MARMARA UNIVERSITY
FACULTY OF ENGINEERING

DEVELOPMENT OF HAPTIC TELEROBOTIC SYSTEMS

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Development of Haptic Telerobotic Systems

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ABSTRACT

Development of Haptic Telerobotic Systems

Telerobotics is a field of robotics interested in controlling robots from a distance. Incorporating visual and haptic (touch) feedback allows the operator greater accuracy in manipulating objects in a remote environment.

Haptic telerobotic systems have been interesting for surgical operations and their importance is increasing day by day. The purpose of this system is to provide more precise, faster and easier operations with minimum damage to the patient.

In our final project, we will develop 4 channel, 3 channel and 2 channel haptic telerobotic systems for linear motors. Afterwards, we will run tests on the system we have developed and see in which situations they are more efficient and stable. We will look for solutions for unstable situations.

ABBREVIATIONS

Eq: Equation

D.O: Disturbance Observer

F.C: Force Constant

PID: Proportional Integral Derivative

D.I: Damping Injection

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1 INTRODUCTION

The goal of this project is develop remotely controllable robotic systems with haptic feedback to the operator. We will develop dynamic models for linear motors and perform simulations in Matlab Simulink. We will develop bilateral (haptic) teleoperation controllers in the simulation environment first, and will then perform experiments on the robotic systems in the Intelligent Machines Laboratory.

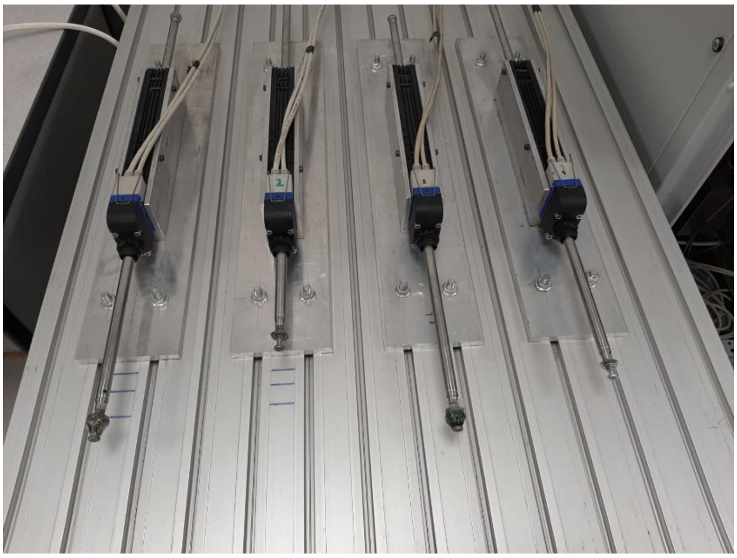

Figure 1-1: Linear Motors

2 LITERATURE SURVEY

2.1 Analysis and Design of Haptic Telerobotic System [1]

Her et al. (2001) for a 'master-slave' telerobotic dynamic system with haptic behavior, a control strategy is developed. A 'master' robot controlled by a human arm and a kinematically identical 'slave' robot stationed at a remote site make up the telerobotic system. The remote 'slave' simulates the movements in a confined or unconstrained environment when the operator moves the handler of the 'master' back and forth. The environment's disturbance and response forces, as well as the loads, are sent back to the 'master's handler and felt by the operator. As a result, the operator gets a sense of what's out there' without actually being there. The integrated dynamics of the operator arm, actuators, and environment in the closed-loop control system for stability analysis is a benefit of the provided control method. It is demonstrated that the practical and theoretical findings correspond well, and that the developed controller is resistant to load disturbances and constrained/unconstrained environments.

2.2 Analysis and Design of a Haptic Control System: Virtual Reality Approach [2]

Her et al. (2002), the analysis and design of telerobotics based on the haptic virtual reality (VR) approach for simulating the clay cutting system is proposed. The main components of the approach include a user interface, networking, simulation, and a robot control scheme. The telerobotics for the clay cutting system and the environment is simulated by a haptic virtual system that enables operators to feel the actual force feedback from the virtual environment just as they would from the real environment. The haptic virtual system integrates the dynamics of the cutting tool and the virtual environment whereas the handle actuator consists of the dynamics of the handle and the operator on the physical side. The control scheme employs a dynamical controller which is designed considering both the force and position that the operator imposes on the handle and feedforward to the cutting tool, and the environmental force imposed on the cutting tool and the feedback to the handle. The stability robustness of the closed-loop system is analysed based on the Nyquist stability criterion. It is shown that the proposed control scheme guarantees global stability of the system, with the output of the cutting tool approaching that of the handle when the ratios of the position and the force are selected correctly. Experiments in the virtual environment on cutting a virtual clay system are used to validate the theoretical developments.

2.3 Development of a Robotic Haptic Interface to Assist the Performance of Vocational Tasks by People with Disabilities [3]

Pernalete et al. (2002) The creation of intelligent mapping from a haptic user interface to a remote manipulator to aid people with impairments in accomplishing occupational activities is described in this study. This mapping, also known as an aid function, is based on an environmental model or sensory input and is used to direct the motion of a telerobotic manipulator while executing a job. The computer augments rather than replaces human input. To apply the various types of support functions aimed to boost human performance, three manual dexterity assessment tests, frequently used in the occupational therapy sector, were chosen. PHANTOM, a six-degree-of-freedom force-reflecting haptic interface device with the GHOST SDK Software, was employed as the test bed for these activities. The results showed that the different types of support offered lowered execution times and improved task performance. Furthermore, our findings imply that the inclusion of haptic rendering capabilities, including force feedback, benefits motion-impaired users by improving their performance on job-related activities.

2.4 A Telerobotic Haptic System for Minimally Invasive Stereotactic Neurosurgery [4]

Medical robotics and computer aided surgery, according to Rossi et al. (2005), are practical and promising robotic technology applications whose key aims are surgical augmentation, information enhancement, and enhanced surgical action. The advent of computers and robots to guide surgical procedures will greatly assist neurosurgery, which faces the most significant problems. This research describes a novel master slave haptic robotic system for minimally invasive neurosurgery that can assist surgeons in overcoming human limitations and performing more precise, repeatable, and reliable stereotactic neurosurgery. A slave mechatronic actuator and a haptic master make up the LANS system. The slave is programmed to move a laser pointer, biopsy needle, or low-energy X-ray emitter along a pre-determined axis in a linear fashion. The surgeon directs the tool's entrance into the brain using the haptic master, which also gives force feedback to the operator. The haptic master can not only replicate the contact force between the surgical instrument and the treated tissue, but it can also generate virtual forces to aid surgeons during operations. Experiments were carried out to show the soundness and correctness of the overall system mechanical design, as well as to evaluate the efficacy of the master and slave control methods.

2.5 Haptics in Telerobotics [5]

According to Preusche et al. (2007), the ultimate aim of telerobotic systems is transparency, which means that the human operator cannot tell whether they are functioning in a local or remote environment. To do this, the telerobotic system is equipped with all of the relevant senses, including visual, auditory, and haptic modalities. This entails study in the following areas for the haptic modality: robotic hardware, both hand controllers and teleoperators, and control elements with time delay. Both supervisory and bidirectional control are included in the latter. The current and future elements of haptics in telerobotics are presented in this study, with a focus on control research. Telerobotic systems may currently be found in a range of various application sectors, such as micro assembly, surgery, and space, thanks to the increasing technology in these study areas.

2.6 Haptic Consensus in Bilateral Teleoperation [6]

Tumerdem et al. (2007) haptic consensus is introduced in this article for networked robots, especially teleoperation systems. Distributed consensus algorithms are used in haptic consensus to require networked robots to agree on system states such as location, acceleration, and force. A haptic connection occurs when the systems agree on these states. Any force exerted on one robot is perceived by the others, and they may move in perfect unison, mimicking what a master does. The topology of a network is represented by graphs, and it is proven using graph Laplacians that the topology is highly important for the overall teleoperation system's stability. The simplest type of haptic consensus in a two-robot network, bilateral teleoperation, is demonstrated in this research. Modified consensus techniques are created because bilateral teleoperation necessitates acceleration control. We offer two novel consensus algorithms for haptic consensus in bilateral teleoperation: one for acceleration consensus and one for a shared acceleration feedforward. The acceleration feedforward is decided using force consensus filters that measure the forces given to the robots, whilst the acceleration consensus is implemented by an algorithm similar to a PD controller. When these methods are combined, it is demonstrated that haptic consensus may be achieved. Without losing generality, the conclusions given in this study may be extended to teleoperation systems with many robots.

2.7 Haptic Consensus in Multilateral Teleoperation [7]

Tumerdem et al. (2008) in this research, we present a distributed control rule based on consensus methods and acceleration control for multirobot haptic teleoperation. By simply sharing the state data and force measurements of the robots on the information network, this unique technology termed haptic consensus allows robots on a network to agree on their accelerations, velocities, and locations, as well as a common force feedforward. The acceleration consensus algorithm and a force consensus filter, which calculate a distributed average of the robots' force measurements, are the fundamental technologies proposed in this research to achieve haptic consensus. We may create the haptic consensus algorithm, which permits multilateral teleoperation, by combining these technologies. We also provide experiment findings for haptic consensus on a teleoperation network with several telerobots, which allows numerous operators to agree on a common teleoperation job through tactile sense.

2.8 Acceleration Consensus for Networked Motion Control of Telerobots [8]

Tumerdem et al. (2008), Consensus techniques allow nodes in a graph to agree on specific values in real time. In this study, a second-order consensus method with a servo input is developed, comparable to an acceleration controller, allowing robots on a network to agree on their acceleration and follow the average of local servo inputs. Acceleration consensus refers to the agreement on acceleration reached by robots using consensus algorithms. Additionally, it is demonstrated that teleoperation may be characterized as a consensus problem that can be solved using consensus techniques. We may achieve reliable haptic teleoperation among any number of robots by writing the servo inputs of an acceleration consensus algorithm as a function of the forces operating on each robot. The tests show that accelerated consensus can be achieved on a variety of network topologies, allowing several teleoperators to perform haptic teleoperation.

