The third image on the right shows the robot being positioned so that only the bottom sensor (S1) was unobstructed by the target, meaning that S2, S3 and S4 were detecting the target. In this situation, the robot would again change its movement pattern and begin moving upwards (+X) until all sensors could detect the object at which point the search algorithm would end and motion would be halted. The detection of the object by all sensors was the selected condition for a stopping point in the algorithm.

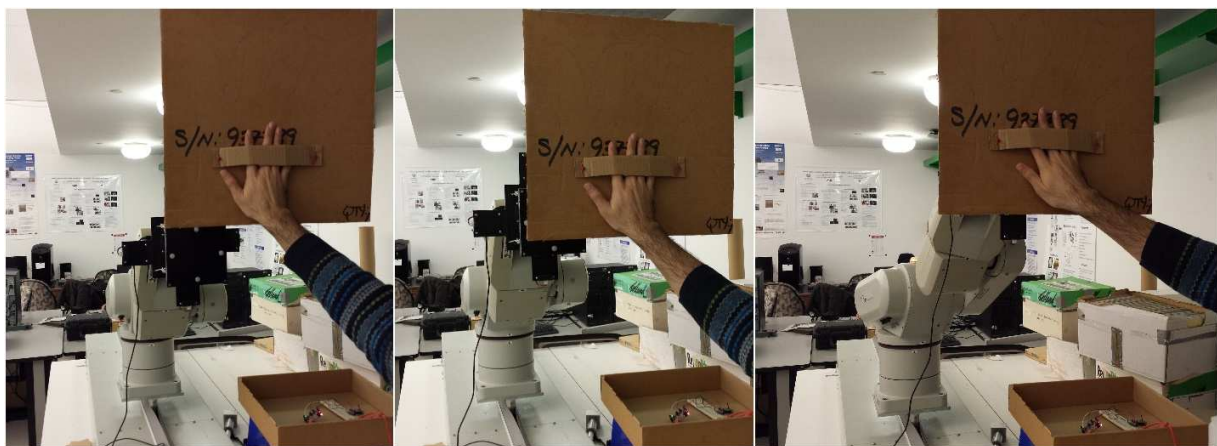


Figure 6.63 : Search Algorithm Experiment

To fully test the rules of the algorithm in this experiment, the behavior of the manipulator robot when no object was present in front of the sensors was first monitored. According to the rules, no movement should occur under this condition. This continues until at least one of the sensors measures a

valid distance. Without any valid distance or any prior movement instructions, the robot has no way of predicting in which direction to search for objects and therefore the logical choice is to remain stationary. In order to obtain a uniform search pattern during motion, the manipulator was forced to travel the same total distance in all possible directions and for this experiment that distance was set to 5 mm.

Figure 6.64 illustrates graphically the progression of a particular instance of this experiment which is unrelated to the images shown in Figure 6.63. It shows that initially, all of the sensors are returning their maximum distance values. From the way the sensor conversions were defined, the maximum distance measurement of each sensor is 400 mm but since, as described in the previous section, the external sensors are offset in position by 135 mm from the contacting surface of the compliant wrist, which is taken to be the 0 point of the Z axis, the offset is subtracted from the total distance measured and results in the 265 mm values shown. The sharp drops in distances correspond to the object coming into the line of sight of each of the sensors. For this case, the valid distance threshold was set to an offset corrected value of 150 mm, which corresponds to an effective distance of 285 mm from the sensors. The first sensor to detect an object is sensor 3, followed by sensor 2, then sensor 4 and finally sensor 1. By comparing the order in which each sensor detects the object and the sensor arrangement shown in Figure 4.10 we can see that the object first enters the field of view from the +X direction with respect to the end effector. Next, we notice that sensor 2 begins to detect the object while sensor 4 does not. In this case, the search algorithm begins moving in a combined direction of +X and -Y. Once sensor 4 begins to detect an object however, the search direction is again modified until the last sensor in the array, sensor 1, is able to detect the object at which point the motion is halted. When combining the results from Figure 6.65, which shows the position corrections made for each of the iterations of the search algorithm, with those of Figure 6.64, we are able to see that the manipulator does in fact adhere to the rules set forth for the search algorithm. It is important to note that the search algorithm does not attempt to match the pose of the detected object but simply steers the robot in a way that allows the sensors to be aligned with the target so that all sensors are detecting the object within the set threshold. This, combined with the fact that the object was being held in place by a person, accounts for the largely differing final distance values for each of the sensors.

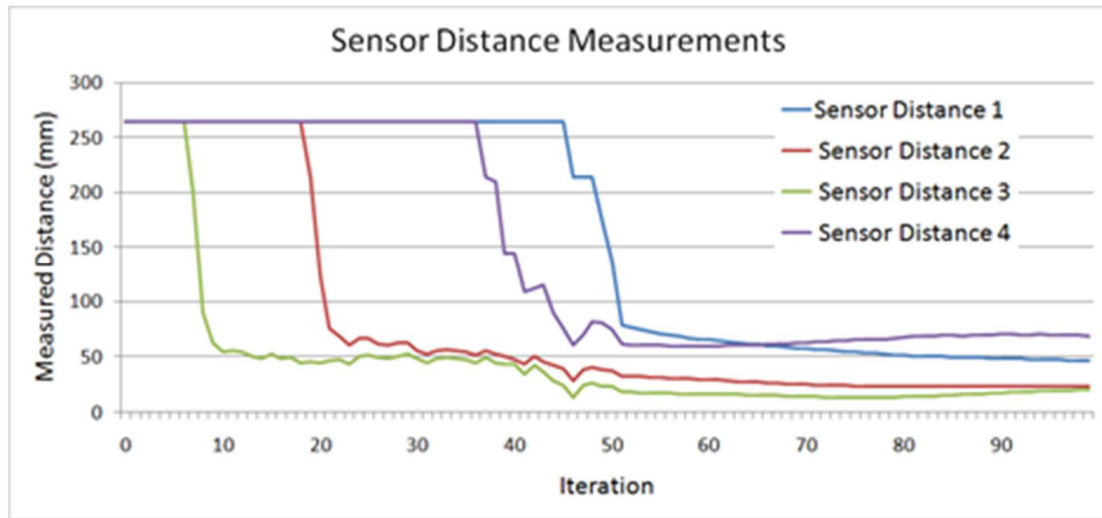


Figure 6.64 : Sensor Distances Measured During Search Algorithm

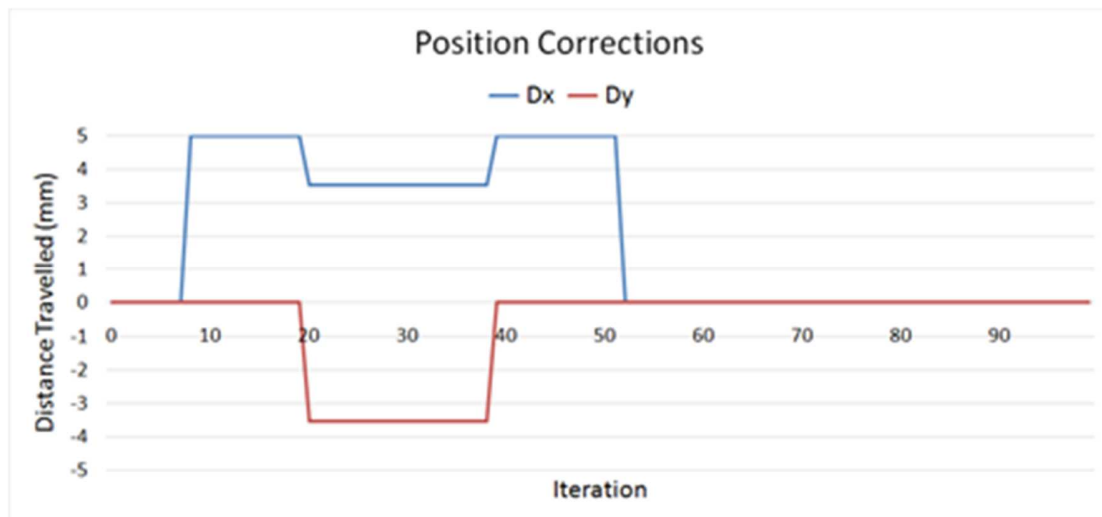


Figure 6.65 : Search Algorithm Position Corrections

6.3.2 Pose Matching

The pose matching algorithm makes use of information coming from either the internal or external set of sensors in order to generate a transformation matrix which describes the relative pose of the object being detected with respect to the compliant wrist in order to move the robot into position. Since this transformation is still defined with respect to the wrist frame, it is also transformed to the robot base frame in a similar fashion as described in equation 6.5.

This algorithm was designed to accept a distance offset parameter which describes the desired final relative distance of the compliant wrist from the object when acting on the data contained in the

transformation matrix. Recall that this transformation matrix contains within it the three parameters of interest, namely the distance along the Z axis of an object relative to the compliant wrist, as well as the orientation of the object about the X and Y axes relative to the wrist. The purpose of the algorithm is essentially to allow the robot to track and follow a target object's motion either from a distance or while in contact with the object, by having each movement of the robot act to compensate for the change of orientation of the object such that the resulting relative rotation about both the X and Y axes are 0° . Depending on which sensors are being polled for data, the distance offset can take on different interpretations. It either describes the desired distance between the object and the contacting surface of the compliant wrist when the external sensors are being polled or the desired compression of the contacting surface when the internal sensors are being polled. The previously described object search algorithm was conceived with the goal of increasing the accuracy of this particular algorithm when the external sensors are being polled for information. If the object search algorithm is able to successfully locate an object with the external sensor array, the pose matching algorithm has a much higher chance of operating successfully as all four external sensors are reporting a meaningful result assuming that the surface has no discontinuities or gaps present. In the case of the internal sensors, since these are always detecting the contacting surface, there is no need to make use of the search algorithm.

In order to assess the behavior of the system when presented with less than ideal conditions such as moving targets and varying object surface types, an experiment using the external sensor array was conducted. In the experiment, the target object was positioned in front of the robot's end effector with the help of a simple mounting device so that all external sensors could detect its presence as shown in Figure 6.66.



Figure 6.66 : Pose Matching Experiment

A total of 25 pose adjustment iterations were performed using the pose matching algorithm. For the first 12 iterations, the target object's distance from the robot was randomly adjusted by manually moving the object either toward or away from the end effector. The last 13 iterations consisted of keeping the object stationary to provide a baseline for comparison. By looking at both of these situations, we were able to examine both the dynamic and static response of the sensor array. The algorithm's objectives were to move the manipulator such that the compliant wrist matched the object's surface orientation in both the X and Y axes and maintained a constant distance of 75 mm from the surface of the object.

Figure 6.67 and Figure 6.68 show the results extracted from the sensors during the operation of the pose matching algorithm. Figure 6.67 shows the angular deviation from the desired rotation angle after every iteration of the algorithm and Figure 6.68 shows the average distance calculated from the returned values of all four external sensors. The latter is the distance value used in the calculation of the homogeneous transformation matrix upon which the robot relies to control its movements. The object was deliberately placed at an initial distance greater than the desired distance we wished to maintain to show that the manipulator could in fact move to the desired position. The resulting mean values obtained for the rotation about the X and Y axes (R_x and R_y) were 0.07 ± 1.85 and 0.30 ± 1.70 degrees for the dynamic iterations, respectively, and -0.15 ± 0.53 and 0.08 ± 0.60 degrees for the static

iterations, respectively. The resulting mean value for the average distance to maintain was 71.7 ± 7.7 mm for the dynamic iterations and 75.2 ± 0.7 mm for the static iterations. Due to the lack of ground truth distances for every iteration, no error calculations could be obtained. However, these types of results, namely the larger variations during movement, warranted further investigation and led to the development of the multiple scenarios presented previously. Although it was not known at the time, the small angular deviations for the last 4 iterations were again due to the inverse kinematic solution used to control the robot.

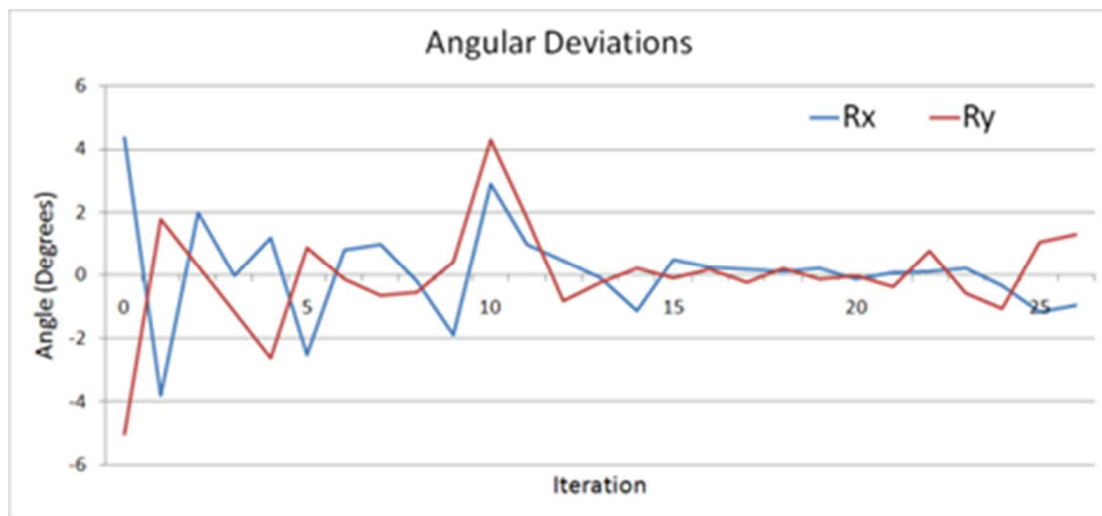


Figure 6.67 : Angular Deviations from Desired Values ($R_x = R_y = 0^\circ$).

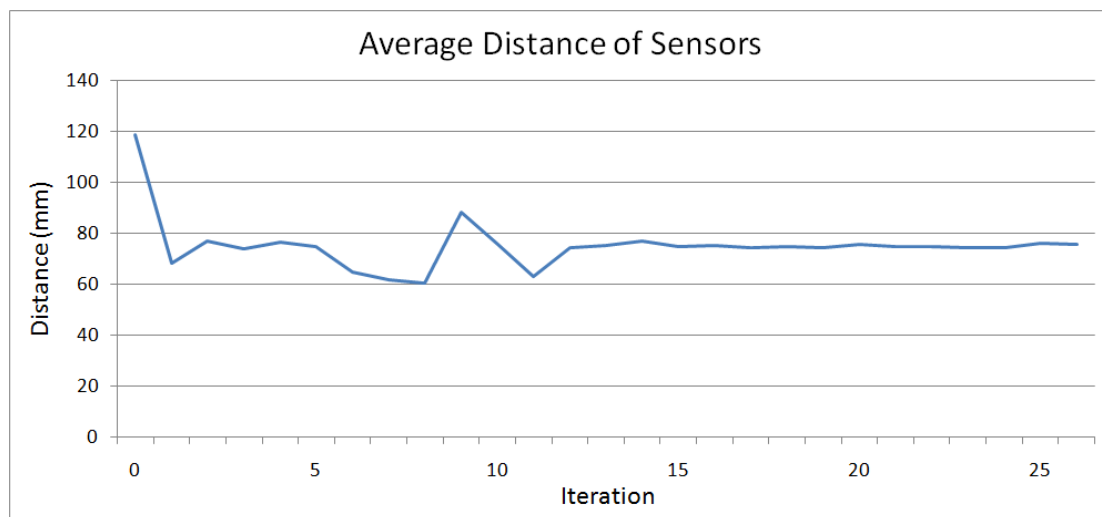


Figure 6.68 : Average distance of sensors (Target distance = 75 mm).

The application described in this section demonstrates the versatility of the compliant wrist system as it allows for a wide variety of data to be collected by control systems in order to drive robotic

motion. The developed API discussed in Appendix C, section C.5 allows for the conception of algorithms with much greater complexity as it does not impose a specific data representation but rather provides multiple means of interpreting the available information coming from the compliant wrist. This aspect is fundamental in promoting the compliant wrist system's adoptability and integration onto a multitude of robotic platforms.