2.9 Multi-robot Teleoperation under Dynamically Changing Network Topology [9]

The purpose of this research, according to Tumerdem et al. (2009), is to achieve resilient teleoperation with many telerobots under changing communication topologies. Forces and locations must be transferred across all robots in haptic teleoperation with numerous operators and multiple robots, which presents challenges in maintaining the system's stability and efficiency when communication failures or time delays occur on particular channels. We reduce the limitations on the control system in our study by employing information graphs and consensus methods to address the multilateral teleoperation challenge. We first demonstrate how consensus filters may be used to achieve decentralized multilateral teleoperation. As long as the network topology is linked and balanced, the haptic consensus method, which includes consensus filters, has been found to be successful even on continuously changing network topologies. Furthermore, we demonstrate that a bilateral teleoperation system for cooperative load carrying may be realized utilizing the haptic consensus algorithm. The haptic consensus method enables multilateral and bilateral multirobot cooperative teleoperation even on switching network topologies where the network topology changes every control sampling time, which in our instance is 100 microseconds, according to the findings of the experiments. This indicates that the control system is highly adaptable and resilient to communication outages.

2.10 Adaptive Control for State Synchronization of Nonlinear Haptic Telerobotic Systems with Asymmetric Varying Time Delays [10]

Hashemzadeh et al. (2012) provide a novel adaptive controller design technique for nonlinear telerobotic systems with changing time delays and unknown variation rates. The developed controller has the capacity to synchronize the local and distant robots' state behaviors. Asymptotic stability in the presence of variable time delays is the focus of this research. Asymptotic stability of the bilateral telerobotic system subject to any finite yet unknown variable delay with a bounded yet unknown rate of change may be assured using the suggested controller. The suggested adaptive controller can adjust to parameter fluctuations in the local and distant robots' dynamics, in addition to the variable time delay. It is demonstrated that position and velocity errors between the local and distant manipulators asymptotically approach to zero, ensuring teleoperation transparency. The efficacy of the proposed approach is demonstrated by experimental and simulation findings using a pair of PHANToM haptic devices and a pair of planar manipulators with various communication time delays.

2.11 A Review of Haptic Feedback Teleoperation Systems for Micromanipulation and Microassembly [11]

Bolopion et al. (2013), A review of the key haptic feedback teleoperation systems for micromanipulation is presented in this research. The management of micrometer-sized items has become a crucial challenge in the recent decade. From material science to electronics, there is a pressing demand for intuitive and adaptable manipulation systems that can handle small-scale industrial projects and assembly chores. Fully automated chores and manual operation are the two primary ways that have been examined. The first requires completely specified jobs, whereas the second requires highly trained operators. To address these challenges, haptic feedback teleoperation, in which the user manipulates the tool through a joystick while receiving force feedback, looks to be a potential option since it provides great intuitiveness and versatility. During the previous decade, significant progress has been made, from systems that allow the operator to feel the substrate topology to the present state-of-the-art, which includes 3D haptic feedback to facilitate manipulation tasks. The primary achievements and solutions created to present 3D haptic feedback for instruments that typically lack 3D force measurements are detailed in this study. Virtual reality is being discussed as a way to improve immersion. The solutions proposed give a high level of help for haptic feedback teleoperation systems and a large range of micromanipulation tools. It is now conceivable to provide microassembly solutions for items as tiny as 1 to 10 micrometers based on this experience in haptic for micromanipulation and virtual reality support. This is a well-developed field that will aid small-scale industrial operations that demand microassembly accuracy and flexibility.

2.12 L2 Stable Transparency Optimized Two Channel Teleoperation under Time Delay [12]

Tumerdem et al. (2015) proposed a unique two-channel control rule for high transparency teleoperation with assured delay independent L2 stability when operating under time delay. When there is no time delay on the communication channels, four channel controllers have long been recognized to offer transparent teleoperation. To keep the system robust, however, a tradeoff between latency and openness must be made. They achieved an L2 stable teleoperation system with greater transparency/performance compared to four channel teleoperation systems under time delay in this study by proposing a two channel control architecture with damping injection and force reflection filters.

2.13 Prevalence of haptic feedback in robot-mediated surgery: a systematic review of literature [13]

According to Amirabdollahian et al. (2017), with the successful adoption and integration of robotic systems in minimally invasive surgery, as well as the growing use of robotic surgery (RS) in a variety of surgical specialties around the world, there is now a need to further develop and improve the technology. One such advancement is the incorporation of haptic feedback technology into RS, which will allow the operating surgeon to get tactile information on the type of tissue being operated on through the console. The fundamental benefit of doing so is that it allows the operating surgeon to feel and regulate the amount of force applied to various tissues during surgery, reducing the risk of tissue injury from both direct and indirect consequences of excessive tissue force or tension imposed during RS. We conducted a two-rater systematic review to identify the most recent improvements in haptic feedback technology for the operating surgeon on the console during RS, as well as prospective opportunities for upgrading technology. This article summarizes scientific advancements in RS, focusing on several stages of development, from proof of concept to cadaver tissue testing, animal surgery, and eventually real-world deployment. While there is universal agreement on the necessity for haptic and tactile feedback at the time of this assessment, there are no solutions or products available that meet this need. New discoveries in haptic augmentation for robot-mediated surgery have the potential and necessity to improve patient care and robotic surgical technology.

2.14 Three-channel control architecture for multilateral teleoperation under time delay [14]

Multilateral teleoperation, according to Tumerdem et al. (2019), is an extension of the bilateral/haptic teleoperation framework to numerous operators/robots and has applications in haptic training. Time delay is a significant issue in multilateral control systems, just as it is in bilateral teleoperation, and stability and transparency, which quantify the teleoperation system's performance, are key in their design. In multilateral teleoperation systems, this study presents a unique three-channel-based multilateral control architecture with damping injection to provide delay-independent L2 stability and great transparency. Experiment data are used to validate the theoretical and computational studies.

2.15 Haptic Telerobotic Cardiovascular Intervention: a Review of Approaches, Methods, and Future Perspectives [15]

According to Hooshiar et al. (2019), heart illnesses are the largest cause of death, hospitalization, and medical prescription worldwide. The percutaneous cardiac intervention, which is conducted under live X-ray imaging, is the gold standard for the treatment of coronary artery stenosis. The surgeon and his team are at risk of major health issues as a result of X-ray exposure and work dangers, according to substantial clinical data. Telerobotic vascular intervention systems with a master-slave design reduced X-ray exposure and improved clinical results, but the lack of haptic input during surgery has been a major drawback. This research looks at the current status of haptic telerobotic cardiovascular therapies. A review of the literature published between the years 2000 and 2019 was conducted. The survey results were assessed for their applicability to this project. The top research disciplines were also recognized based on the survey's findings. In addition, alternative approaches for sensor-based and model-based haptic telerobotic cardiovascular intervention, haptic rendering and actuation, and relevant procedures were evaluated and compared. Finally, the existing constraints of state-of-the-art research, as well as untapped study topics and the future viewpoint of research on this technology, were outlined.

3 THEORY

3.1 Telerobotic Systems

Telerobotics systems permit human operators to accurately understand a remote environment, sanctionative them to properly move with a telerobot to manipulate objects set therein remote environment. It’s a mixture of 2 main sub fields, teleoperation and telepresence.

A general definition of teleoperation is performing work in a distant location while not really being therein location. During this definition “work” refers to controlling a robot accurately, while “remote location” may be related to either physical distance, wherever by the operator is separated from the telerobot over an oversized distance, or a amendment in scale, where large changes on the operator aspect can be translated into minor adjustments on the telerobot side and contrariwise (e.g. micro surgery).

3.1.1 History of Telerobotic

Telerobotics systems date back to the middle 1940's, wherever a method of safely handling radioactive materials in World War II were necessary. Raymond Goertz, known nowadays as the pioneer in telerobotics, was the primary person to with success develop a human-robot telerobotic system for this purpose.

The telerobotic field, up to the current stage, was in the main targeted on the teleoperation aspects (performing beat up a distance) and thus, still needed the operator to be in eye contact with the unsafe material. Realizing this shortcoming, Goertz later introduced a telepresence system, in the form of closed-circuit television screens, which allowed the operator to be an arbitrary distance away .Since then, the field of telerobotics has broadened with several noticeable advancements being made up to the early 90's.

3.1.2 Telerobotic Control Architectures

The control system can make use of many completely different control structures, depending on the intended application, of which position, force, hybrid, impedance and admittance are the foremost popular.

The position control architecture refers to controlling the positions between the robotic mechanisms (Master) and also the telerobot (Slave) to minimizing the positional error between the two. The control system, thus, compares the position of the Slave to it of the Master (with relevance their respective coordinate systems). If the positions differ, the position of the telerobot is adjusted to reduce the positional error.

The force control architecture looks to reduce the resulting force error between the Master and Slave devices. The control system, thus, compares the force on the Slave to the force on the Master. If the forces differ, the position of the telerobot is adjusted to minimize the force error.

The hybrid control architecture combines the previous two ways by attempting to accomplish each however specifying a priority to 1 of the 2 just in case of a conflict. This projected method, therefore, needs the communication of both position and force information to the control system. The priority between position and force control depends on the applications and it's not uncommon for it to change many times throughout a particular operation.

3.2 Haptics

Haptics refer to the human sense of touch and might be divided into 2 primary components, connective tissue and kinaesthetic touch. Cutaneous touch refers to the human tactile perception specifically concerning pressure experienced by the skin. It allows humans to detect vibration, surface roughness, skin stretch, skin curvature, etc.

A typical example of tactile perception is that the ability to distinguish ate to tell apart} between different surface textures. Kinaesthesia on the other hand, refers to the sense of force within the muscles and tendons. It provides awareness of the position and motion of the human body (static and dynamic) moreover as larger scale details, similar to basic object shape and mechanical properties, such as hardness of materials.

The sense of touch is, this, priceless once a way of presence in an exceedingly remote/virtual surroundings is needed because it is one of the foremost informative senses that humans possess. Unlike the other human senses (sight, sound and smell), touch is that the solely human sense that's a true bilateral sensation as touch receptors and activators share constant pathways - permitting humans to directly influence the amount of sensation being perceived. In and of itself haptic input systems would like actuators to provide haptic feedback as well. Haptic feedback, that is basically force or cutaneous feedback in a man-machine interface, permits the remote/virtual environment to relay realistic, tangible sensations to an operator. With the incorporation of tactile feedback into virtual or remote environments, users have the flexibility to push, pull, feel, and manipulate objects in an exceedingly remote environment via manual dexterity, instead of simply seeing a illustration on a video screen.

4 METHOD

We did all of our work on Matlab Simulink. We prepared Simulink models for linear motors and did many different experiments on them. We had the opportunity to work mostly on linear motors.

We have worked on different telerobotic control architecture structures. In general, we created a Simulink model for Four - Channel and then, for example, if we are going to make P-PF for 'Three - Channel', we extracted the force control part in our master over this general Simulink model we created.

In our work on time delay, we added time delay blocks on our model and made various changes on our model.

We tried to make our system as stable as possible by making a lot of changes on the PID control values, force constants, and damping injection values in our model.

5 RESULTS

In this section, we have explained our work under three main headings. We showed the problems and solutions we experienced while performing our experiments and shared the results we gathered.

5.1 4 Channel Control System

The main Simulink scheme we use in 4 channel control systems is shown in the **Figure 5-1**.

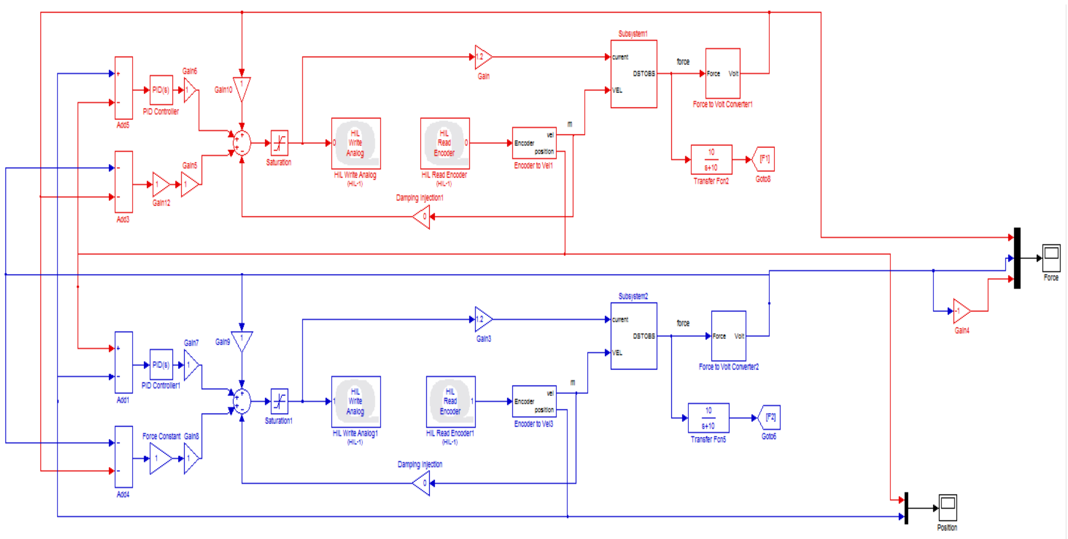

Figure 5-1: 4 Channel Simulink Scheme

In our 4 Channel control system, we first examined the position and force graphs of our linear motors at the time of contact with the hard and soft surface.

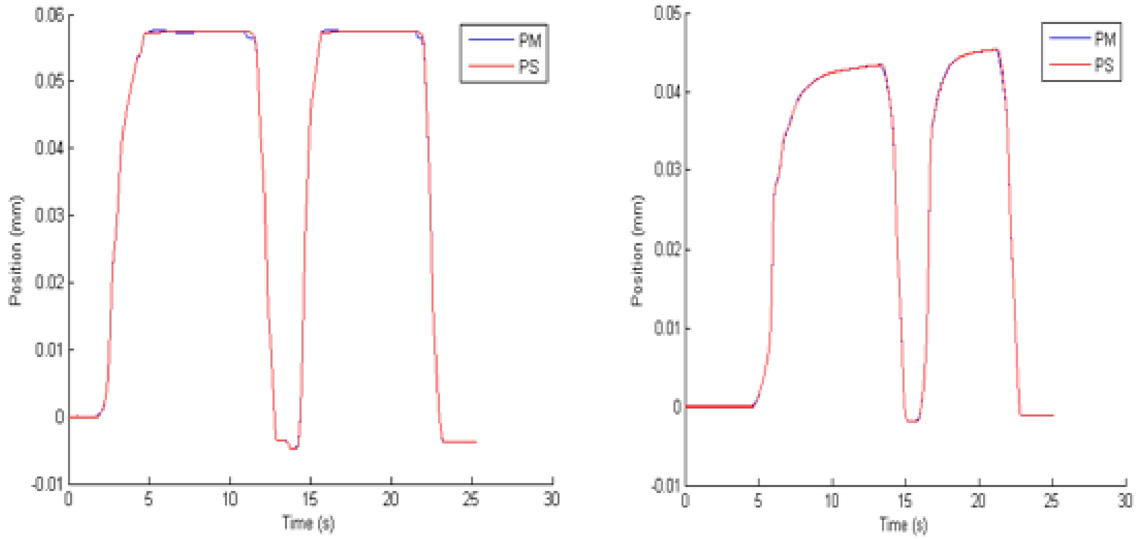

Figure 5-2: Position graphs for hard and soft surfaces respectively.

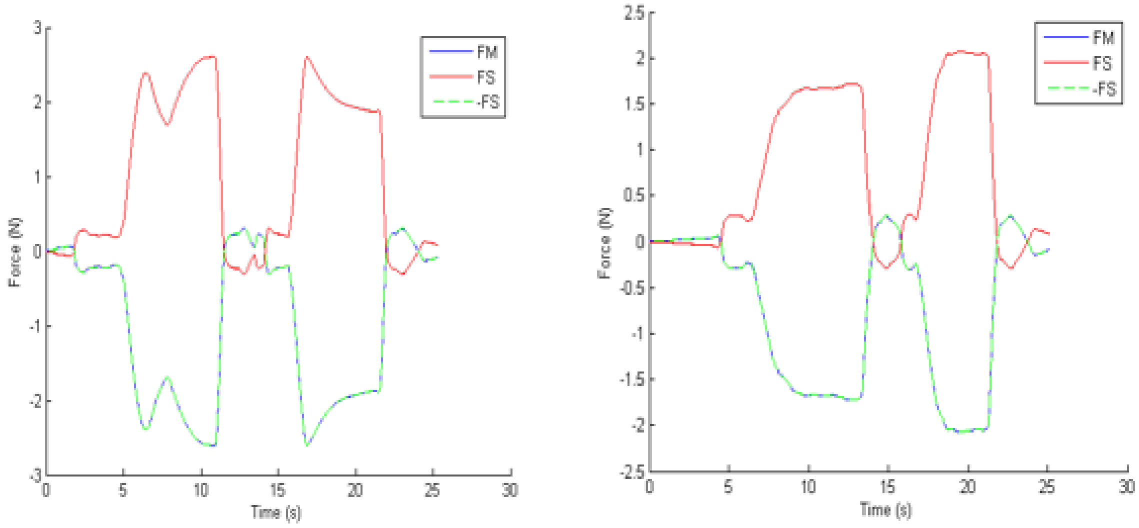

Figure 5-3: Force graphs for hard and soft surfaces, respectively.

As a result of the applications we have made, we have observed that the model we have prepared works efficiently. At the same time, we achieved more desired results on the soft surface than on the hard surface.

As the next step, we wanted to add 'Time Delay' to our 4 channel control system and observed the results.