6.4 Summary of Experimental Validation

In order for the compliant wrist to become an adoptable solution for providing additional sensory feedback to a robotic platform a compilation of its characteristics is essential. To determine if a robotic platform can accommodate the compliant wrist structure, its physical dimensions are beneficial to determine encumbrances which might need to be considered during operation and its weight allows for the determination of its viability in terms of payload restrictions.

From the dimensions provided in section 4.1 and knowledge of the IR sensor distance limits, namely the minimum distance of 30 mm and maximum of 400 mm defined by the response curve, it is possible to determine the limits on the rotational degrees of freedom and the effective sensor measurement range for the sensors. The summary of mobility characteristics is provided in Table 6.6. As reported earlier, the worst-case rotational range that the internal sensors are capable of detecting is $\pm 40^\circ$ for both axes. These are considered the minimum rotation ranges due to the fact that these values are imposed by the geometry of the device when the contacting plate and translational shaft have been fully compressed by 25 mm. When the translational shaft is fully extended at 10 mm, larger rotations can be achieved reaching upwards of $\pm 58.5^\circ$.

The same minimum rotation range is applied to the external sensors due simply to the fact that if the contacting plate is experiencing these constraints due to an object applying forces upon it, the physical movement of the compliant wrist would then also be constrained preventing the external sensors from reading larger rotations. The external sensors also have a smaller maximum rotation range due primarily to the distance that separates the sensors and the maximum distance that can be detected by the sensors. Given the geometry of the device and the initial conditions, determination of the effective sensor measurement ranges for the sensors is also possible. The values provided for both the internal and external sensors are those which are physically achievable including the offset due to the sensor positioning.

Table 6.6 : Mobility Characteristics

Parameter	Minimum	Maximum
Rotation (Internal)	$\pm 40^\circ$	$\pm 58.5^\circ$
Rotation (External)	$\pm 40^\circ$	$\pm 54.5^\circ$
Translation (Internal)	-25 mm	+10 mm
Effective Sensor Measurement Range (Internal)	-65 mm	+85 mm
Effective Sensor Measurement Range (External)	-87 mm	+283 mm

The calculations required to obtain the effective internal sensor measurement range of Table 6.6 can be explained with the help of Figure 6.69, Figure 6.70, Figure 6.71, and Figure 6.72. In all of the figures, the gray dotted line represents the origin of the sensors distance measurements, i.e. when the sensors report a distance of 0 mm. The solid black line at the bottom of each image represents the surface of the sensors with the red dotted line indicating the minimum allowable distance between sensors and the compliant wrist's contacting surface, also represented by a solid black line which appears in different configurations throughout the images indicating its current translation and rotation with respect to the sensors. In Figure 6.69, the green dotted line represents the positioning of the contacting surface were it to be fully extended but with no rotation while the blue dotted line represents the fully compressed position also with no rotation. The brackets of corresponding colors indicate the actual distances between different items in the images. Note that the images are not to scale and are simply for illustrating the concepts.

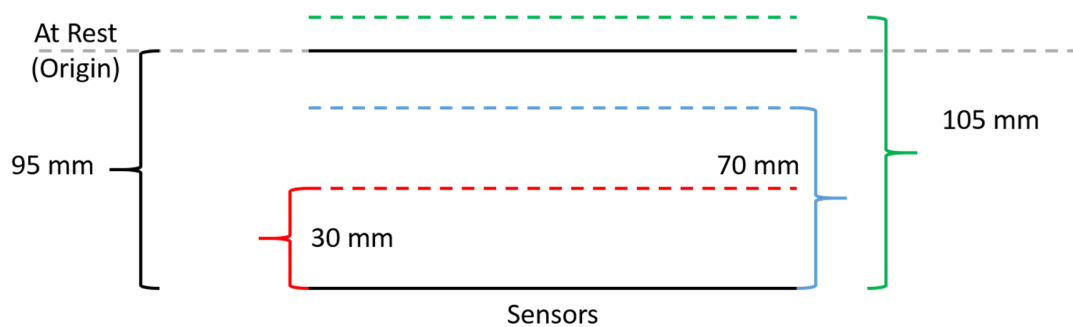


Figure 6.69 : Effective Internal Sensor Measurement Range (At Rest with No Rotation)

Figure 6.70 shows the compliant wrist's contacting surface fully rotated with its center positioned at the origin indicating that there is no compression nor extension. The concept of full rotation is determined by the minimum distance between the sensors and the contacting surface which in this case results in a distance of -65 mm being reported by the sensors on one side of the axis and +65 mm on the other side. Recall again that due to symmetry, all calculations apply to both axes.

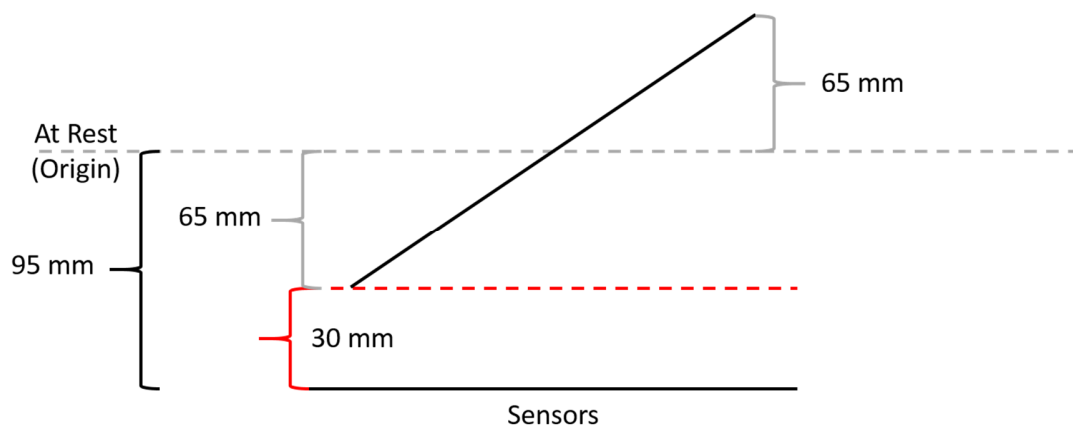


Figure 6.70 : Effective Internal Sensor Measurement Range (At Rest with Maximum Rotation)

Were the contacting surface of the compliant wrist become fully compressed, the center of the contacting surface would be positioned at a distance of 70 mm away from the sensors however in this case the full rotation would be less than in the previous case as the maximum allowable distance between the origin in the sensors remains unchanged at a value of -65 mm.

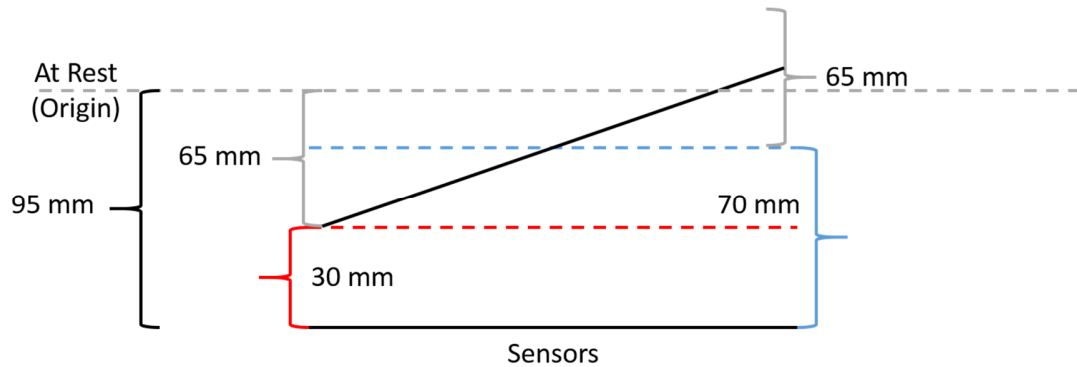


Figure 6.71 : Effective Internal Sensor Measurement Range (Fully Compressed with Max Rotation)

The reverse can be seen when the compliant wrist becomes fully extended as in Figure 6.72, due to the extension, the contacting surface is allowed to rotate to a greater extent as one side of the contacting plate can travel an additional 10 mm for a total of 75 mm before generating a distance reported by the sensors to be -65 mm. This leads to a maximum positive distance of +85 mm by the opposite sensor.

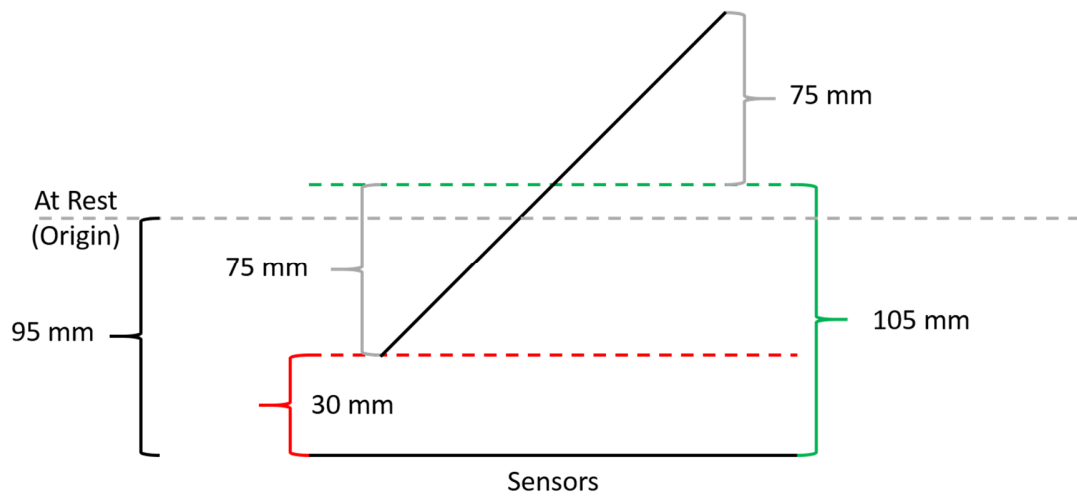


Figure 6.72 : Effective Internal Sensor Measurement Range (Fully Extended with Max Rotation)

Due to the materials chosen for the fabrication of the compliant wrist and despite its large size, its weight, including all of the sensors, electronics and the components used to attach the device to a robotic platform, is approximately 900 grams. A lightweight device is desired especially in the case of manipulator robots where the payloads can be extremely limited when compared to mobile platforms which tend to have fewer weight restrictions. For example, the total payload for the CRS-F3 onto which the prototype was integrated is a mere 3000 grams.

Regarding the operational parameters of the compliant wrist, those which should be reiterated are the rate at which the sensors can make individual measurements as well as the precision and accuracy of distance measurements over the range of operation that is achievable by the sensors. The refresh rate of the sensors is dependent on several factors but is essentially linked to the amount of processing required by the microprocessor to generate the final outputs for each active sensor. This can vary depending on the type of filtering that is being performed on the samples as well as the number of sensors that are actively being processed. As mentioned previously, the refresh rate was found to have an upper limit of approximately 850 Hz when sampling all 8 sensors with a moving average filter with a window length of 33 samples being applied to the input samples.

The distinction between precision and accuracy comes from their interpretation and the method used to estimate both parameters. Precision is understood to be the repeatability of measurements over time and this was estimated via the standard deviation from the mean. Meanwhile, accuracy is understood to be the closeness of the measured signals with the expected value or rather the ground truth value established and verified by more accurate instruments. The estimate of accuracy is obtained by calculating the absolute difference of the mean of a measured signal and the ground truth value, leading to an offset indicating to which degree the two values differ.

The precision of measurements was found to vary according to the absolute distance of detected objects from the sensors with precision increasing with decreasing distances. The resulting precision for the distance estimates produced under the conditions just mentioned, namely the selected filtering method, is plotted in Figure 6.73. The values presented are the standard deviation of distance measurements in millimeters averaged over the 16 sensors during the characterization of the IR sensors presented in section 6.1. The data points correspond to the 18 calibration distances discussed previously. Recall that the interpolation technique used to obtain intermediate distance values between the calibration points when converting the voltage values requires two data points at each end of the curve. These four data points tend to lead to skewed results due to the lack of intermediate values between them and are shown in blue while the valid data points are shown in orange.

Figure 6.74 attempts to illustrate the accuracy with which the distance estimates can be made by providing the remaining offset from the target values used during the calibration as a percentage of the absolute distance. These values were also obtained as an average over the 16 available sensors. Again the two points at both extremities of the curve should be ignored as these are skewed by the

interpolation technique. The plot shows that the calibration procedure is capable of achieving an offset of less than 1% of the distance measurement up to a distance of 300 mm. That is, at each of the calibration points, the generated distance estimates from the sensors deviate from the target distance value by less than 1% which corresponds to 3 mm at a distance of 300 mm. These larger offsets apply mainly to the external sensors as these are expected to operate over a larger range of distances however for the internal sensors, typical offsets for distances below 150 mm are less than 0.3 mm.

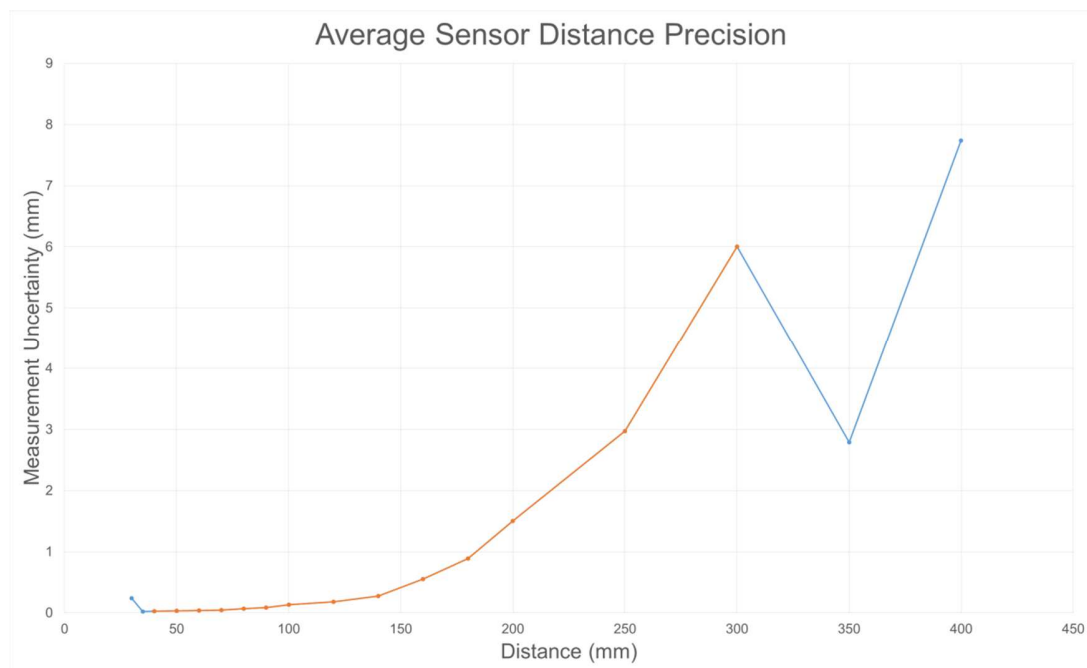


Figure 6.73 : Distance Estimate Precision

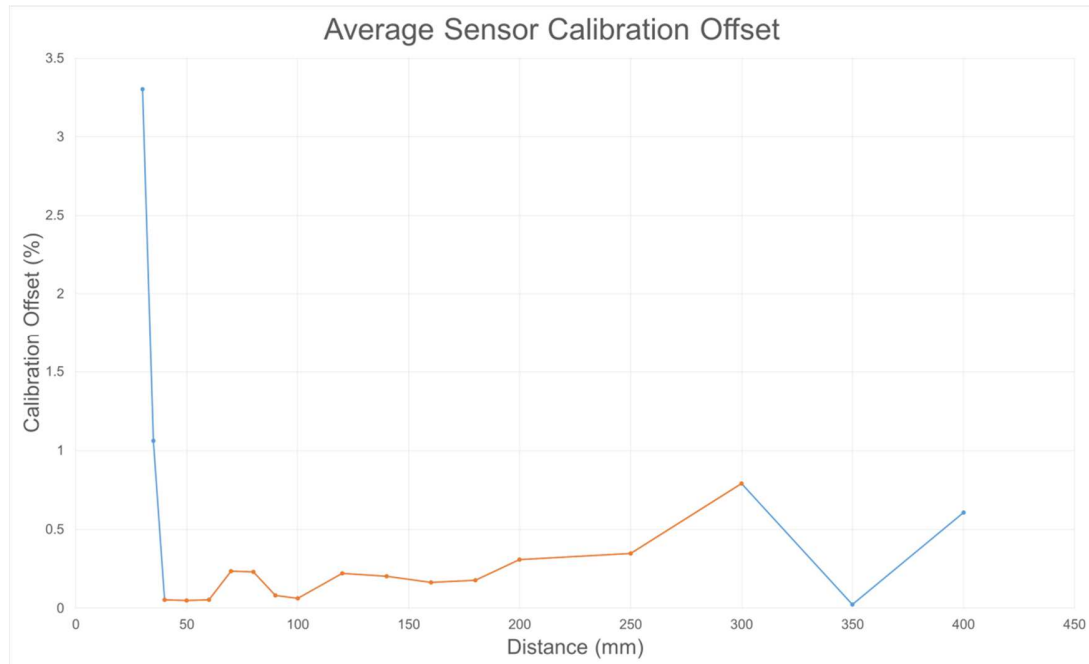


Figure 6.74 : Distance Estimate Accuracy

Although one of the goals of the sensor characterization was to determine whether the infrared sensors could achieve better measurement accuracy and precision than the Kinect sensors, a direct comparison of these parameters could not be made due to the lack of overlap in operating ranges for the two types of sensors. According to [112], the suggested optimal operating range of the Kinect sensors when detecting objects is 2 meters while objects placed at distances of 40 cm or less cannot be properly detected. This makes the infrared sensors of the compliant wrist a complimentary asset to the originally envisioned system for rapid vehicle inspection.