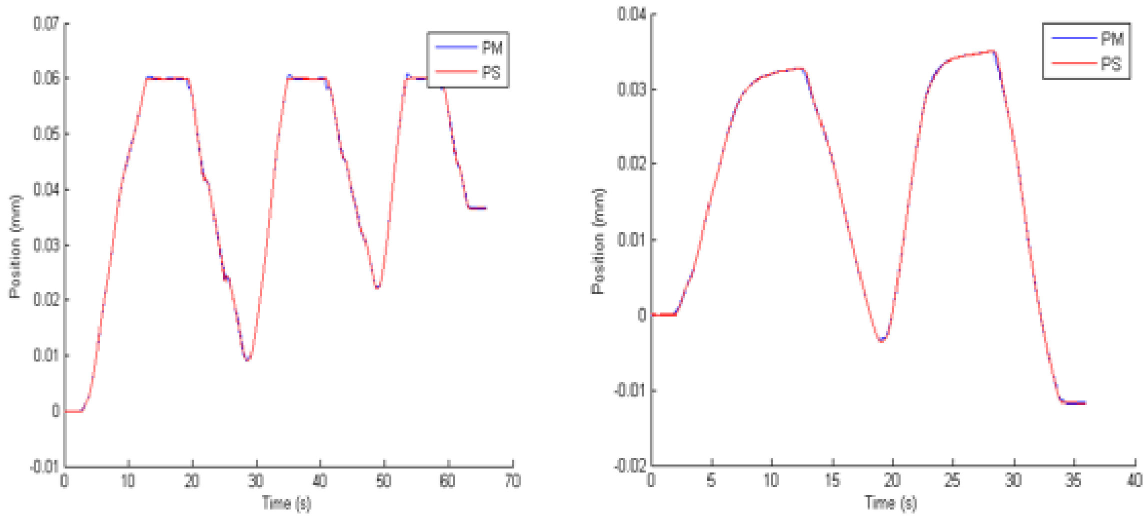

Figure 5-4: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

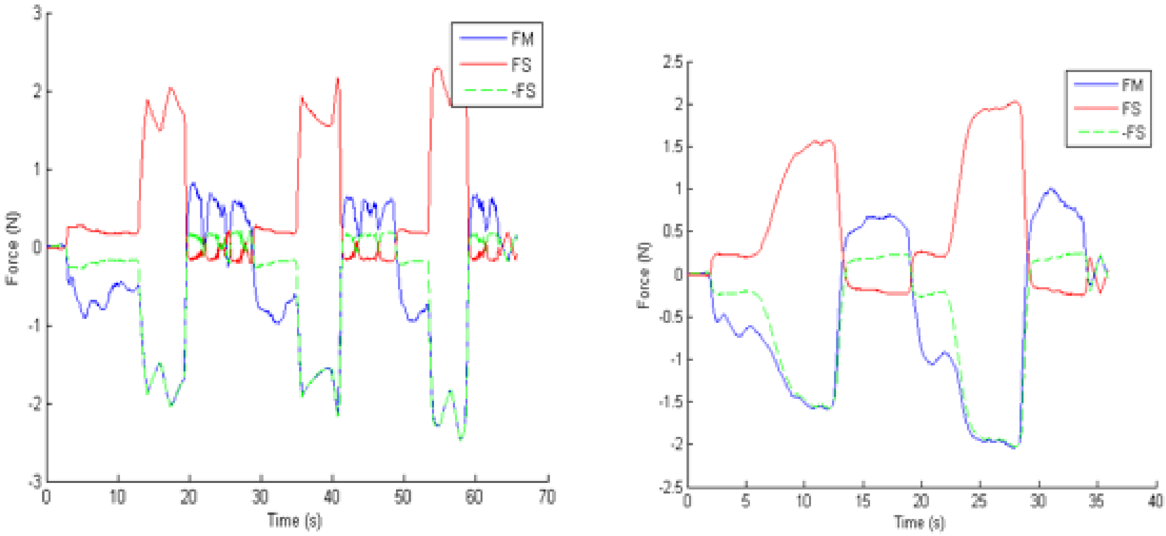

Figure 5-5: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

When we look at the position and force graphs we have obtained under the 'time delay' effect, we can say that the results are as expected in the position tracking, but when we examine the force graphs, we saw that there is a problem in our force feedback in free motion.

To overcome this problem, we first added 'dumping injection' to our model and repeated the experiments. When we examined the graphics, we observed that our force feedback in free motion still did not work at the level we wanted.

Then we increased the 'force constants' in our model, in which we had already added 'dumping injection', and repeated the experiments. When we examined the graphics, we observed that our force feedback in free motion was still not at the desired level.

As a result of our experiments, we observed that our 'slave' did not have a problem in position tracking when 'time delay' was added to our 4 channel control system, but there was a problem in force feedback in free motion.

As a result, we observed that our 4 channel control model works more efficiently without 'time delay'.

5.2 3 Channel Control System

In this section, we analyzed the position and force graphs in contact with the hard and soft surface in our 3 channel (P-PF, F-PF, PF-P, PF-F) control models.

5.2.1 P-PF Control System

The main Simulink scheme we use in P-PF channel control systems is shown in the **Figure 5-6**.

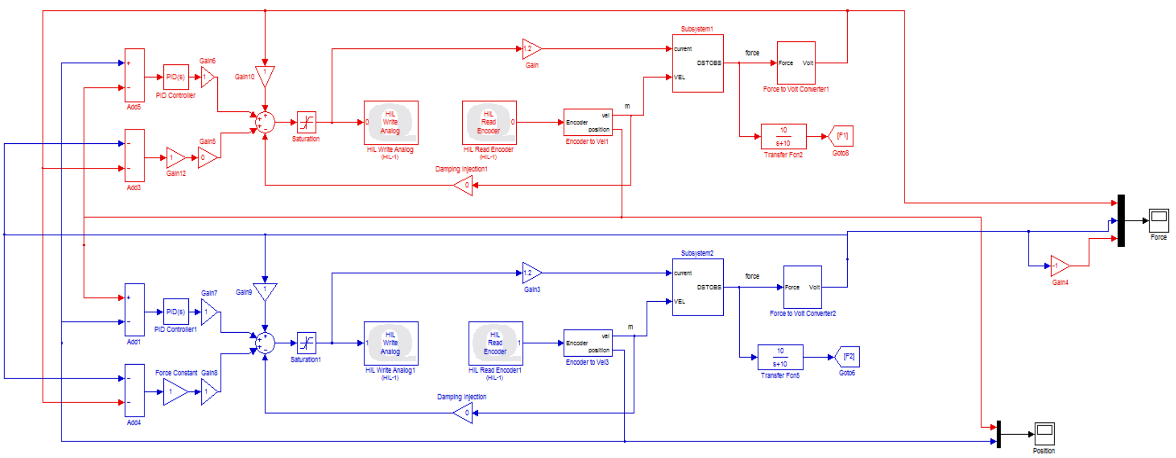

Figure 5-6: P-PF Simulink Scheme

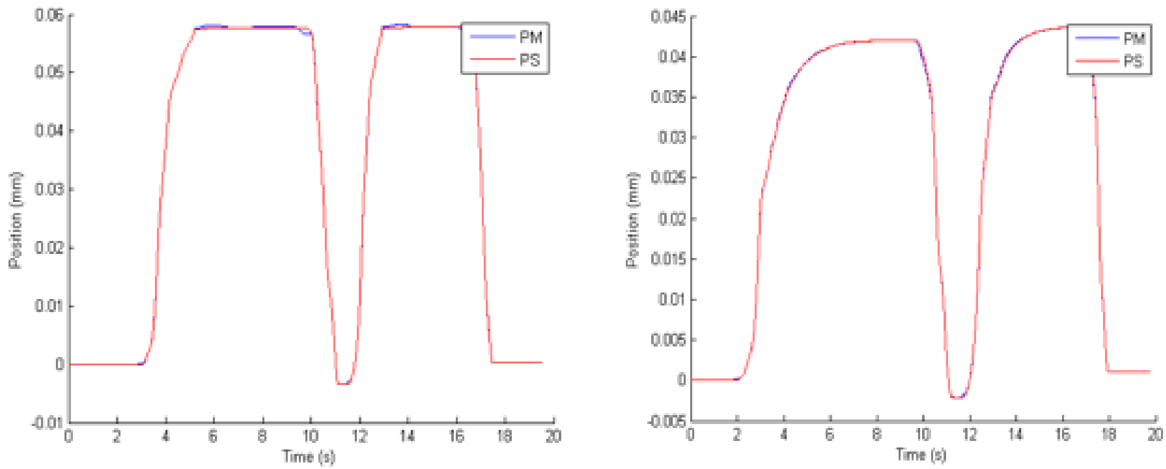

Figure 5-7: Position graphs for hard and soft surfaces, respectively.

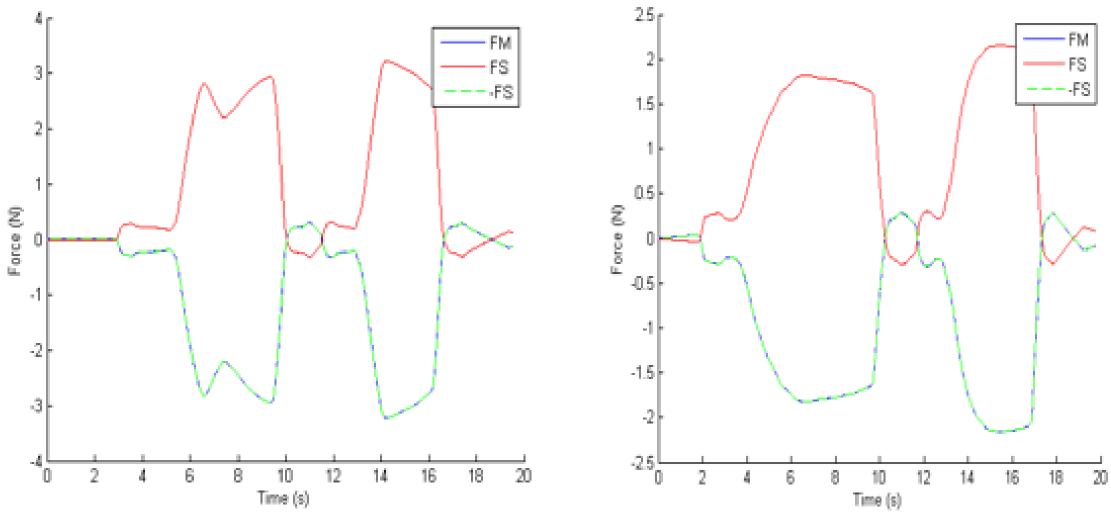

Figure 5-8: Force graphs for hard and soft surfaces, respectively.

When we examined the graphics, we observed that the model we created for P-PF control systems worked efficiently for hard and soft surfaces.

In the next step, we added 'Time Delay' to our model and repeated our experiments. We also added 'Damping Injection' to our model so that our results are more accurate.