Chapter 7. Conclusion

The motivation for this thesis was to address the existing limitations in an automated guidance system using visual and depth information for the inspection of vehicles. The limitations arose from the achievable depth sensing resolution of the particular measurement system being used, namely the Kinect sensor. As research progressed, it was determined that a variety of robotic control systems relying solely on vision could potentially benefit from additional sensory input to refine the description of the nearby environment and the physical structures contained therein.

As a result, a flexible mechanical structure was designed and equipped with the necessary sensing apparatus to allow the development of a multi-step strategy for interaction between a robot and its environment. The multi-step strategy consists of an initial gross information gathering using a peripheral vision sensing system which provides a depth map of the nearby surroundings of the robot such that objects of interest can be identified and marked for further inspection. The second step in the strategy consists of the integration of the information provided by the external sensors of the compliant wrist into the control loop in order to provide real-time refinements of the initial distance estimates.

The third step in the strategy is also the most critical since it involves an important change in state, namely going from a state of free motion, where no external forces are acting on the robot, into a state of constrained motion, where information about the dynamics of the objects being contacted are essential to the successful completion of interaction tasks. Once contact has been made, information from the internal sensors of the compliant wrist can be used to control the robot's motion during contact while simultaneously obtaining an estimate of the object's pose in the workspace. An intrinsic benefit of this strategy comes from the characteristic response curve of the infrared sensors being used as the multi-step strategy consists of steps in which each successive steps brings the robot and hence the sensors closer to the target object and as such simultaneously increases the precision of the distance estimates and hence pose estimates.

The second and third step of the strategy were implemented and validated via experiments whose results showed that the compliant wrist system is capable of achieving precise measurements, reaching sub-millimeter variations in favorable conditions and although absolute comparisons were not made between the precision of the compliant wrist and the Kinect sensors, it was shown that the compliant wrist system provides the added benefits of being mobile and providing information in near

real-time whereas the Kinect sensor system was stationary and the algorithm responsible for mapping the environment needed to be conducted offline. The mobility of the sensing device allows for the selective inspection of targets of interest or possibly the further examination of occluded areas not readily seen by a stationary peripheral vision system. Additionally, all remaining errors in accuracy were also easily compensated for by the physical compliance afforded by the compliant wrist preventing large impact forces to be incurred during non-contact to contact transitions by the manipulator's end effector.

7.1 Summary

This thesis began with a look at several reasons why the field of robotics requires further advancements, primarily in the manner in which robotic devices interact with their environments as these environments are becoming more and more difficult to model and can rarely be completely defined prior to the operation of the robots within those spaces. This led to the determination of three major requirements for being able to function in unstructured environments such as the ability to detect objects in proximity of the robotic system, the ability to safely make contact with those objects as well as the ability to determine an object's pose while making contact with said object.

In order to determine the optimal method to implement the necessary components to obtain the desired functionality of the device, existing technologies were explored. The goal was to determine which of these could be used to address the requirements of the design starting with the methods of motion control used in the field of robotics. This led to the selection of IR sensors providing easily interpretable measurements which needed very little processing to convey practical pose information representing the state of the compliant wrist and its environment to the control system..

An overview of the existing project in which the developed compliant wrist solution would play a critical role served to highlight the shortcomings of the overall system. Shortcomings such as limited resolutions available for mapping the environment and the concerns associated with the requirement of a rigid manipulator robot coming into contact with objects were the primary targets. These essentially prescribed what was required for the compliant wrist system in order to improve the overall solution.

These requirements called for the integration of a multitude of components into a self-contained module. The completed prototype assembly was introduced in the fourth chapter and showed that by designing a custom mechanical assembly it was possible to create a structure which not

only provides the compliance necessary for the safe interaction with objects in an unstructured environment but also provides the facilities necessary for the proper positioning of the sensors which allow for the sensing of the necessary distances for detecting external objects as well as estimating the deflection by objects in contact with the wrist, all in a single module.

As a means of validating the operation of the compliant wrist, a thorough analysis and characterization of the IR sensors is provided in chapter six with the goal of illustrating the behavior of the raw voltage signals generated by the sensors as well as the behavior of the distance measurements generated after the system has processed those raw signals. Statistical data confirmed the Gaussian distribution of noise present in the signal allowing for simple filtering methods to be employed leading to stable distance measurements. Finally experimental results were obtained for the compliant wrist through the application of several path planning algorithms which were implemented to leverage the data in a control loop for a CRS-F3 manipulator arm.

7.2 Contributions

This thesis proposes a compliant wrist for the purpose of improving a robotic system by allowing it to incorporate physical stimuli into a control loop during autonomous guidance thereby supplementing any existing data being used for the same end. This work resulted in multiple contributions to the fields of instrumentation and robotics, as follows:

- The design and fabrication of a lightweight and low-cost stand-alone module capable of estimating the pose of surfaces in the environment both at a distance and during contact which can easily be mounted to a multitude of robotic platforms.
- An in-depth analysis and characterization of infrared range sensors with the goal of determining the accuracy and precision of measurements provided.
- The development of a calibration procedure for the infrared sensors which enables the user to match the generated outputs of individual sensors allowing for the concurrent use of multiple sensors with low inter-sensor errors, a feature which is essential to the proper operation of the proposed instrumented device.

- The implementation of a companion software suite with a graphical component allowing for the control of the internal operational settings and the visualization of the data generated by the compliant wrist module.
- An extensive experimental validation of the operating principles of the compliant wrist by using live feedback generated by the wrist to adapt the pose of a rigid manipulator in two stages, namely through an approach phase and a contact phase.

The most notable contribution is the design of a mechanism to provide tactile feedback into a control loop along with significant compliance integrated into the mechanism. The design takes into consideration cost of materials and ease of fabrication so that it can more readily be adopted, as it supplies a method of mounting the mechanism onto any robotic platform capable of accommodating its size with minimal physical modifications to the existing structure. The tactile feedback methods making use of force sensors discussed in section 2.1.2 required direct contact prior to returning any sort of signal and compliance tended to be dealt with as a separate problem. By incorporating compliance and a means of detecting nearby objects into a single device, direct contact isn't required to obtain guidance information and furthermore, the motion problem becomes simplified as position based algorithms can be used regardless of the state of system, be it in free motion or constrained motion, or even during transitions between the two modes.

The project which stimulated the conception and development of the compliant wrist first introduced its operational principles in [25] while the design and operation of the device was first published in [128]. Once the device was completed and integrated onto a CRS-F3 manipulator, the initial results meant to validate the operation of the device and its use in path planning algorithms and robot control were published in [127]. The work also garnered recognition in the form of an IEEE award at the Engineering and Computer Science and Graduate Poster Competition in March of 2015 held at the University of Ottawa.

7.3 Future Work

The compliant wrist developed in this thesis currently suffers from a problem in scalability, that is its current size somewhat limits its practical applications on smaller robotic platforms. The size of the device was initially more compact; however the compliance afforded by the antagonistic spring system was somewhat restricted. The lengthening of the center shaft was needed to increase the translational travel of the device once the corner tensions cords were attached because the center compression

spring which was available could not be substituted for one which offered a greater resistance. A more rigorous mechanical analysis of the spring constants and the physical forces capable of being withstood could allow for a more robust model of the system allowing for the proper selection of components to obtain the desired stiffness in a more confined space. The use of carefully fabricated springs with well-known spring constants could also potentially allow for the estimation of external forces being applied to the compliant wrist.

Also, since the device was primarily constructed using plastic material, 3D printing technology could be leveraged to speed up prototyping for the purposes of gathering additional experimental data from multiple robotic platforms. This could also serve to increase the device's adoptability in the robotics hobbyist sector which often offers a significant wealth of independent research. Going further in this direction, an ROS package could be developed for simplifying interfacing with the device.

Considering the precision and accuracy achieved by the compliant wrist's sensors, a multitude of applications beyond that of integration onto a manipulator robot are conceivable. One example of these applications is that of a "smart" bumper for mobile robots doubling as a form of manipulator in its own right. There have been several attempts at leveraging multiple smaller mobile platforms in an attempt to move objects in a cooperative fashion such as in [129] and [130]. In both cases force sensors attached to the platforms provide contact force feedback to the robot controllers for use in control algorithms to determine how each robot should react to each other's movements. The incorporation of a compliant wrist onto these platforms would provide the benefit of calculating optimal approach vectors to the target object using the external sensors to estimate the pose of the object that the robots will be attempting to move. Knowledge of surface pose of the object while in contact could also help with the final positioning of the object in a desired orientation and position should the need arise. Compliance also allows for the careful handling of objects which could be deemed fragile. Using the combination of the external sensors and movable contacting plate of the wrist, knowledge of initial conditions of the object's geometry could be obtained and compared to data gathered while in contact with the object to determine if the object is being deformed to a significant degree. Even for such a basic task such as displacing an object using one or multiple robots, there are multiple benefits which can be provided by the compliant wrist and with its simple attachment process, its integration onto platforms is rather trivial. In short, further investigation of possible applications is warranted.

The accuracy of the measurements could also be further improved by incorporating the findings of [131] where many additional parameters are considered during the conversion from voltage to distance. The main parameter of interest here is the angle of incidence which can have a more significant impact on the readings obtained from external sensors at greater distances. Currently the problem is minimized due to the operating range of the sensors however with longer range sensors errors could be significantly larger depending on the situation.

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Appendix A - Supplemental Information



Figure A.1 : Sensory Homunculus [132]

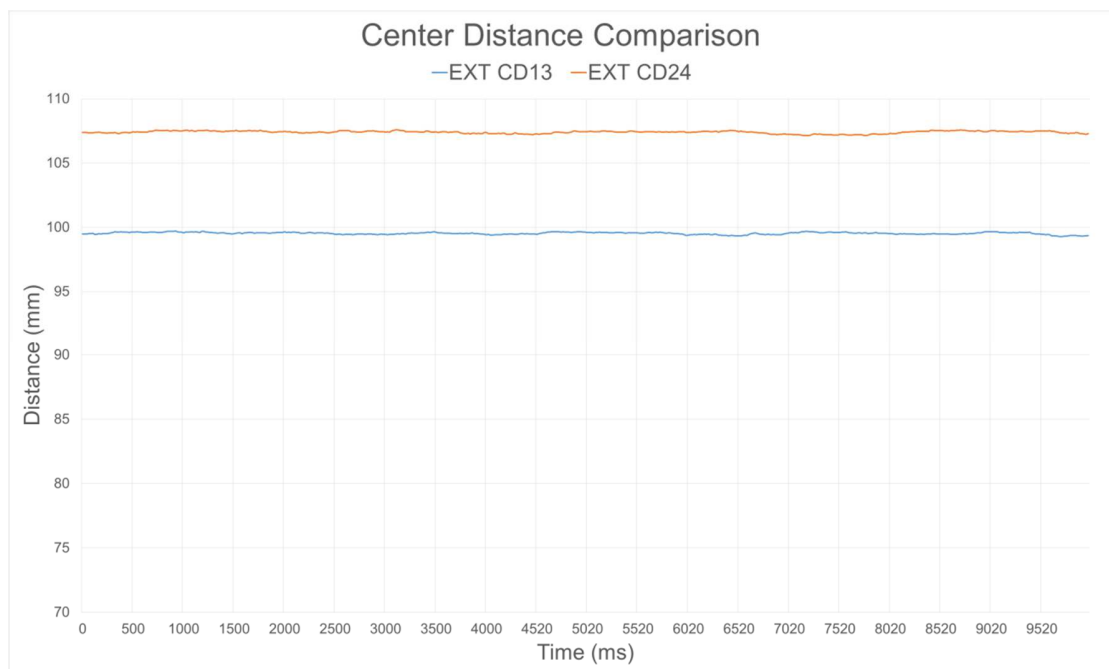


Figure A.2 : Uncalibrated Center Distance Comparison

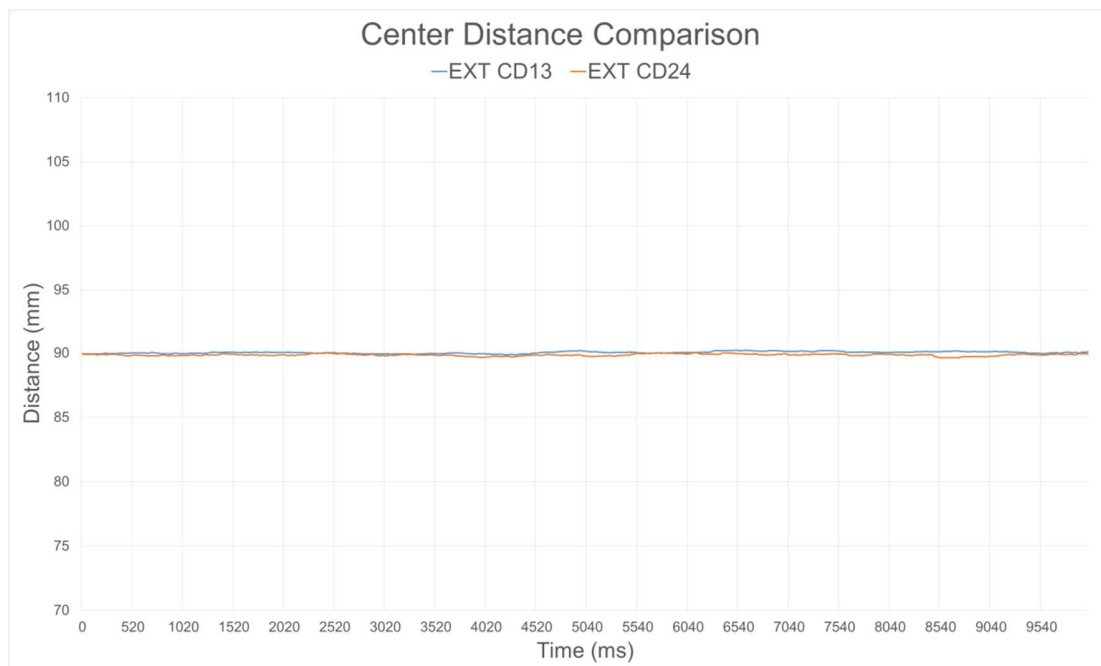


Figure A.3 : Calibrated Center Distance Comparison

Appendix B - Compensation Control Algorithm Pseudocode

Pseudocode:

- Request sensor information from compliant wrist
 - Internal sensors polled when compliant wrist is in contact with an object
 - External sensors polled when compliant wrist is not in contact with an object
- Move end effector into desired relative position of object described by sensor information
 - Desired relative position is described by two rotational offsets and one translational offset
- Wait until movement is complete
- Repeat

Appendix C - Control and Operation Software

This appendix describes the application that was developed to work in conjunction with the compliant wrist and its embedded software. Development of this application began as a simple means of visualising what the sensors of the system were recording. As the system grew in complexity, so did the application which required additional controls to manipulate the newly implemented features. It now serves as accompanying software providing an intuitive way of making changes to the available settings of the compliant wrist such as the digital filters being applied to the input data, the sampling frequency of all the sensors and the sensor coordinates with respect to the compliant wrist's platform. It also serves as a means of testing the compliant wrist and evaluating the settings that have been applied. The many features of the application were grouped into different categories and are now displayed in multiple tabs, or views, in order to be neatly presented to the user. Each part of the interface is presented and its use explained. The following subsections are organized based on the views available in the interface application which do not reflect each view's importance but is simply how they are organized in the application.