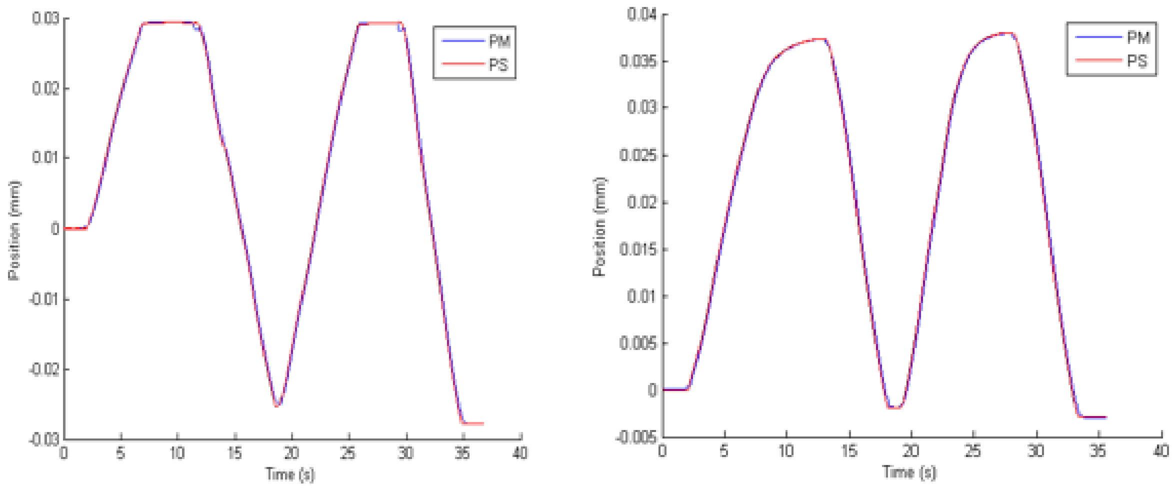

Figure 5-9: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

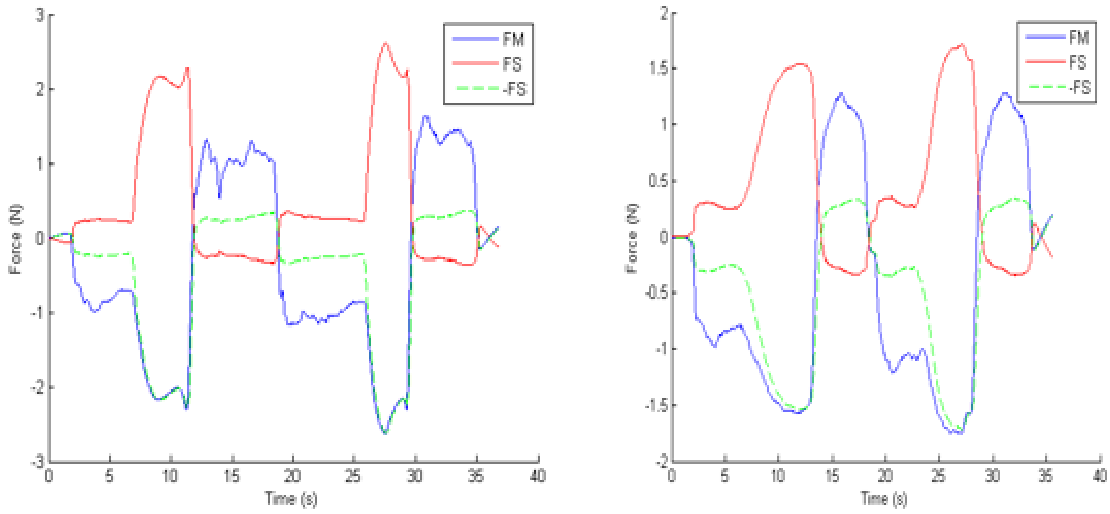

Figure 5-10: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

When we examine our graphics, we can see that our system does not have a problem in position tracking on both surfaces. However, although there was no problem in force feedback at the moment of contact, we could not achieve the results we wanted in free motion.

As a result, it is possible to get more efficient results without 'Time Delay' for P-PF control systems.

5.2.2 F-PF Control System

The main Simulink scheme we use in F-PF channel control systems is shown in the **Figure 5-11**.

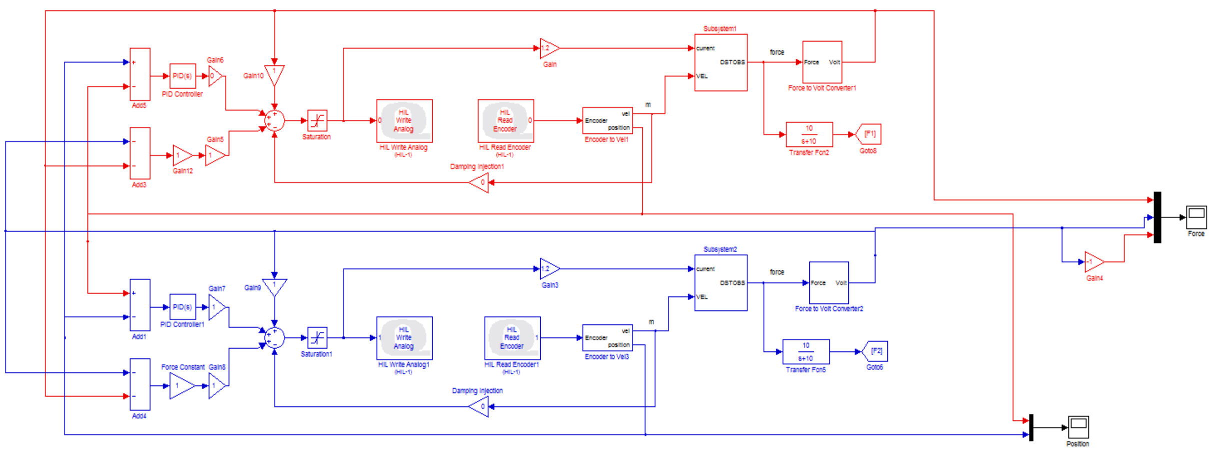

Figure 5-11: F-PF Simulink Scheme

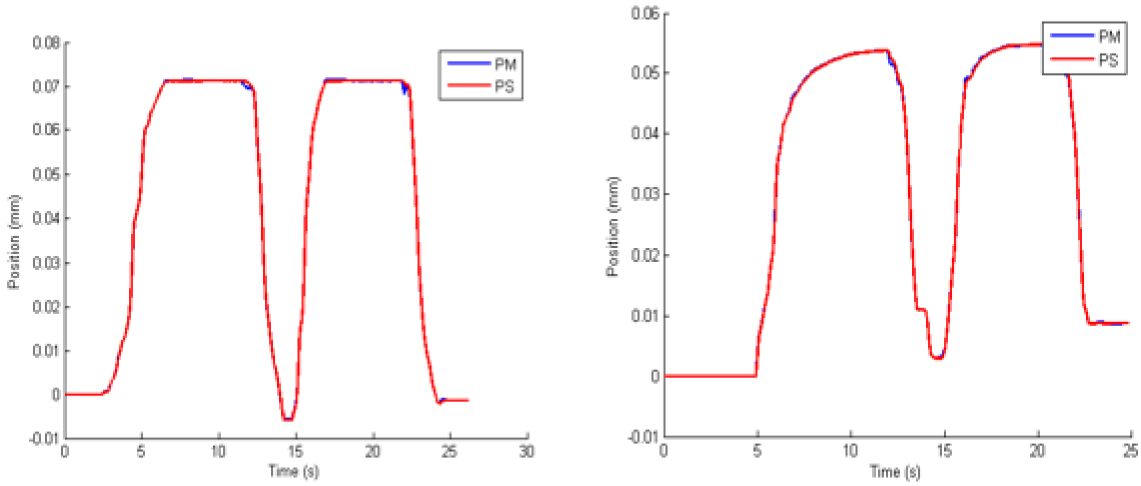

Figure 5-12: Position graphs for hard and soft surfaces, respectively.

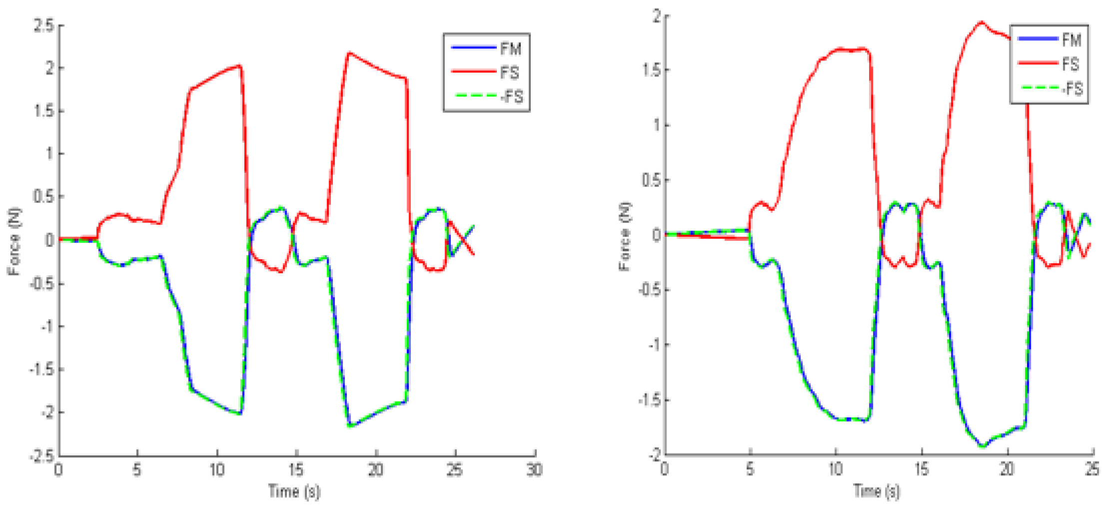

Figure 5-13: Force graphs for hard and soft surfaces, respectively.

When we examined the graphics, we saw that our 'master' had a problem in position tracking at the time of contact with the hard surface. When we look at our force feedback, we can say that it works as we want in both cases.

We added 'Damping Injection' to our model in order to solve the problem experienced during contact with the hard surface.

When we examine the outputs of our model to which we added 'Damping Injection', we can say that the trackinglessness at the time of contact with the hard surface has decreased, but it is still not at the desired level.

As a result, we observed that more efficient results were obtained in contact with the soft surface for our F-PF model.

As the next step, we added 'Time Delay' to our system and analyzed the results.

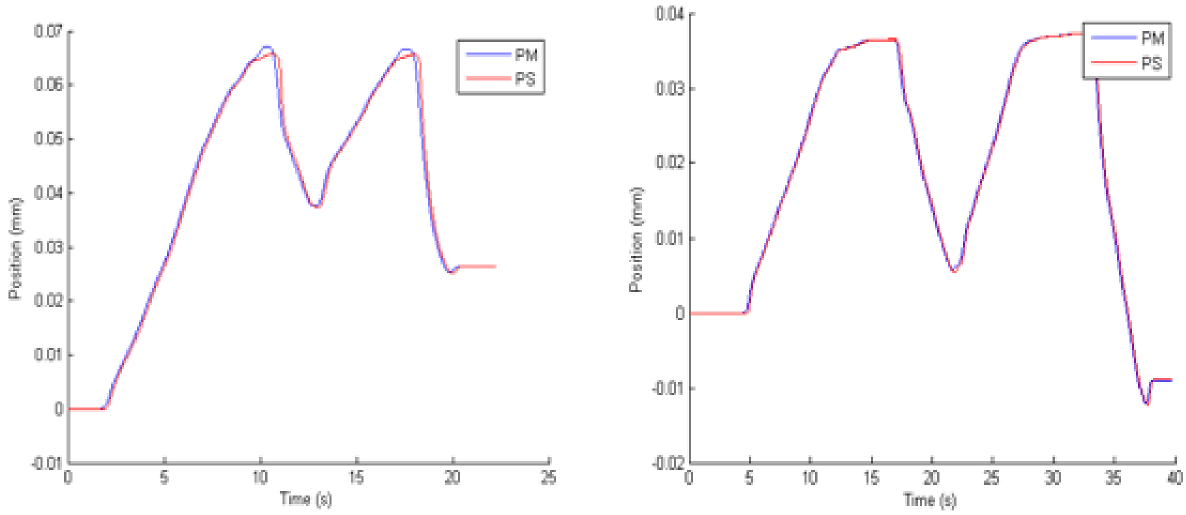

Figure 5-14: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

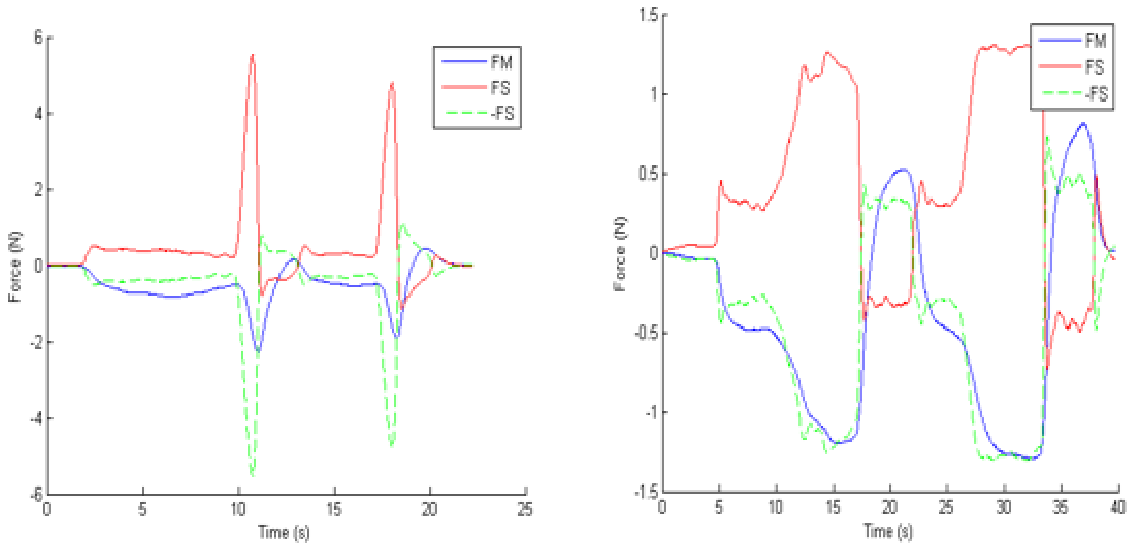

Figure 5-15: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

When we examine our graphics, we see that our 'master' bounces back upon contact with the hard surface and receives almost no force feedback.

On the other hand, when we look at the moment of contact with the soft surface, we get more desired results in position tracking, but the problems still continue in force feedback.

5.2.3 PF-P Control System

The main Simulink scheme we use in PF-P channel control systems is shown in the **Figure 5-16**

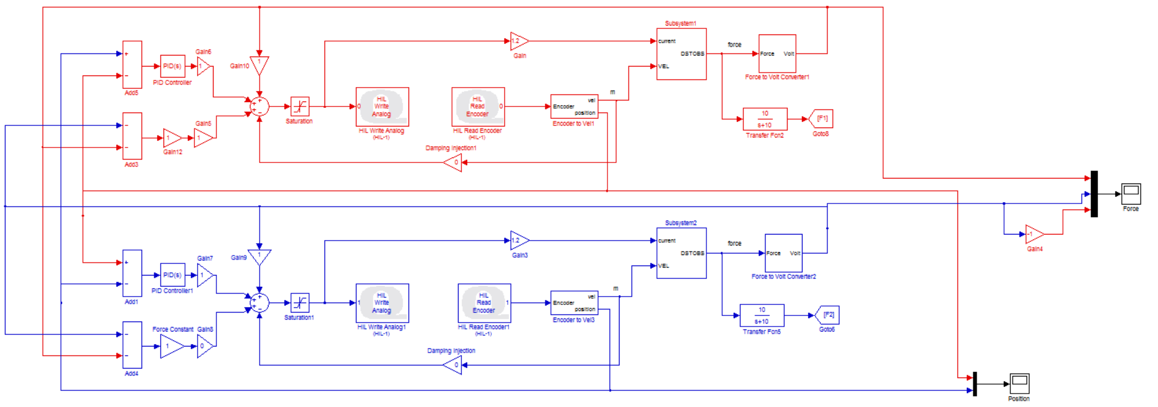

Figure 5-16: PF-F Simulink Scheme

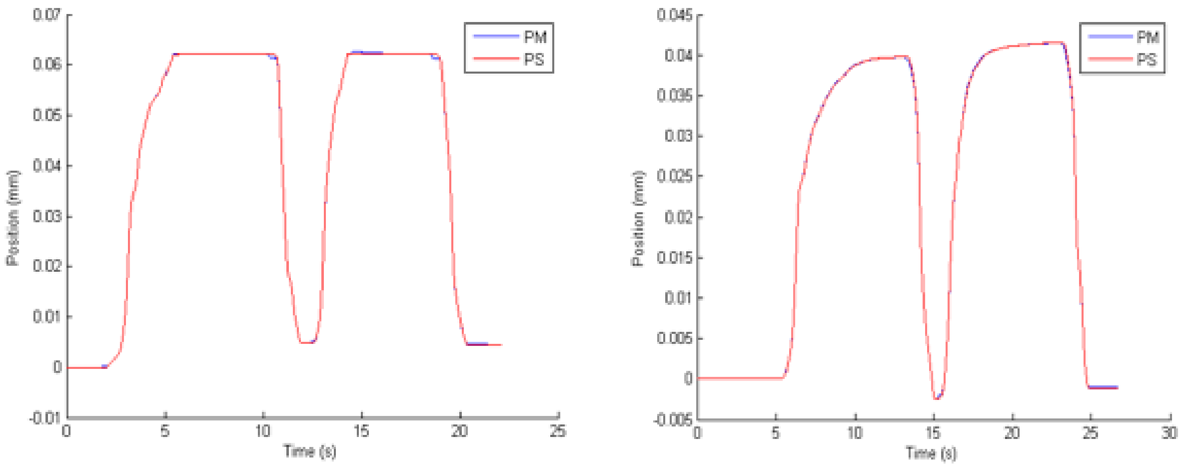

Figure 5-17: Position graphs for hard and soft surfaces, respectively.

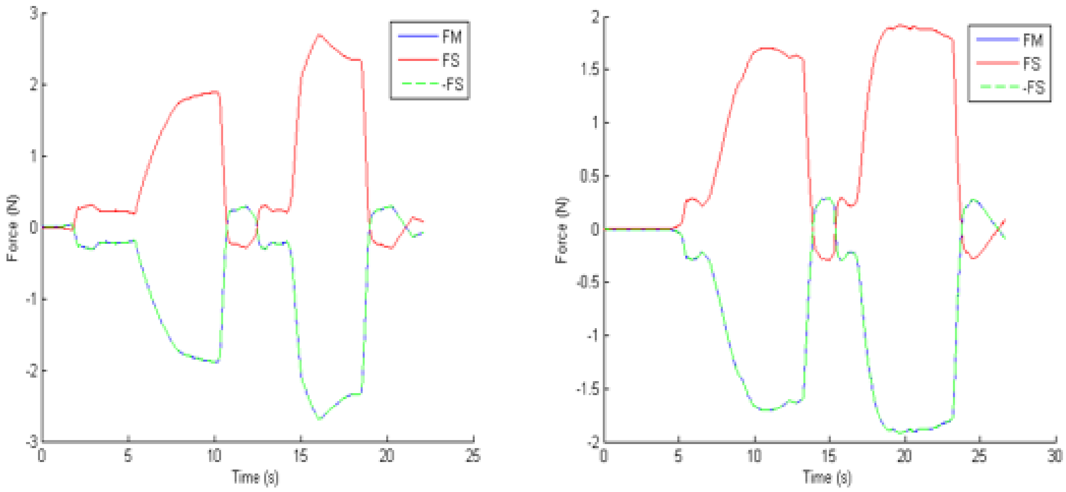

Figure 5-18: Force graphs for hard and soft surfaces, respectively.