In order to provide some context of how this application can be utilized it is useful to refer again to Figure 4.19. During development, the robot controller's role often needed to be simulated manually by sending individual commands to the compliant wrist to test newly added features and to ensure correct operation by extracting information from the device. A PC equipped with an XBee radio module was used to this effect which is why the robot controller in the image is represented by a terminal. The programming environment used to develop this interface is called Processing and provided the necessary libraries for the user interface controls such as sliders and toggle buttons, means of sending data through a serial port to which the Xbee module was connected, as well as a simple way of creating visual graphics in three dimensions to represent the physical configuration of the compliant wrist structure.

C.1 Setup View

Upon starting the application, the initial view that is displayed is shown in Figure C.1. It provides the necessary functions to allow the PC on which the application is running to connect to the desired compliant wrist module. The system has been designed such that multiple compliant wrists could potentially be connected to a single robot controller should the need arise. In order to reflect that idea, would multiple compliant wrists be connected to the PC, each of these could be configured and tested

one by one by simply choosing to which device the application should connect. The only thing that is required is knowledge of the corresponding communications port each device is using in order to select the individual devices. Communications with the compliant wrist system is currently achieved with the use of a second microcontroller and XBee radio connected directly to the PC. This microcontroller serves as a simple information relay, meaning it accepts outgoing data from the PC and transmits it to the compliant wrist via the XBee radio. This is accomplished through a simple algorithm which reads data coming in from the microcontroller's serial port connected to the PC and retransmitting that same data to the XBee module via the microcontroller's second serial port. Also since these serial ports are bidirectional, via the XBee radio, the microcontroller is also able to receive incoming data from the compliant wrist and transmit it to the PC.

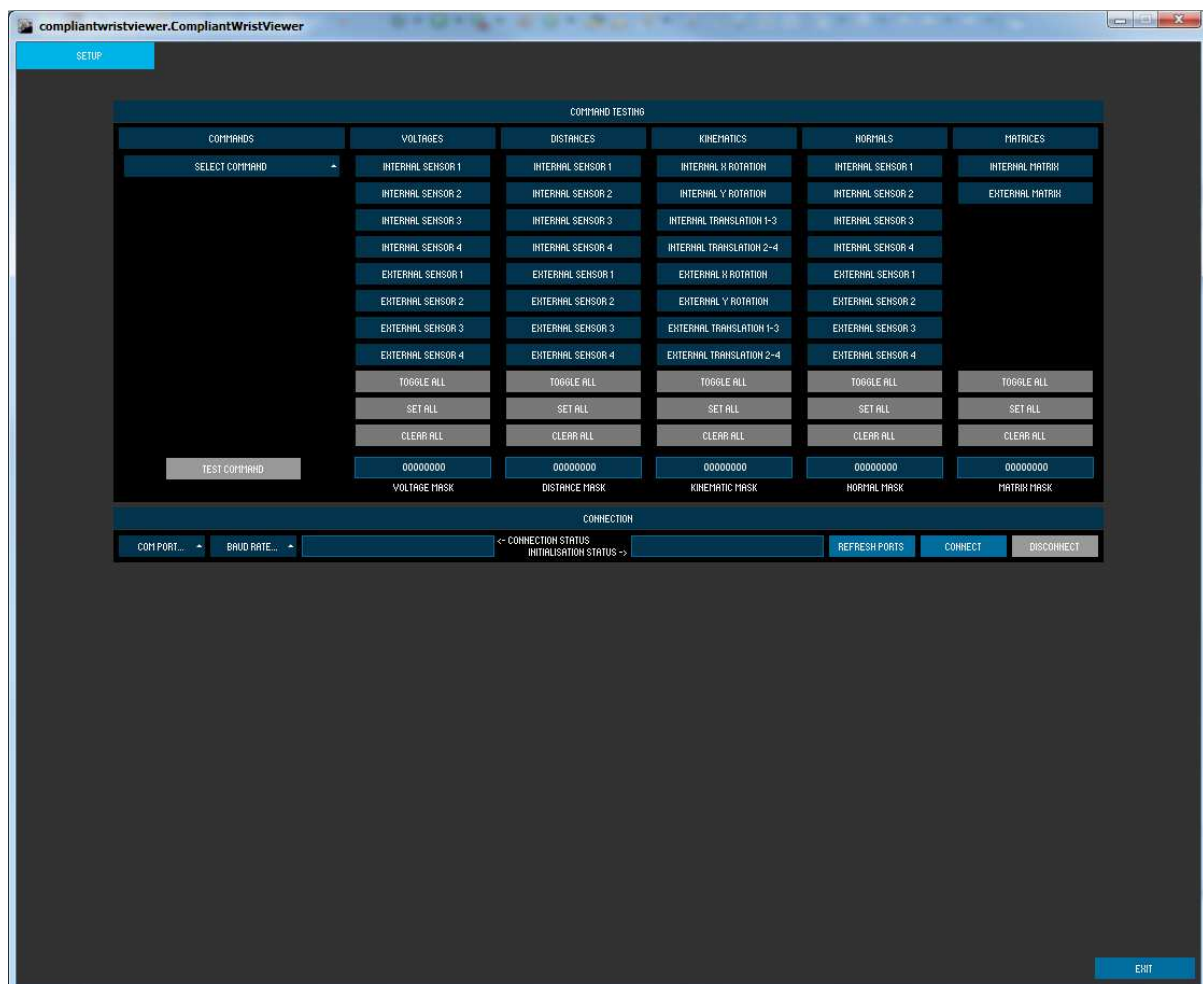


Figure C.1 : Setup View

C.1.1 Connection Control

A connection to the compliant wrist is established through the previously mentioned relay microcontroller. As also mentioned, the user must first select the desired COM port to which the relay is connected with an appropriate baud rate. By pressing the connect button, an attempt is made at establishing a connection over the selected COM port. If the correct COM port is not selected, the connection will fail with no adverse effects on the operation of the compliant wrist. Once a connection has been established, an initialization routine is invoked in order to obtain any of the existing settings from the compliant wrist's internal memory. For this to happen, both the XBee radio connected to the PC and the one housed in the compliant wrist assembly need to have been previously setup so that they are operating on the same network in order for them to transmit information between the two. The existing settings, if any, are used to properly initialize the application and provide a full picture of the compliant wrist's behavior. This is an essential feature as it also allows a robot controller to examine the current settings and determine if the device will operate as expected. This concept is illustrated by the software component denoted as "Virtual Wrist" in Figure 5.1. This initialization routine is not implemented in the compliant wrist but rather is a sequence of queries for information that a robot controller should effectuate and this is what is currently being done by the application once a connection has been established. Any robot controller would need to have memory reserved to store the all of the compliant wrist's settings and incoming data in an organized fashion.

To provide the user with additional feedback during connection attempts, which require several seconds, two text fields also display the current connection status and the initialisation status of the application. After a set delay following a connection attempt, the system will either display a successful connection message or a failed connection message in the connection status text field. During the initialisation routine, several updates to the initialisation status text field are made as the routine progresses through each of its steps. If at any time the initialisation routine detects a lack of communication, the initialisation routine will be aborted and a failed initialisation message will be displayed. If the initialisation routine is successful, a message in the initialisation status text field will be provided and the application will make three additional control views available to the user to perform further tasks with the compliant wrist as these are all initially made unavailable upon start up. This makes the application somewhat more intuitive to use as the user is not presented with a myriad of disabled functions.

Figure C.2 shows the section of the setup screen that relates to the connection procedure. In this particular scenario, COM4 was selected to operate at a baud rate of 57600, which led to a successful connection followed by the retrieval of the current settings of the compliant wrist. To further ensure ease of use of the interface, certain controls are deactivated to prevent the user from interfering with certain processes, illustrated by the change in colors of the controls such as the “Connect” button which has been greyed out. The “Disconnect” button is now also blue in color, indicating that the connection procedure can be cancelled or terminated once a connection is established. This illustrates the types of visual cues provided for the user to further improve the user experience.



Figure C.2 : Connection Status

C.1.2 Command Selection

After connecting to the compliant wrist and retrieving the necessary settings, the application is now ready to allow test the compliant wrist system and its responses to the many commands available. A lot of effort went into making the compliant wrist module as flexible as possible in order to increase its usability for different projects in the future. The command section of the setup view reflects this fact by providing the user with a large degree of control over the type and amount of information being requested from the compliant wrist. This part of the application was instrumental in assessing the behavior of the compliant wrist. As mentioned previously, during the initial phases of development, testing of the commands was done manually by entering text into a more basic implementation of this application which was command line based. As it became apparent that a greater number of commands would be implemented, the arduous process of typing each command individually was not an ideal one. On the left of Figure C.3 is a drop down menu which provides a list of the vast majority of available commands for which the compliant wrist has been programmed to provide a response. The remaining commands to which the compliant wrist responds are distributed throughout the rest of the application and will be covered throughout the following subsections.

The commands can essentially be separated into two groups, those which require additional information to fully describe the action performed by the compliant wrist and those which do not. The list provided consists mainly of commands which require no additional information in order to generate a response from the compliant wrist and are primarily data requests for specific data combinations or

commands that toggle settings from true to false in the compliant wrist. For the few commands which do require information along with the request, rather than type in values manually, additional controls are provided.



Figure C.3 : Command Selection

Each of the commands provided in the list has a corresponding data exchange protocol associated to it on the compliant wrist which retrieves and transmits the desired information. These commands are used to determine what information will be retrieved from the compliant wrist and sent to a robot controller. The application provides a button which can be clicked to issue the selected command to the compliant wrist in order to examine the output provided. However, the more useful feature which makes use of the command selection part of the application is the display view that will be discussed in section C.2. On the right of Figure C.3 are buttons which serve a dual purpose. For the majority of the commands available in the menu, they show what information will be requested from the compliant wrist; however, they also allow the user to quickly and easily select the desired information to be requested when the few specific commands which require additional information to be sent along with the command are selected from the menu. For example, the command “CMD_GET_INTERNAL_SENSOR_DISTANCES” will send a request to the compliant wrist for distance estimates from all of the internal sensors simultaneously, and the command “CMD_GET_EXTERNAL_SENSOR_1_VOLTAGE” will send a request for a single voltage measurement coming from the first external sensor. In each case, the buttons in the associated columns corresponding to the desired sensors will become highlighted confirming which information will be received. Both cases are shown in Figure C.4 and Figure C.5, respectively.

COMMAND TESTING					
COMMANDS	VOLTAGES	DISTANCES	KINEMATICS	NORMALS	MATRICES
CMD_GET_INTERNAL_SENSOR_DISTANCES	INTERNAL SENSOR 1	INTERNAL SENSOR 1	INTERNAL X ROTATION	INTERNAL SENSOR 1	INTERNAL MATRIX
	INTERNAL SENSOR 2	INTERNAL SENSOR 2	INTERNAL Y ROTATION	INTERNAL SENSOR 2	EXTERNAL MATRIX
	INTERNAL SENSOR 3	INTERNAL SENSOR 3	INTERNAL TRANSLATION 1-3	INTERNAL SENSOR 3	
	INTERNAL SENSOR 4	INTERNAL SENSOR 4	INTERNAL TRANSLATION 2-4	INTERNAL SENSOR 4	
	EXTERNAL SENSOR 1	EXTERNAL SENSOR 1	EXTERNAL X ROTATION	EXTERNAL SENSOR 1	
	EXTERNAL SENSOR 2	EXTERNAL SENSOR 2	EXTERNAL Y ROTATION	EXTERNAL SENSOR 2	
	EXTERNAL SENSOR 3	EXTERNAL SENSOR 3	EXTERNAL TRANSLATION 1-3	EXTERNAL SENSOR 3	
	EXTERNAL SENSOR 4	EXTERNAL SENSOR 4	EXTERNAL TRANSLATION 2-4	EXTERNAL SENSOR 4	
	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL
	SET ALL	SET ALL	SET ALL	SET ALL	SET ALL
	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL
	TEST COMMAND	00000000	00001111	00000000	00000000
	VOLTAGE MASK	DISTANCE MASK	KINEMATIC MASK	NORMAL MASK	MATRIX MASK

Figure C.4 : Internal Sensor Distances Command

COMMAND TESTING					
COMMANDS	VOLTAGES	DISTANCES	KINEMATICS	NORMALS	MATRICES
CMD_GET_EXTERNAL_SENSOR_1_VOLTAGE	INTERNAL SENSOR 1	INTERNAL SENSOR 1	INTERNAL X ROTATION	INTERNAL SENSOR 1	INTERNAL MATRIX
	INTERNAL SENSOR 2	INTERNAL SENSOR 2	INTERNAL Y ROTATION	INTERNAL SENSOR 2	EXTERNAL MATRIX
	INTERNAL SENSOR 3	INTERNAL SENSOR 3	INTERNAL TRANSLATION 1-3	INTERNAL SENSOR 3	
	INTERNAL SENSOR 4	INTERNAL SENSOR 4	INTERNAL TRANSLATION 2-4	INTERNAL SENSOR 4	
	EXTERNAL SENSOR 1	EXTERNAL SENSOR 1	EXTERNAL X ROTATION	EXTERNAL SENSOR 1	
	EXTERNAL SENSOR 2	EXTERNAL SENSOR 2	EXTERNAL Y ROTATION	EXTERNAL SENSOR 2	
	EXTERNAL SENSOR 3	EXTERNAL SENSOR 3	EXTERNAL TRANSLATION 1-3	EXTERNAL SENSOR 3	
	EXTERNAL SENSOR 4	EXTERNAL SENSOR 4	EXTERNAL TRANSLATION 2-4	EXTERNAL SENSOR 4	
	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL
	SET ALL	SET ALL	SET ALL	SET ALL	SET ALL
	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL
	TEST COMMAND	00010000	00000000	00000000	00000000
	VOLTAGE MASK	DISTANCE MASK	KINEMATIC MASK	NORMAL MASK	MATRIX MASK

Figure C.5 : External Sensor 1 Voltage Command

For these types of commands, the buttons are deactivated and serve merely as a visual aid, however, due to the large possibility of combinations available from 8 sensors, i.e. 256, it was not practical to implement each of these combinations in code as its own command and therefore an additional set of commands were created to allow for the manual selection of the data to be requested. These commands take advantage of the packet structure described in section 5.4.1 to include an eight bit mask indicating what information should be retrieved. When a command allowing for the selection of information is selected, such as “CMD_DATA_GET_SENSOR_NORMALS” which clearly indicates that additional “data” is required, the buttons in the normals column are activated and can be selected one by one, or with the help of the additional 3 convenience controls at the bottom of the column, i.e. toggle all, set all and clear all, can be quickly selected in groups. The bit mask is directly related to which of the provided buttons have been activated. An example of this is shown in Figure C.6, with 3 sensors

selected, one from the internal set and 2 from the external set. It should be noted that no information requests are sent from the selection of the commands and selection of the sensors unless the “test command” button is pressed after a connection has been established. As mentioned above, the command selection process is also directly coupled with the display view which is able to generate similar data requests to the compliant wrist and display the retrieved information in the available formats depending on the type of information requested.

COMMAND TESTING					
COMMANDS	VOLTAGES	DISTANCES	KINEMATICS	NORMALS	MATRICES
CMD_DATA_GET_SENSOR_NORMALS	INTERNAL SENSOR 1	INTERNAL SENSOR 1	INTERNAL X ROTATION	INTERNAL SENSOR 1	INTERNAL MATRIX
	INTERNAL SENSOR 2	INTERNAL SENSOR 2	INTERNAL Y ROTATION	INTERNAL SENSOR 2	EXTERNAL MATRIX
	INTERNAL SENSOR 3	INTERNAL SENSOR 3	INTERNAL TRANSLATION 1-3	INTERNAL SENSOR 3	
	INTERNAL SENSOR 4	INTERNAL SENSOR 4	INTERNAL TRANSLATION 2-4	INTERNAL SENSOR 4	
	EXTERNAL SENSOR 1	EXTERNAL SENSOR 1	EXTERNAL X ROTATION	EXTERNAL SENSOR 1	
	EXTERNAL SENSOR 2	EXTERNAL SENSOR 2	EXTERNAL Y ROTATION	EXTERNAL SENSOR 2	
	EXTERNAL SENSOR 3	EXTERNAL SENSOR 3	EXTERNAL TRANSLATION 1-3	EXTERNAL SENSOR 3	
	EXTERNAL SENSOR 4	EXTERNAL SENSOR 4	EXTERNAL TRANSLATION 2-4	EXTERNAL SENSOR 4	
	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL	TOGGLE ALL
	SET ALL	SET ALL	SET ALL	SET ALL	SET ALL
	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL	CLEAR ALL
	TEST COMMAND	00000000 VOLTAGE MASK	00000000 DISTANCE MASK	00000000 KINEMATIC MASK	01100010 NORMAL MASK

Figure C.6 : Manual Normal Selection Command

C.2 Display View

Once a connection has been established with the compliant wrist, the application then makes available additional screens such as the display view. The display view, shown in Figure C.7, was developed to allow the user to visualize the information being retrieved from the compliant wrist both through the help of 3D simplified displays as well as text fields reporting numerical data. It accomplishes this by repeatedly sending the selected command and from the setup view and parsing the retrieved information according to the protocol established for each command.

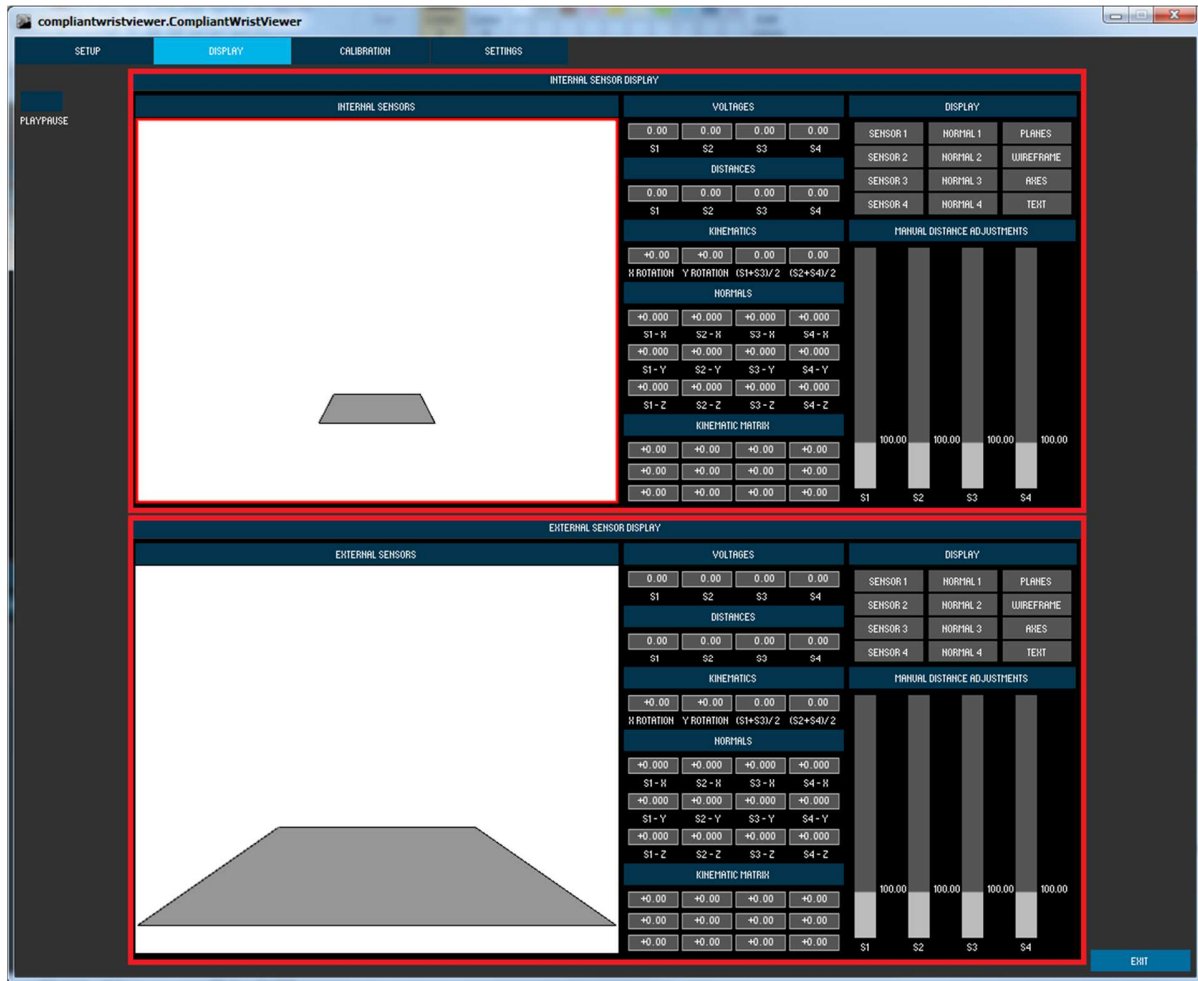


Figure C.7 : Display Screen

C.2.1 Real-Time 3D Display

The display view in Figure C.7 is divided into two sections shown by the large red rectangles delimiting the upper section, for the internal sensors, and the lower section, for the external sensors. Both sections have a viewing window on the left which animates, in real time, the information being received in the form of a rudimentary 3 dimensional mock-up of the compliant wrist structure. The display is referred to as a viewing window since the view point seen of the display can be fully customized through the use of a combination of keyboard keys and mouse clicks to rotate, zoom and translate the view point allowing for the careful inspection of the entire scene. The displays are activated via a small button control shown in the top left corner of the screen with the caption PLAY/PAUSE. When the button is toggled on, the application begins the continuous loop of data requests corresponding to the command selected in the setup view described in section C.1. As the information is

received by the PC, the displays are updated with the most current data available. The most useful information that can be retrieved however, in terms of the visual display, is the distance estimates from the sensors. This is due to the fact that all other parameters, such as the normal vectors, the rotations as well as the transformation matrices, are derived from the distance estimates and are somewhat more difficult to interpret visually. The application is also able to replicate, based on the previously retrieved compliant wrist settings, all of the calculations performed on the compliant wrist allowing it to provide the best possible description of the compliant wrist's current state depending on the actual data being retrieved. Retrieving the rotation values about the X and Y axes, for example, would not allow for the application to infer, or calculate, sensor distances solely from this information. The most that could be discerned from the rotation values is the difference in distance estimates between two sensors. However, if the distance estimates from the sensors are requested, since the application initially acquired the compliant wrist's settings, all of the kinematic information represented by these are calculated by the application and displayed as well.

Figure C.8 shows an example of all the possible information that can be included in a single display when distance estimates are being requested from a set of IR sensors of the compliant wrist. Before continuing with an enumeration of the different types of information contained in the display, it is useful to explain how the compliant wrist structure is represented in the display. Although units have been omitted in the displays themselves, voltage values displayed are in millivolts, distance values are in millimeters and rotation angles are in degrees.

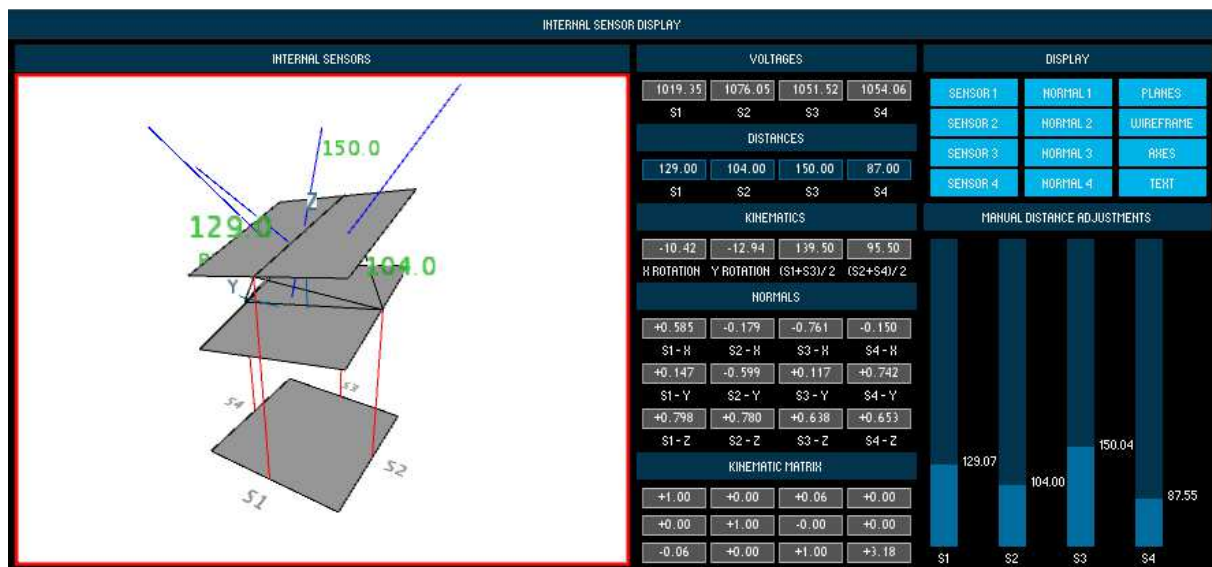


Figure C.8 : Display View with Complete Visual Information

Firstly, a gray square represents the reference frame associated with a single set of the compliant wrist's IR sensors, either internal or external as the case may be, and remains fixed in the display's frame of reference. In order to represent what the sensors are detecting, be it the movable plate of the compliant wrist by the internal sensors or the surface of a detected object by the external sensors, not one, but 3 moving squares are provided in each of the displays. Two of these moving squares are gray and a third is red. The reason for using 3 squares is related to the attempt at describing planarity discussed in section 5.3.3 which resulted in two separate calculations for the translation using the average distance from pairs of sensors as well as another calculation using information from all four sensors in a set, either internal or external. Rather than placing a single gray square at a distance equal to the average of the 4 distance estimates of the sensors, which could be misleading to the user as this could be interpreted as a planar surface, two gray squares were used with each one positioned in the virtual space according to the average distance of two distance estimates corresponding to a pair of sensors aligned along a single axis. Only when the detected surface is planar (under the assumptions made in section 5.3.3) will these squares appear to be coplanar in the display. The third red square is only displayed when the two gray squares are approximately coplanar, i.e. their center distances differ only by a small amount. The two conditions of a non-planar configuration and an approximately planar configuration are illustrated in Figure C.9 and Figure C.10, respectively.

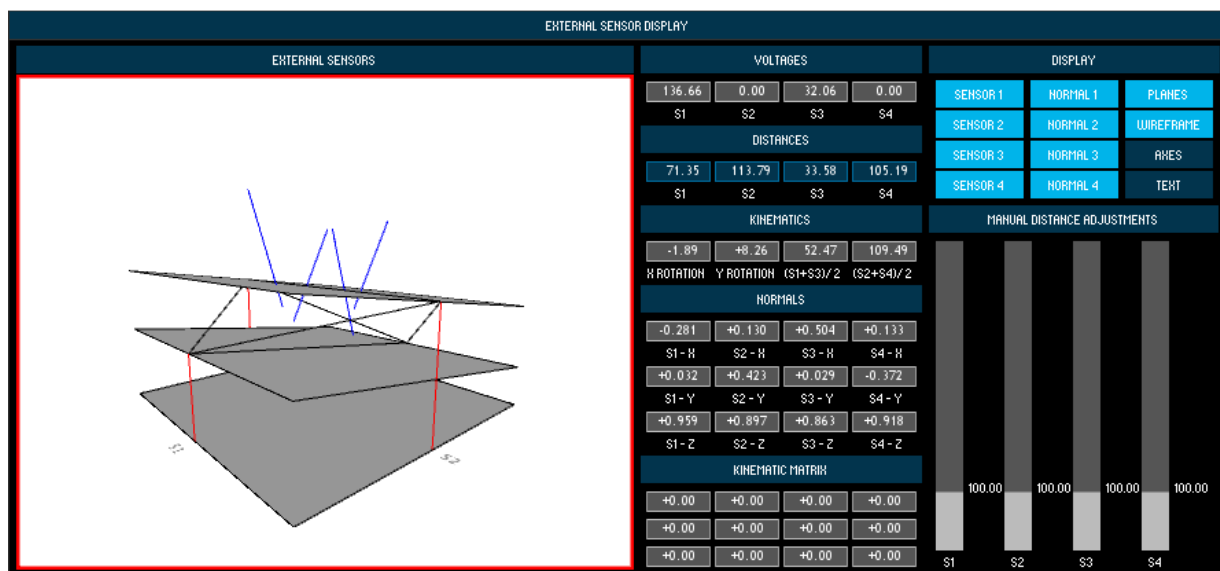


Figure C.9 : Display View of External Sensor Distances Illustrating a Non Planar Configuration

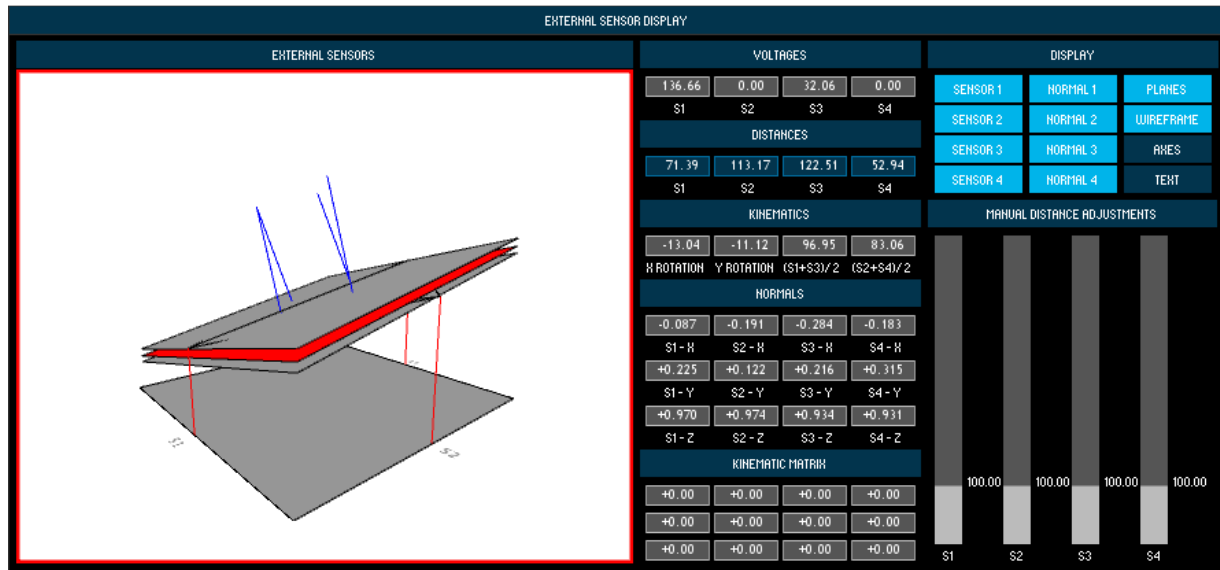


Figure C.10 : Display View of External Sensor Distances Illustrating a Near Planar Configuration

This difference in distance which causes the red square to either be hidden or displayed is currently set to a fixed value in the application. When the red square is displayed it appears at a position between the two gray squares and it is effectively positioned at the average distance of all the sensors providing the user with a visual cue to determine if the surface is approximately planar. This simplified representation of the compliant wrist was inspired by the physical appearance of the device.