When we examine the graphics obtained as a result of our experiments with the PF-P control model, we can say that both position tracking and force feedback work smoothly and stably on both surfaces.

In the next step, we added 'Time Delay' to our system and repeated our experiments.

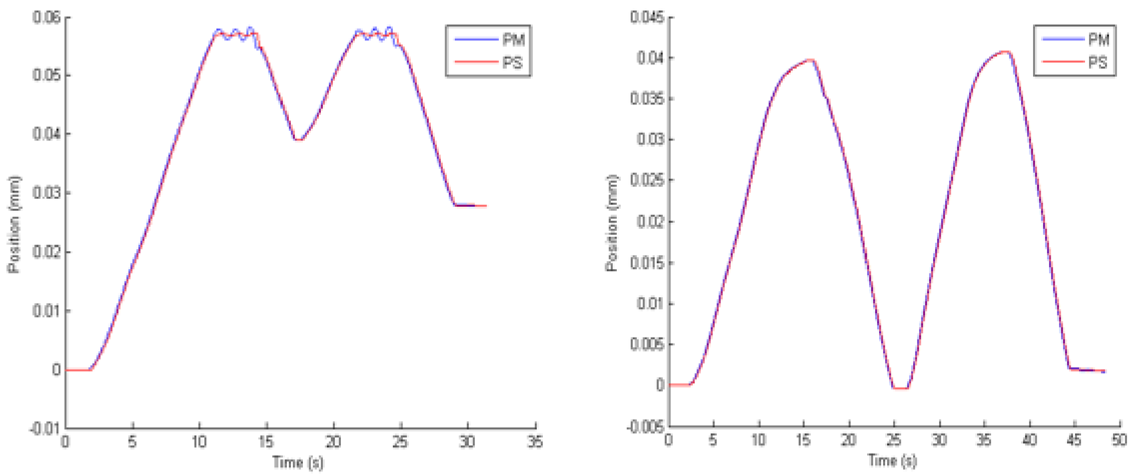

Figure 5-19: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

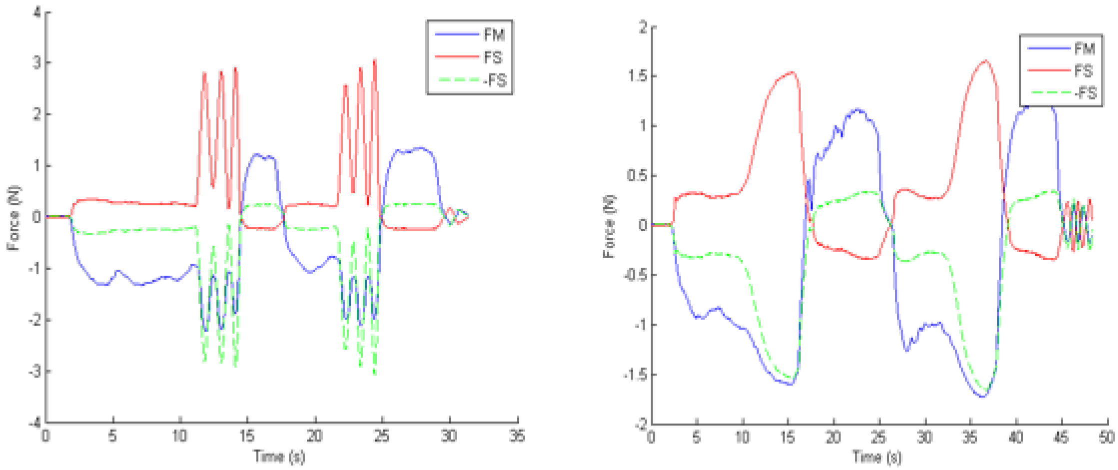

Figure 5-20: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

When we looked at the graphics we obtained as a result of our work with our model with 'Time Delay' added, we observed that there were kickbacks at the time of contact on hard surfaces. When we look at the force feedback, we see that it works inefficiently in both cases.

As a result, we can say that PF-P control systems operate smoothly without the 'Time Delay' effect.

5.2.4 PF-F Control System

The main Simulink scheme we use in PF-F channel control systems is shown in the **Figure 5-21**

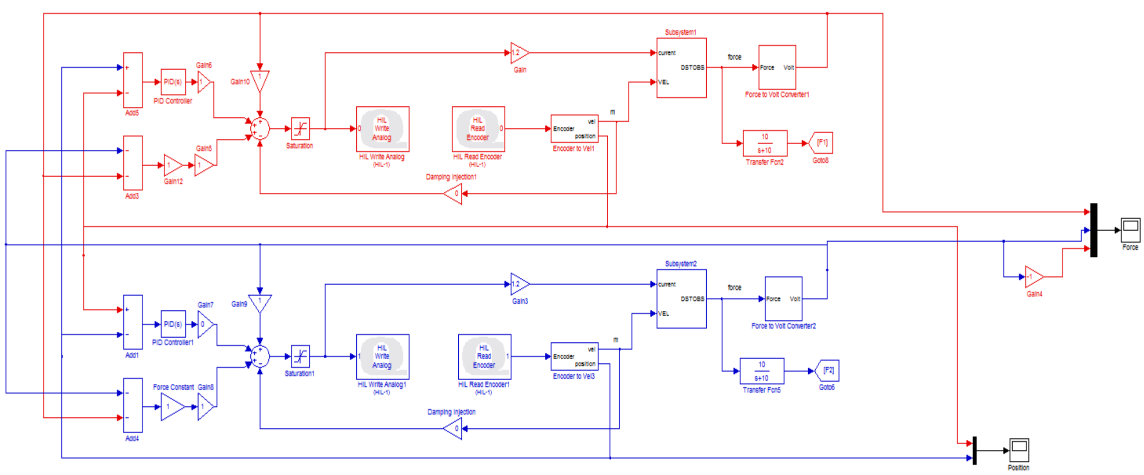

Figure 5-21: PF-F Simulink Scheme

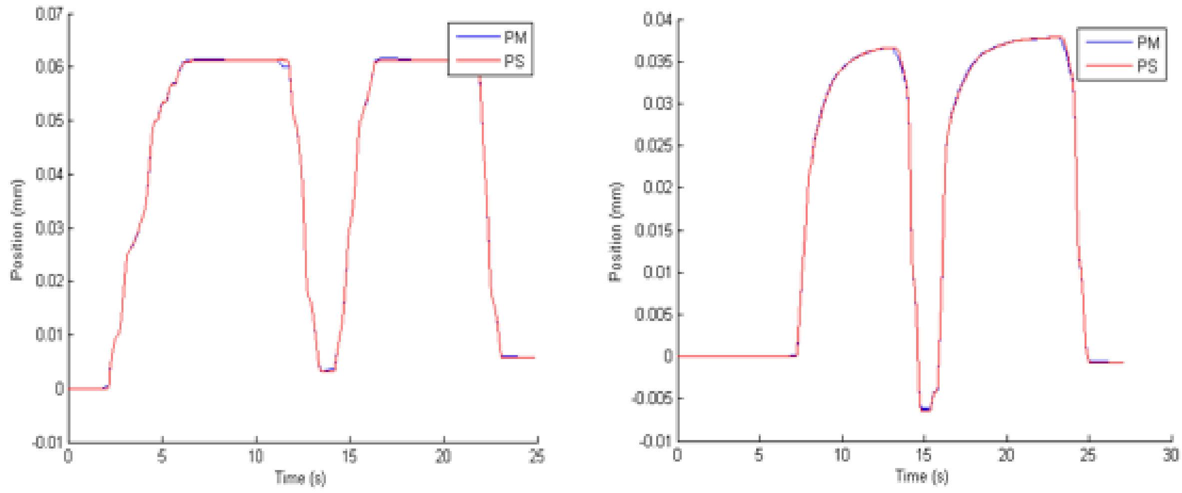

Figure 5-22: Position graphs for hard and soft surfaces, respectively.