Coming back to Figure C.8, it is now possible to address all of the additional information which can be overlaid onto the compliant wrist model. In order to determine how the device is positioned in the display, the labels S1, S2, S3 and S4 are added to the perimeter of the fixed gray square representing the base of the device to indicate the proper orientation. These labels also serve to indicate which of the compliant wrist's sensors are generating the associated data. Also to help with orientation is a small set of axes, showing the orientation of the reference frame associated to the compliant wrist's sensors. These axes were positioned at a fixed offset in the Z direction in an attempt to avoid having too many visual cues overlap and interfere with the interpretation of the pertinent sensor information. By default, when the application is first initialized, the display begins with the Z axis of the compliant wrist pointing upwards. Vectors representing the distance measurements of the individual sensors as well as a wireframe connecting the tips of these vectors are also included. The distance measurement vectors are red in color, synonymous with the beams of infrared light emitted by the actual sensors while the wireframe is colored black. The wireframe represents the four planar surfaces which can be derived from combinations of 3 sensor distances as discussed in section 5.3.1. The blue lines projecting from the

planar surfaces are the normal vectors describing their orientation. Figure C.9 and Figure C.10 also show how it could be difficult to infer planarity from only the normal vectors depending on the orientation with which the model is viewed. Finally, the green text in the figure shows the current distance values of each sensor in millimeters.

Each of the 12 buttons shown in the upper right hand corner of Figure C.8, in the section with the “Display” heading, allow for the selection of the desired information to be included in the display. These toggle controls are mutually exclusive and the display can be configured to show as much or as little information as desired. The display of each of the individual distance estimate vectors as well as each of the normal vectors can be turned on or off and these correspond to the first column and second column of controls respectively. The third column of controls allows, in order of top to bottom, to turn on or off the display of the moving planes, the wireframe, the axes and the numerical distance text.

These controls were included out of necessity as there are certain situations where not all of the information can easily be viewed such as in the case of Figure C.11. This figure is illustrating the “at rest” condition of the device and will be discussed shortly. By allowing the user to select which information should be displayed, it greatly increases the visual feedback as unwanted information or information which is not pertinent to the current situation is not creating additional distractions.

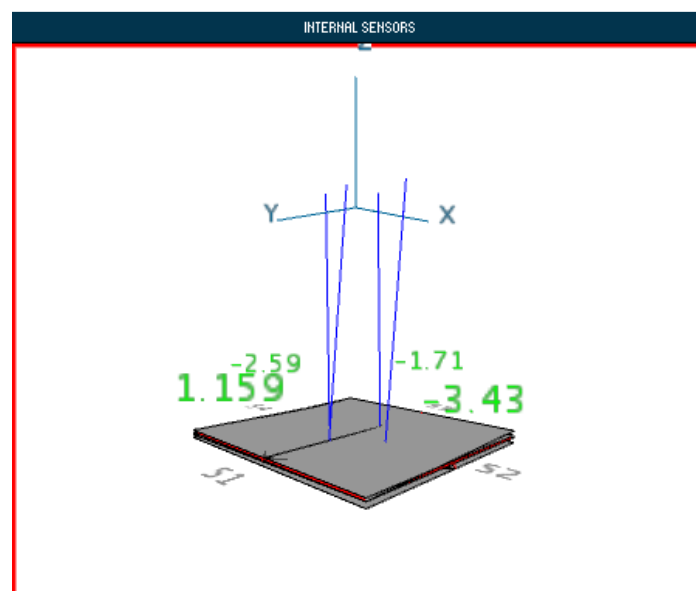


Figure C.11 : Display View with Complete Visual Information (at rest condition)

Other examples of how the display can be configured are shown in Figure C.12 and Figure C.13 which shows how only the vectors representing the sensor distances can be selected and also how all of the normal vectors, the wireframe mesh and the small reference axes can be selected, respectively.

Again, it should be noted that, most of this information is not displayed when data other than the distances are requested from the compliant wrist. For example, if the normals are being requested, these will in fact be displayed. However, the sensor distances which led to these normals cannot be inferred by this information unlike the rotations about the x and y axes which can be inferred as this is essentially contained in the description of the normal vectors. In such cases, additional information will be displayed, given that the proper buttons have been activated.

In order to further clarify the visual displays, it should be noted that the text fields displaying numerical data will change in color depending on which data is being requested from the compliant wrist. A blue text field indicates that the application is querying the compliant wrist for that particular data while a gray text field indicates that the data being displayed is not actively being retrieved from the compliant wrist. In general blue text fields will have continuously changing values as new data is acquired from the compliant wrist while the gray text fields will display the last retrieved value. However, in the event that data can be calculated from the retrieved values from the compliant wrist, e.g. the sensor distances, some of the grayed out text fields will also be updated continuously from the calculations made on the retrieved data. An exception to this is the text fields representing the kinematic matrix which is not updated when retrieving sensor distances as it offers no new information as this has already been captured by the text fields representing the kinematic information such as rotations and translations. This accounts for the disconnect between some of the displayed voltage values and distances in several of the figures as the voltage is not inferred from distances and the voltage values displayed were retrieved at an earlier point in time.

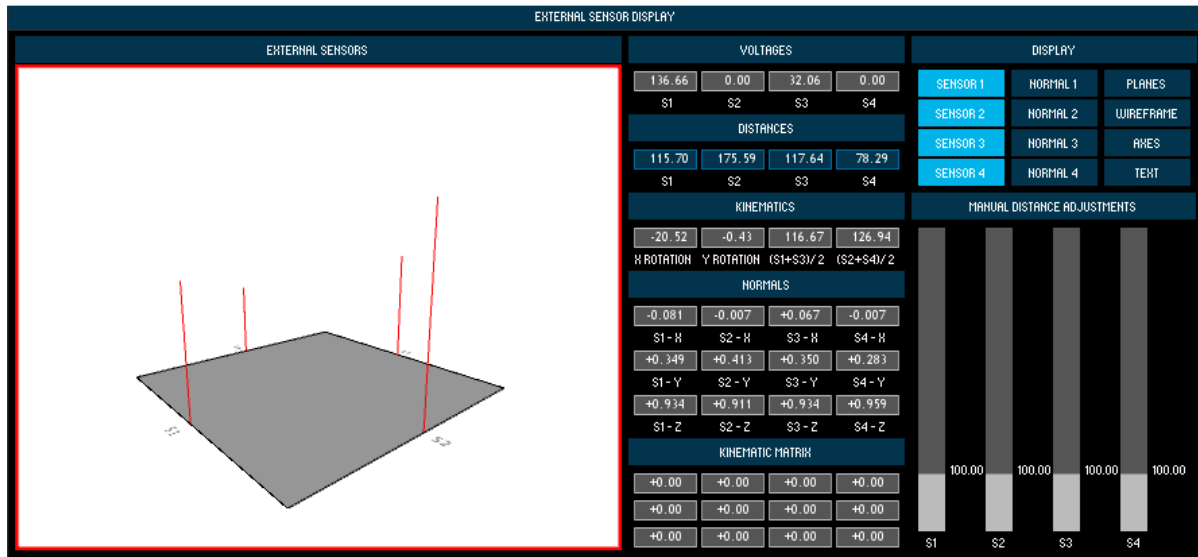


Figure C.12 : Display Toggles (Distances Only)

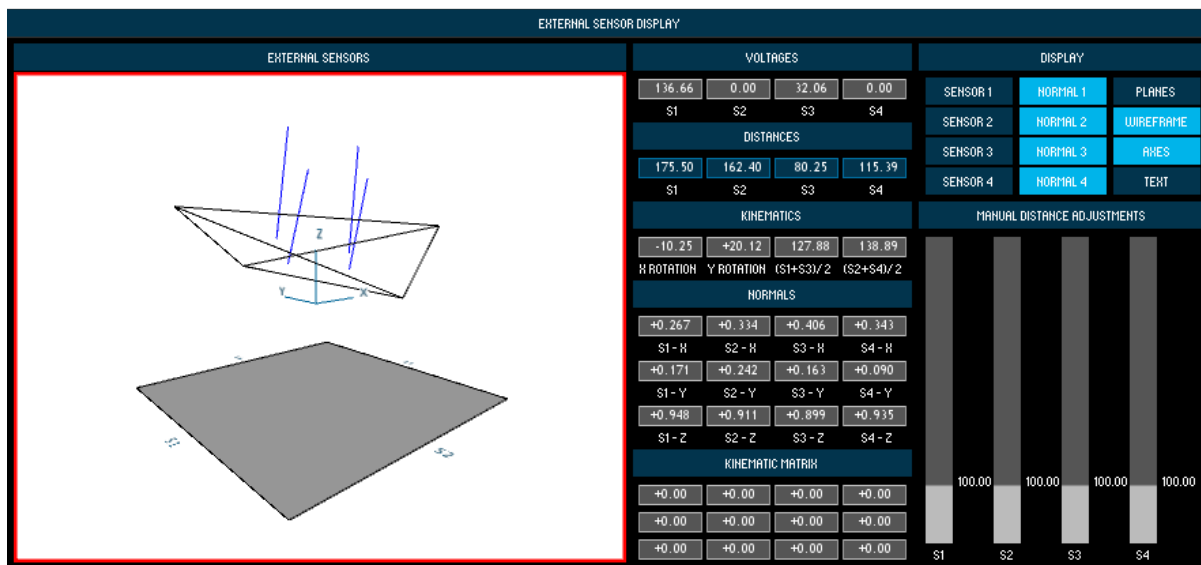


Figure C.13 : Display Toggles (Normals, Wireframe, Axes)

As mentioned previously, Figure C.11 represents the “at rest” state of the internal sensors. In order to produce the final distance estimates the microcontroller subtracts the physical distance offset present between the sensors and the movable plate of the compliant wrist from the converted voltage values obtained from the sensors. This results in measured distance estimates of approximately 0 mm (ideally) when the compliant wrist is in equilibrium, i.e. when no external forces have been applied to the mechanical structure. This is represented in the display by the fact that the three moving squares (the 2 gray and 1 red) are overlapping the fixed gray square. It should be noted that some of the values illustrated by the green text for the distance estimates in are in fact negative. These values are a result

of the small differences in the amount of tension applied to each corner of the movable plate which caused the plate to not be perfectly parallel with the fixed plate of the compliant wrist. This is an issue arising from manually adjusting the length and tension of the bungee cords. More accuracy would be obtained from using carefully machined springs of equal length to ensure equal distances between the plates when in the equilibrium state.

The subtraction of the offset was done in order to transform the information coming from the sensors to values which corresponded with the physical structure such that if any forces result in the movable plate becoming nearer to one of the sensors a negative value indicating compression has occurred. This type of information is more readily useful for a robot controller as this can be interpreted as contact and the transformation matrix associated with the data coming from the sensors would be properly interpreted. The subtraction of the offset is essentially the pure translation in the compound transformation matrix of equation 5.7.

The visual display feature was solely responsible for allowing the detection of the improper operation of the compliant wrist when the IR sensors were misaligned. Due to its correct implementation, the visual display showed how physical rotations about one axis caused the outputs of the misaligned sensors along that axis to have very different values. Had only text been used to interpret the operation of the compliant wrist, this behavior could have gone unnoticed leading to poor and possibly dangerous performance during robot control operations.

C.2.2 Numerical Displays

In order to provide a full account of the compliant wrist's current state, all of the numerical data retrieved from the compliant wrist is organized by section and displayed as text to the right of the viewing window. Again, the values which are updated depend entirely on the command that was selected in the setup view. To draw attention to which command was selected, the text fields are highlighted by a change of color from gray to blue. The sections include voltage, distance, kinematic parameters such as rotation and translations, normal vectors shown by component and transformation matrices (excluding the fourth row of such matrices which consists of the constant values $[0\ 0\ 0\ 1]$). The text shown is updated continuously when the user activates the data requests and new values are received.

C.2.3 Manual Controls

The manual controls are remnants of the earlier phases of the development of the application's visual interface. These come in the form of sliders which are used to manually set the distances of each sensor. These have been kept in place for code testing purposes in the event that changes are made to specific algorithms. Having a means of directly testing the resulting values from calculations without being physically connected to a compliant wrist to generate the necessary distances has been a valuable tool in the development of the application. In order to use these manual controls, the "MANUAL" command needs to be selected from the command selection menu.

When the command is selected, the sliders are unlocked and can be adjusted to any desired value within the available range set in the code. This range is set in accordance with the maximum values capable of being measured by the sensors. It should be noted that no actual data requests are sent to the compliant wrist when this command is selected and is used solely for informing the application of the user's intent to control the sliders. Figure C.14 shows a random placement of each slider used to control the internal sensors. The display reflects the adjustments made to the sliders as well as the fact that the object being represented by these distances is far from a planar surface. Each set of sensors can be controlled individually as each half of the display view comes equipped with controls associated with the sensors being represented.

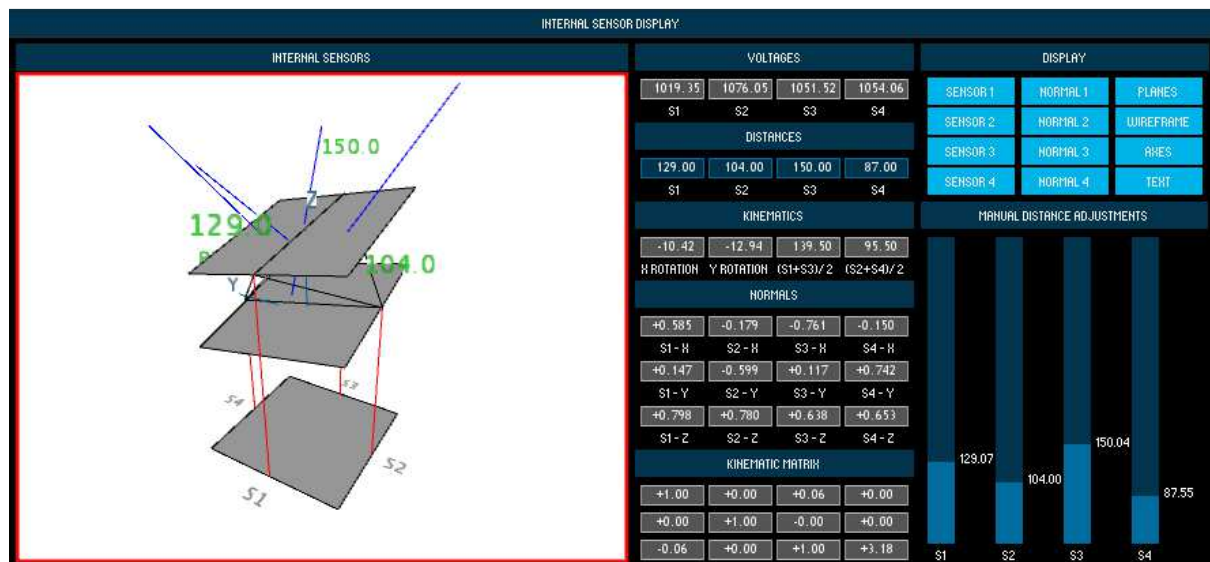


Figure C.14 : Manual Distance Control

C.3 Calibration View

The need for a more rapid and efficient means of performing the calibration procedure described in section 5.1.2 resulted in the incorporation of a dedicated group of controls for this task into the application. The view shown in Figure C.15 is divided into four sections. The first section, located under the heading “Flash Memory Access”, provides a single control which verifies whether or not the application can access the microcontroller’s onboard flash memory. The functions used to implement the necessary access to the flash memory came from a third party library whose documentation required this verification procedure prior to manipulating the actual flash memory as this would determine if the data will be properly stored or retrieved during successive memory access related commands. This onboard memory provides an effective means of storing a small amount of settings data which is persistent on the device between power cycles. It is in this memory that the sensor calibration results are stored, as well as all of the data acquisition and filter settings which are manipulated on the settings view, that will be discussed in the following section.

The second section is the voltage offset adjustment control panel, which provides multiple sliders for manual adjustments of the voltage offsets as well as text fields providing both a means of displaying the current voltage offset as well as allowing the user to enter a desired voltage offset via a keyboard. Manual entry is useful in the event that previously recorded settings are desired to be input since any reprogramming of the microcontroller on the compliant wrist effectively erases all settings in memory. Rather than recalibrating the device, the only thing which is required is to enter the individual offsets for each calibration position of each sensor, assuming that the values were previously recorded elsewhere.

The third section consists of text fields showing the voltage and distance values of each data point for which the calibration will be performed. The values shown in Figure C.16 are the same as the ones found in Table 5.2. These too can be adjusted as desired if different calibration points are preferred for a particular task. The application uses the values found in the sensor’s datasheets as the default however, by allowing the calibration points to be altered, the device could be calibrated for use with a variety of different IR sensors.

The fourth section is an active graph, showing the effective sensor response curve. The blue circles are positioned horizontally at the distance values of the selected calibration points while their

vertical positions correspond to the sum of the voltage values of the calibration points and the respective voltage offset values set via the sliders or manually entered in the text fields.

Before any of the commands accessing the flash memory become available to the user, it must be determined if the settings will be properly stored or retrieved. This is done by sending a command packet to the microcontroller indicating that memory access is desired; the response to this command will inform the application whether or not the flash memory is currently available for use. To send this command, a click of the “Access Memory” button suffices. If the memory is available, the application then makes the sensor selection menu available. The sensor selection menu is located to the right of the slider controls and determines which sensor will be affected by the settings.

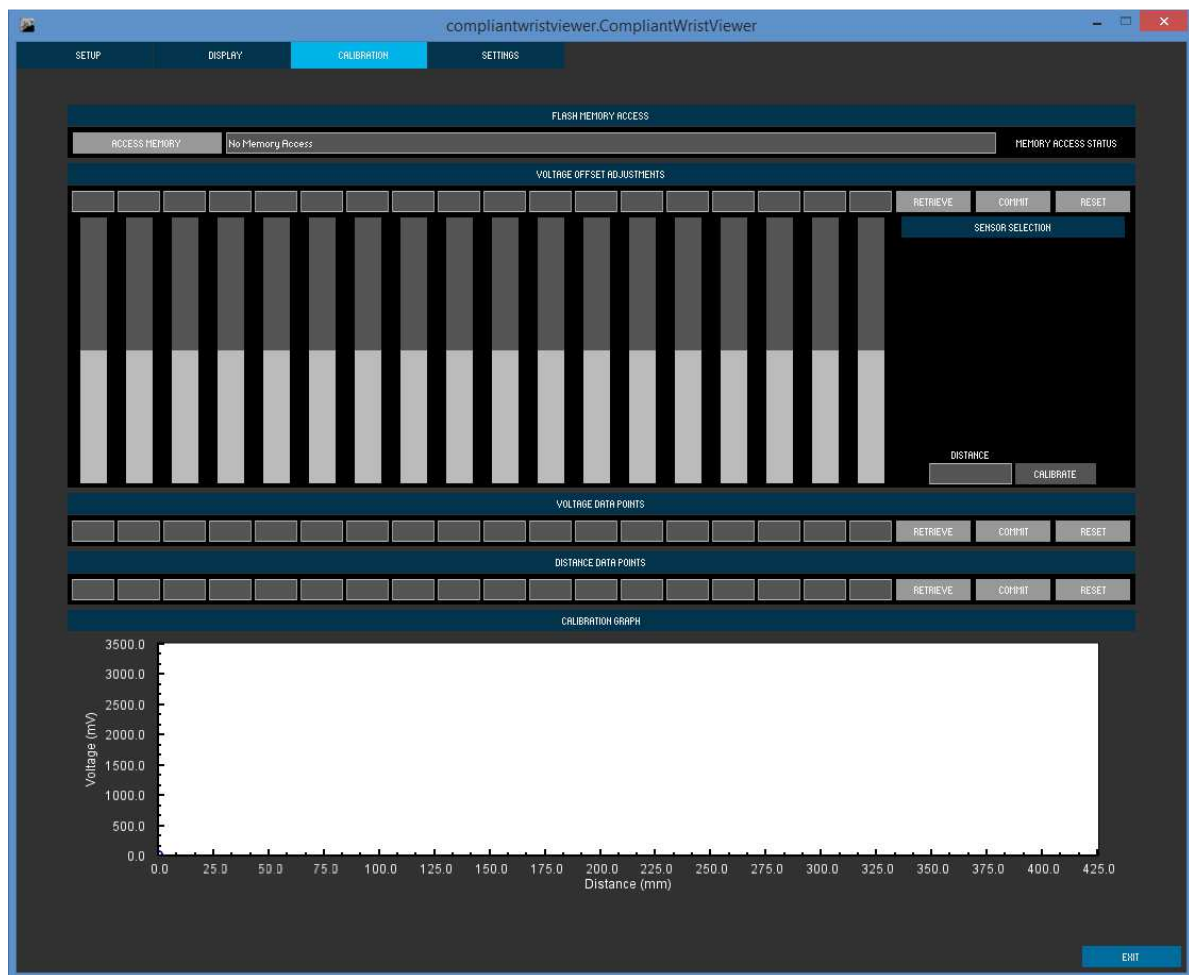


Figure C.15 : Calibration Screen

Before a sensor has been selected, the calibration view has practically all of its controls deactivated since these require knowledge of a particular sensor in order to function as expected. Again,

visual cues such as changing the color of controls and mouse pointers are used to lead the user through the operation of the application. The general theme is that grays and whites are meant to indicate that controls are unusable while blue colors indicate that the controls are active. Figure C.16 shows these visual cues in action in the calibration view after the first internal sensor has been selected by changing the color of many controls and displaying additional controls.

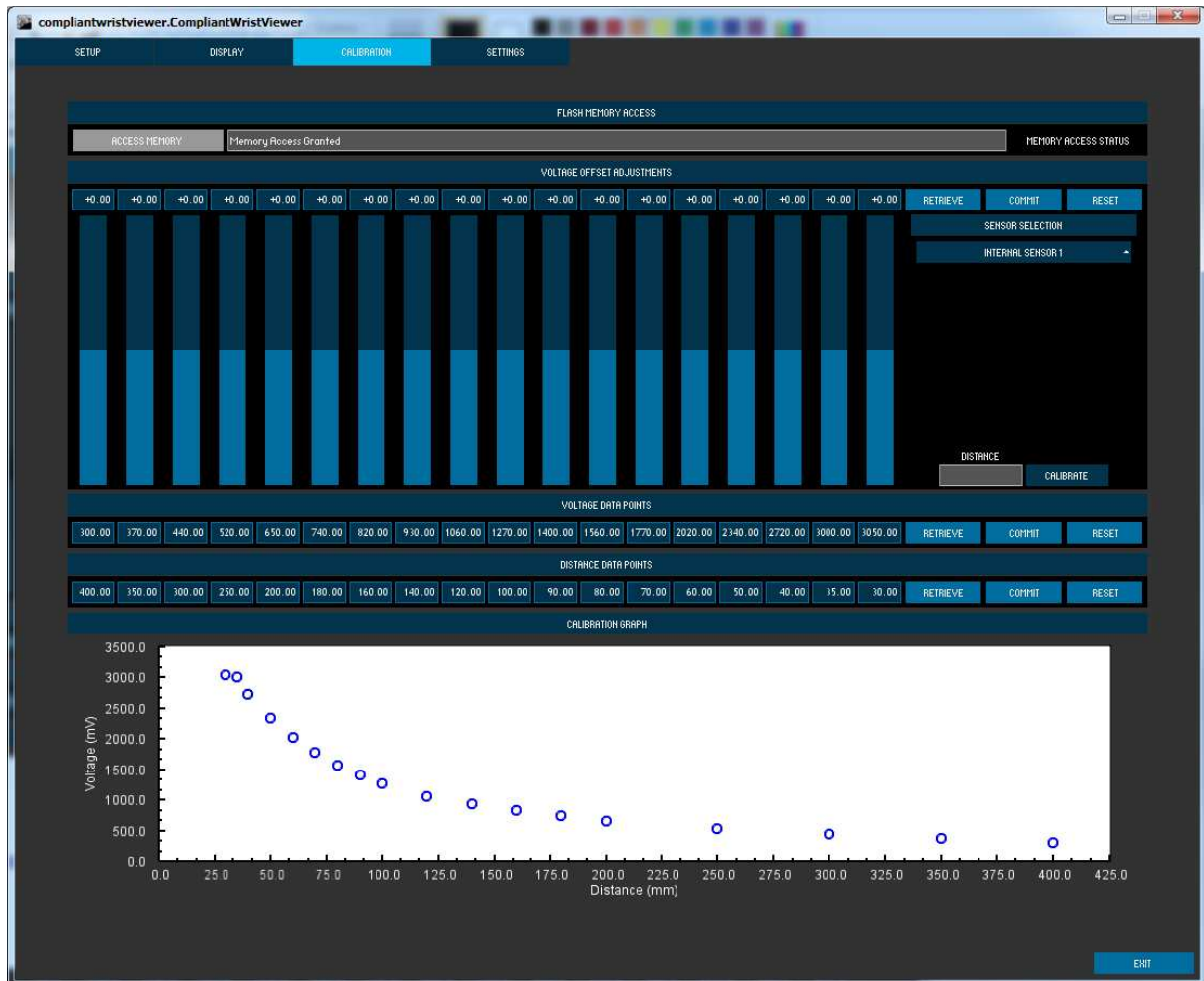


Figure C.16 : Uncalibrated Settings of Internal Sensor 1

In the example of Figure C.16, we can see that the sensor has yet to be calibrated since the voltage offset adjustments are all reading 0, an unlikely occurrence for a calibrated sensor. The slider controls also reflect this fact as they are centered at 0 between their maximum positive value and minimum negative value. A more likely scenario for a calibrated sensor is that shown in Figure C.17. In this case, the third internal sensor was selected from the sensor selection menu.

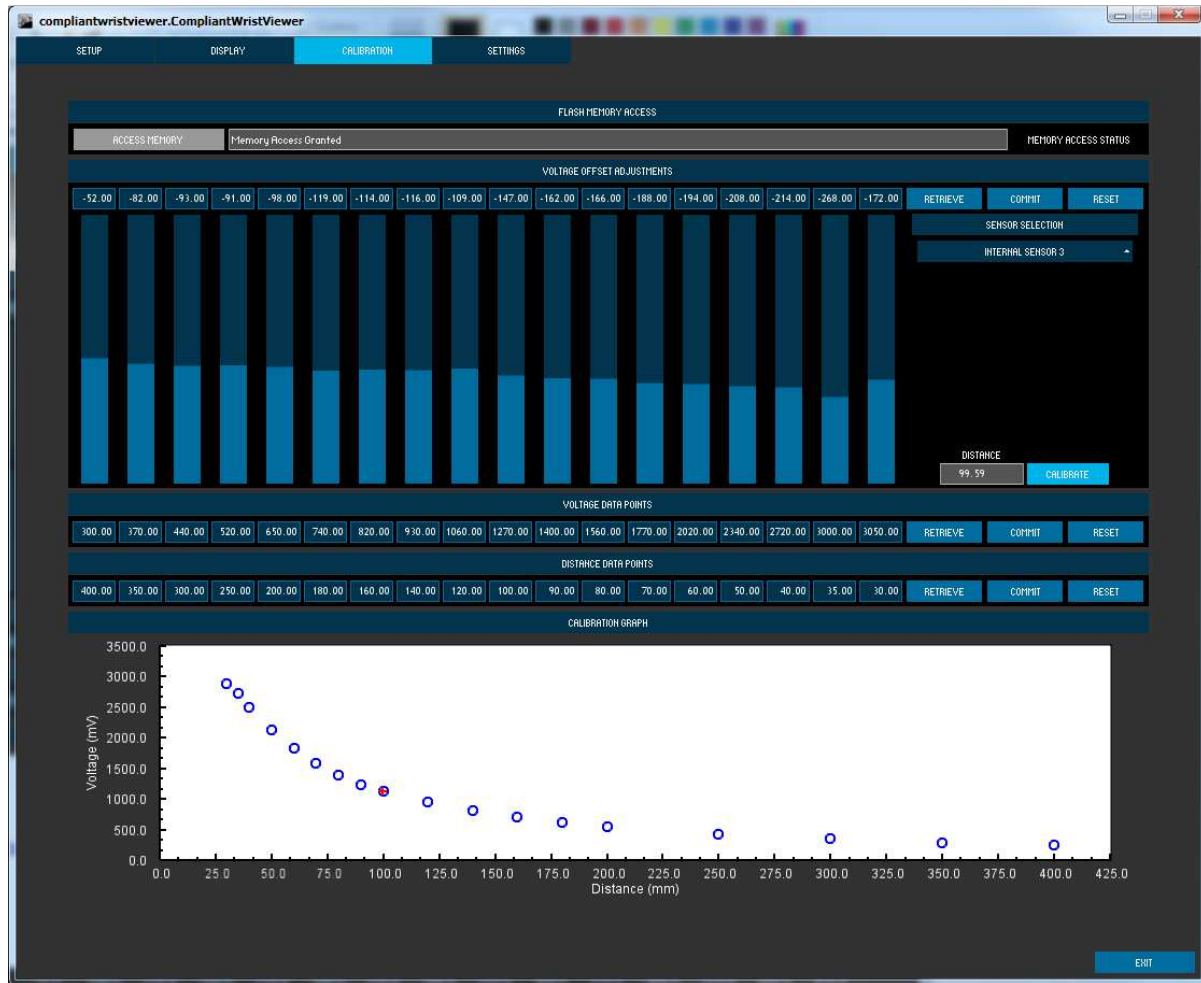


Figure C.17 : Calibration of Internal Sensor 3

In order to calibrate a sensor, the procedure described in section 5.1.2, or an equivalent one, should be used. Any device which can be used to produce controlled and known distance variations of a planar surface positioned in the path of the sensors is adequate for this task. The accuracy of the compliant wrist system depends greatly the accuracy of the system being used to calibrate the sensors. Although the entire process could have been automated for the motorized track used in calibrating the sensors, as it was powered by a similar microcontroller device which accepted commands via a serial port, it was decided to keep the two processes separate in order to maintain a degree of generality and not create a dependence on specific hardware to accomplish such a critical task.

Once the necessary physical setup has been achieved the application allows for a step by step calibration of the selected distance data points. The procedure begins with placing the target planar surface in front of the sensors at the initial distance to be calibrated. This is where the accuracy of the

device being used to set and report the ground truth distances comes into play. The application indicates the distances at which the calibration device should be positioned and the voltage values generated by the sensors which are expected to produce these distances in the conversion process. It is up to the calibration device to ensure that the position of the target surface is in fact at the selected distance in order for the calibration to succeed.

Once the target surface is in position, each sensor should then be selected one by one from the sensor selection menu in order to adjust the voltage offset to a value which will produce a voltage to distance conversion that matches the set distance indicated by the calibration device. During the calibration procedure, activating the calibrate button, located directly below the sensor selection menu, begins continuously sending data requests from the compliant wrist to obtain live information regarding the effective distance being estimated by the selected sensor.

The requested information in this case are the voltage values produced by the sensors rather than the distance estimates. The reason this is done is because of the fact that the voltage offsets are stored in the flash memory. According to the documentation provided by those who implemented the library used to interact with the microcontroller's flash memory, this type of memory has an effective limit of how many times data can be written to it (in the range of several thousands of times) before it becomes physically degraded. This prevented the application from continuously updating the voltage offset values directly on the microcontroller during calibration. Therefore, to limit wear on the device, instead of having the application update the calibration settings after each modification of the values, special controls were created to retrieve and upload the sensor settings, as well as reset them to their default values which were hardcoded in the microcontroller. These are provided next to each set of text fields and are labelled "Retrieve", "Commit" and "Reset", respectively.

Since the microcontroller cannot be continuously updated with the sensor settings, the voltage values are requested from the microcontroller and converted by the application using the same spline interpolation technique as the one implemented on the microcontroller. The application is able to do this due to the fact that upon initial connection to a compliant wrist, all of the calibration settings for the sensors are retrieved and stored in the application's memory. In order to produce the live distance estimates, the voltage offset values are applied to the corresponding voltage information of the calibration points prior to conversion so that the distance estimates being reported take these into account.

The application displays this distance information in two ways. The first is a text field which displays the converted distance numerically and the second comes in the form of a plot which provides a visual comparison of the distance estimates of the sensors with the desired distance for the selected calibration position. The information contained in the plot consists of the calibration data points and the reported distance estimates from the selected sensor. The vertical axis is voltage expressed in millivolts (mV) while the horizontal axis is distance expressed in millimeters (mm). The plot was inspired by the voltage to distance conversion curves such as the one seen in Figure 5.2. The 18 calibration data points are represented by the blue circles. When the calibrate button is activated, a red cross also appears in the plot and this represents the current distance estimate resulting from the effective voltage produced by the sensor.

As the voltage offsets are adjusted the plot changes along with them such that a positive offset will raise the corresponding blue circle by an equal amount in the plot, and a negative offset will lower the circle. When actively calibrating, and assuming the voltage produced by the sensor is in the range of data points being used to interpolate the distance estimate, the red cross will move along the interpolation curve. The reason for using blue circles and a red cross was because as the offsets are adjusted, when the proper voltage offset has been found, both the adjusted voltage produced by the sensor and the distance estimate should match the modified voltage data point and calibration distance. This is represented in the plot by having the red cross align with the blue circle of the corresponding calibration distance. This makes the plot a very useful visual aid during the calibration procedure and essentially reduces it to a simple task of placing the red cross in the blue circle target associated with the physical distance of each calibration point. Figure C.17 shows an example of the red cross centered on the blue circle at a distance of 100 mm which, assuming a ground truth distance of 100 mm for the target surface, indicates that this particular position has been properly calibrated.

It should be noted however, that since the voltage data coming from the sensors is very erratic in its raw form, the task of finding the correct offset could have been somewhat challenging. It was decided that signal averaging should be applied to the voltage values, using the implemented filter module, in order to stabilize the variations in the signal thereby reducing the jitter seen in the position of the red cross in the plot as well as the numerical display.

C.4 Settings View

As mentioned previously, there was some concern regarding the statistical characteristics of the sensors and how this should be approached in terms of signal processing. The implementation of the digital filters, described in section 5.2.3, led to a very versatile module which could generate a wide variety of filters based on multiple parameters. Due to the large number of combinations of these parameters, it was not feasible to reprogram the compliant wrist's microcontroller with new parameter values to test the sensor's behavior. This led to yet another collection of controls to manipulate the filter settings. Also, since the device had gone through some physical modifications causing the positioning of the IR sensors to change, it also seemed more practical to include controls which would allow the position of the sensors to be set without requiring the compliant wrist's microcontroller from being reprogrammed should the need arise.

The settings view, shown in Figure C.18, provides the controls required for the manipulation of the data acquisition system's sampling frequency, the sensor filter properties, the physical coordinates of the sensors on the compliant wrist, the moveable plate dimensions as well as controls for recording data onto optional storage media such as an SD card. The last set of controls, dealing with the SD card, was only included in the application due to the need for collecting and storing sensor data for characterization and validation purposes. Provisions for an SD card to be connected to the microcontroller came in the form of yet another commercially available shield and third party libraries which allowed for the permanent storage of collected data. Again, it should be noted that the SD card functionality is not essential to the operation of the device and is rather application specific to the data analysis task described in this work and was therefore not presented alongside the electronic components in section 4.2.

As mentioned previously, due to the fact that the settings manipulated on this view are saved to the microcontroller's flash memory, the same type of control scheme used in the previous calibration view was adopted to communicate changes of the settings to the compliant wrist.

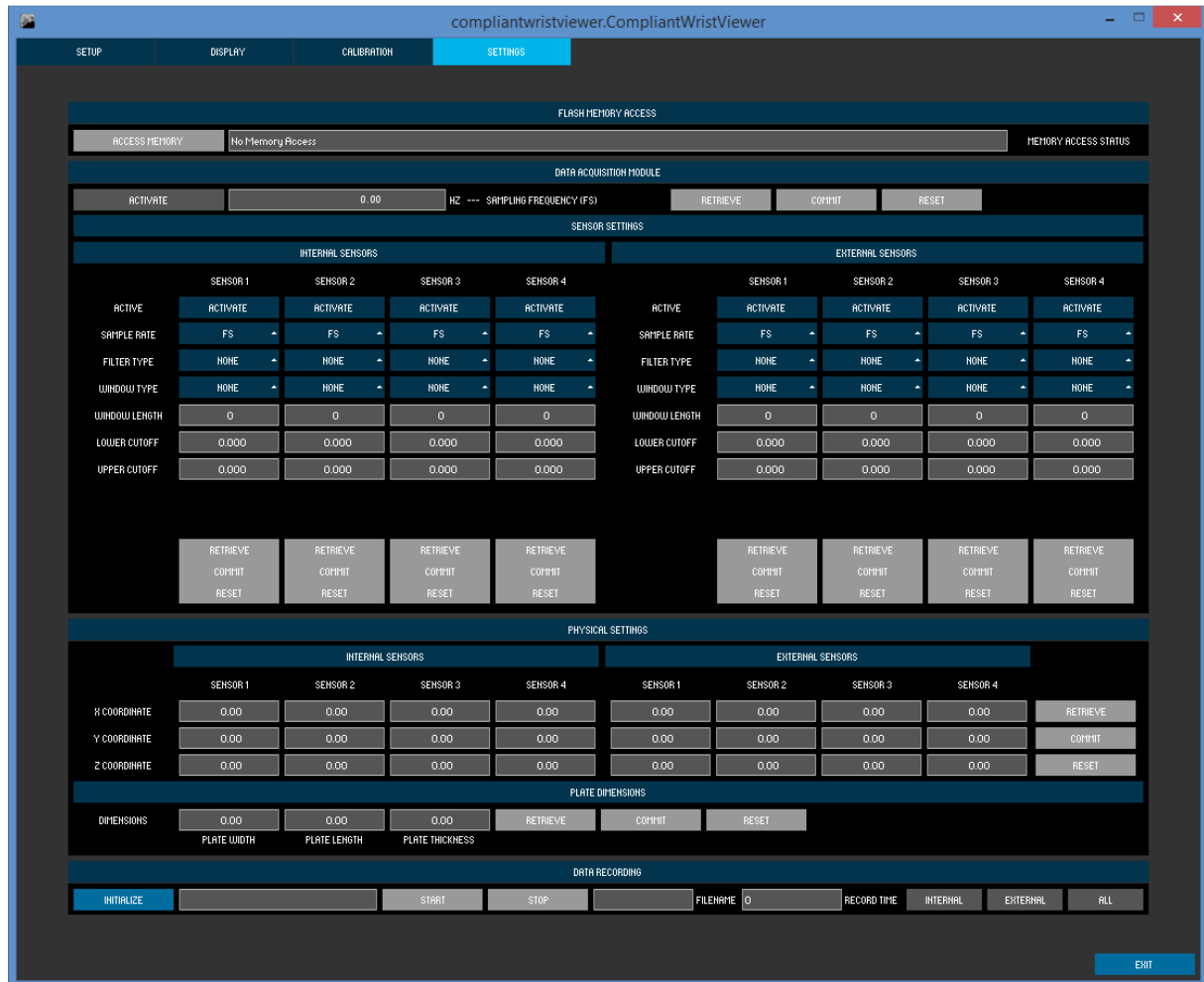


Figure C.18 : Settings View

The first set of controls provided at the top of the view is a copy of the controls found at the top of the calibration view and is used to determine if memory access is available. Once it has been determined that the microcontroller is ready to accept memory related commands a text field will display that this is so. The next set of controls consists of a toggle button to activate or deactivate the data acquisition system, a modifiable text field for entering the desired sampling frequency of the system and three button controls used to retrieve, save and reset the selected settings. The sampling frequency can be set arbitrarily however, the true sampling frequency of the system might not be the exact frequency entered into the text field. Depending on the selected frequency, an algorithm selects the necessary settings for the timing circuitry which generates the sampling interrupt. Since there are a total of 8 sensors, the sampling frequency for the ADC is also multiplied by a factor of 8 to account for this as the output of the sensors are sampled sequentially.

The settings for the filters which are applied to the sensor voltage outputs are manipulated in the largest section of the screen. The following controls are provided for each sensor: a toggle button to activate or deactivate the sensor, a dropdown menu for selecting the effective sampling rate, a dropdown menu for selecting the filter type, another menu for window type, and three modifiable text fields for entering the window length, the lower cut-off frequency and the upper cut-off frequency as well as the button controls for dealing with the three memory commands used to upload, retrieve and reset the filter settings. These controls provide the user with full control over the behavior of the sensor sampling and filtering algorithms.

The first toggle button mentioned is used to allow the user to control whether or not the sensor will be part of the list of sensors to be sampled on every data acquisition system sampling cycle. As mentioned previously, during development, it was unclear whether or not the microcontroller would be able to perform all the necessary calculations on the full set of sensors concurrently and one option that seemed viable was to reduce the number of active sensors being sampled depending on the situation and switch between the four internal and the four external sensors. Once a sensor is deactivated, the system simply discards the sample and does not perform any further processing on the sample such as passing it through the filtering process.

The next dropdown menu, which is used for selecting the effective frequency of the sensor, provides 8 options from which to choose. These options are all dependent on the data acquisition system's sampling frequency which controls the actual sampling of the physical sensors and therefore sets the upper limit. The options provided only allow the user to reduce the primary sampling frequency by factors of 2 from FS , the sampling frequency, to $FS/2$, $FS/4$, $FS/8$ and so on, down to $FS/128$. Whenever the sensors are active and a lesser sampling frequency is selected, only the 2nd, 4th, 8th down to 128th samples, respectively, are processed with all others being discarded. This allows for varying the individual sampling frequencies of each sensor. Again, the main concern which led to the implementation of these options was the ability to process the incoming data at a specified rate to ensure that the system maintained the desired sampling frequency. One practical use for this is that it would be possible to increase the data acquisition system's sampling frequency in order to achieve a higher bandwidth for the internal sensors, where speed is important to increase the responsivity during contact between the compliant wrist and objects, while at the same time reducing the effective sampling frequency for the external sensors to compensate and ensure once again that the filtering operations aren't affecting the system's performance.

Section 5.2.3 introduced the filters and described how they are applied to the samples obtained from the sensors. The filter types available to choose from are as follows: none, window, normalized window, low pass FIR, band pass FIR, band stop FIR and high pass FIR. The first option results in the direct use of the samples to generate a final output. The window and normalized window options allow the user to select a window from Table 5.3 and apply the resulting sequence of weights directly to the samples. The difference between the two is that for the normalized window, the weights are modified so that the sum of all the weights equals 1. This normalization is also applied when any of the FIR filter options are selected and is used to maintain signal amplitude otherwise there would be signal amplification or attenuation depending on whether the weights summed to a value greater than 1, or less than 1, respectively.

It should be noted that technically any modification of a digital signal can be considered as a type of filtering. In general however, windows are rarely applied directly to a signal but are rather used in conjunction with Sinc derived FIR filters. A special exception is the averaging filter which is in fact just a normalized rectangular window convolved with the desired signal. This is why the FIR filter options also require the selection of a window in order to obtain the final filter response. The window options generally have the effect of modifying the frequency domain characteristics and are mainly used when trying to meet specific gain and roll off requirements in the transitions between pass bands and stop bands.

The window length text field sets the length of the window, in samples, for the selected filter and has a direct impact on the frequency response of the filter. Although the sampling frequency does not appear in the FIR filter coefficient generating equations, the window length does. Depending on the filter type, the lower and upper cut-off values also come into play when generating filter coefficients. The low pass filter makes use of a single cut-off value, namely the lower cut-off while the high pass filter makes use of the upper cut-off. Both the band pass and band stop filters make use of both cut-off values in order to set the range of frequencies which will be filtered out.

The physical settings section pertains to the physical coordinates of the sensors in the compliant wrist's mechanical assembly. These coordinates are necessary in order to determine the distance separating the pairs of sensors aligned along each axis in order to properly calculate the rotations based on the differences in distance estimates produced by these sensors. Instead of hardcoding these values in the algorithm, it was decided to make these values adjustable in the event that the compliant wrist

structure were to be changed as well as to compensate for any fabrication defects which could result in slight deviations in sensor placement from the design specifications. The compliant wrist is however pre-programmed with default values for the position of the sensors obtained from the construction specifications of the current prototype and should normally not need to be modified. The modifiable text fields allow for manually entering the necessary coordinates.

Also included in this section are text fields to specify the moveable plate dimensions. These were added in anticipation of additional distance estimate errors arising from the thickness of the moveable plate since the sensors measured distances from the underside of the plate while contact was being made from the top side of the plate. When the plate sits without rotations about either axis, the plate thickness can be added to the distance estimate directly to obtain the final distance. However, when the plate is rotated slightly, the effective thickness from the underside to the top side also increases slightly. Currently, the algorithm used for determining distance values adds the moveable plate thickness to the distance estimates as it was deemed that these errors would not significantly influence the results due to the size of the errors coming from the sensor accuracies. The plate width and height were included as well in order to allow the user to make use of this information in control algorithms developed in the future for more precise path planning. By knowing the moveable plate dimensions, and the distance separating the external sensors, a more complete model of the physical structure is available for obstacle avoidance and similar tasks.

With such a diverse range of controls available for manipulating the compliant wrist system's settings, this accompanying application became a very powerful development and testing tool. Initially, all of the system settings were hardcoded and any changes made to these required reprogramming of the device. As the code base grew, programming times increased and became a significant sink in development time. By dedicating time to this interface, productivity was greatly increased allowing more time for data collection and testing.

C.5 Application Programming Interface (API)

The software development also involved one final component. The companion software just described is essentially a visual wrapper for an API that was developed concurrently alongside the application for directly interacting with the compliant wrist system. The API provides the set of all commands to which the compliant wrist responds. Every time a control is used in the user interface of

the application, a function from the underlying API is called with the necessary arguments obtained from the user input in the application.

In order to incorporate the compliant wrist onto an existing robotic platform and determine the device's performance, the API was used in the robot controller algorithms developed for performing the specific tasks described in sections 6.2 and 6.3. The API was essentially used as a library in the robot controller's program to send commands to the compliant wrist to obtain data from it. In order for the API to be used, there is a requirement for an available serial port and an XBee radio module to allow the robot controller to communicate with the compliant wrist.

A robot controller would normally not require the use of the complete set of available functions in the API as the most practical functions for robot control would pertain to data retrieval from the compliant wrist. However, the provided companion application is not absolutely required to perform any of the calibration tasks or making modifications to the filter settings, as the API allows a user to programmatically make these changes. The compliant wrist's operating system was designed to run a continuous loop which both acquires sensor data for processing and waits for incoming commands from external sources such as robot controllers. Therefore, if changes are required to be made to any of the device settings, commands need only be sent using the API which adheres to the communications protocol in place.