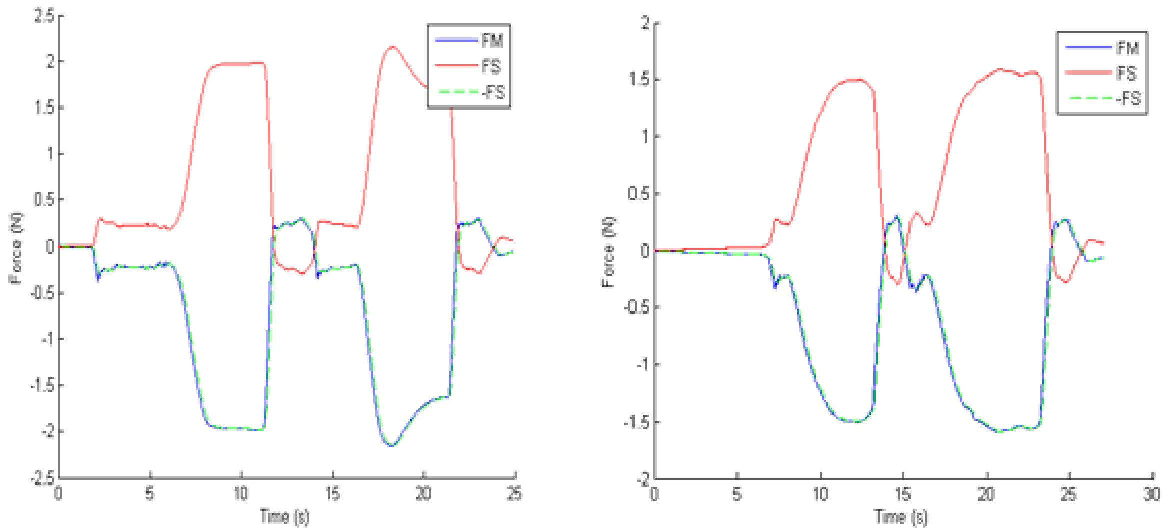

Figure 5-23: Force graphs for hard and soft surfaces, respectively.

When we examine our graphics, we observe that there is a high level of oscillation in free motion in our system. In addition, we can say that the position tracking of our master at the time of contact with the hard surface is not efficient. When we look at the force graphs, we can say that the force feedbacks work efficiently at the moment of contact on both surfaces.

In order to solve the oscillation problem we are experiencing, we decided to add 'dumping injection' to our system and repeated our experiments.

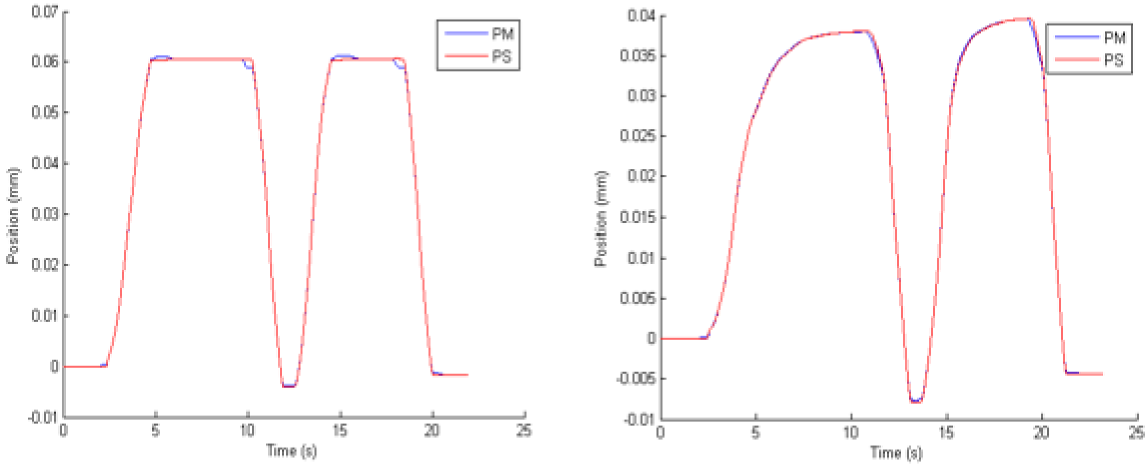

Figure 5-24: Position graphs for hard and soft surfaces, respectively, with adding damping injection.

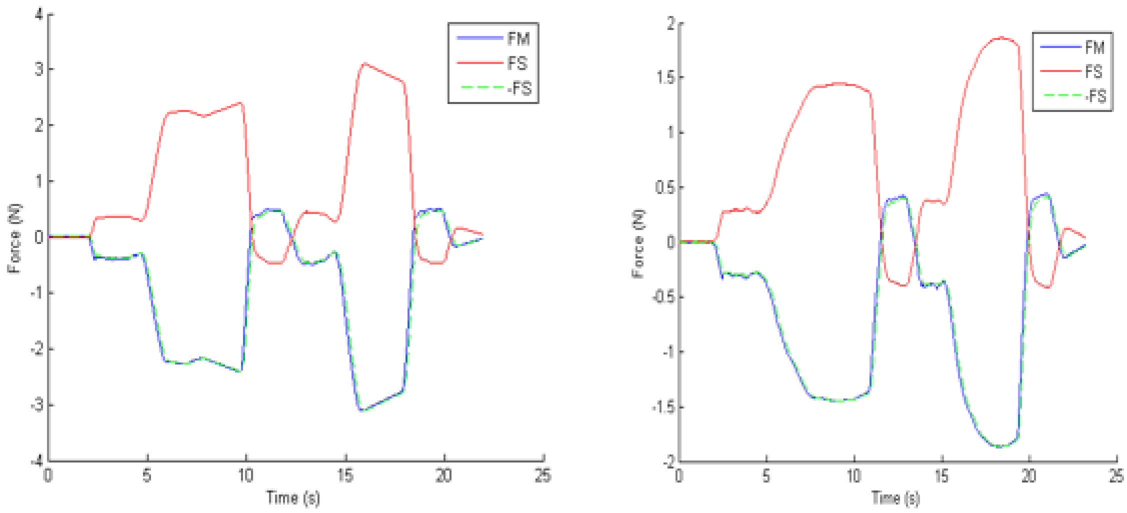

Figure 5-25: Force graphs for hard and soft surfaces, respectively, with adding damping injection.

When we examine our dumped graphs, we can say that we have completely eliminated the oscillation problem and our model has started to work efficiently for both surfaces.

As the next step, we added 'Time Delay' to our system and repeated our experiments.

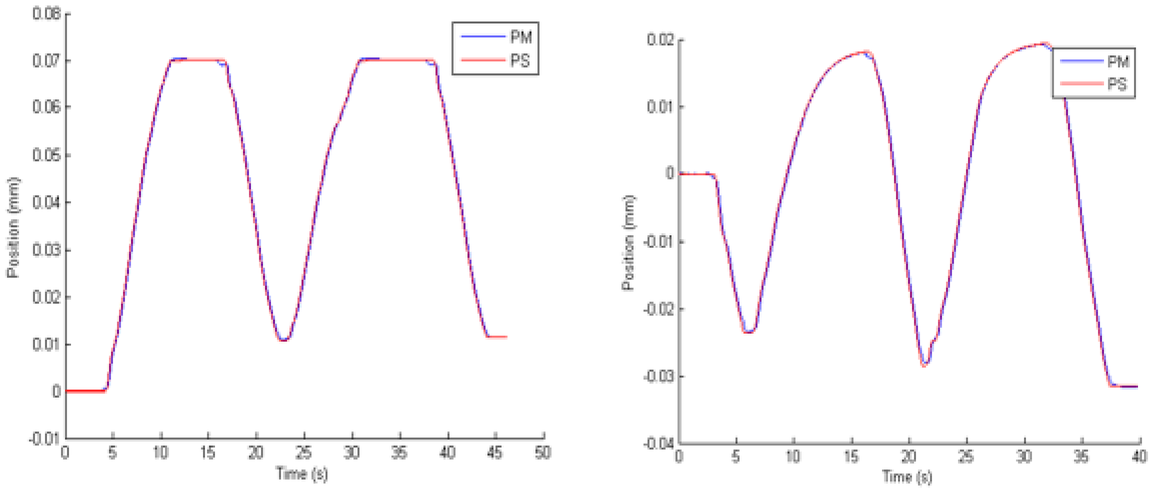

Figure 5-26: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

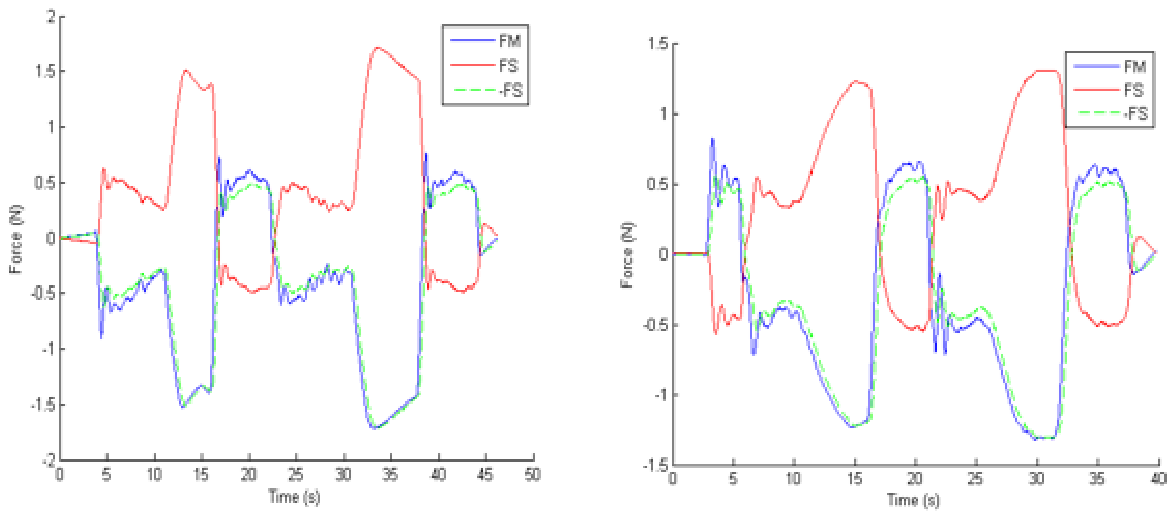

Figure 5-27: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

When we examine our position graphs, we can see that our model also follows the position efficiently under the 'Time Delay' effect. When we look at our force graphs, we observe that the efficiency of force feedback decreases in free motion.

As a result, we can say that models with 'Time Delayless' and 'Damping Injection' are more efficient for PF-F control systems.

5.3 2 Channel Control System

In this section, we analyzed the position and force graphs in contact with the hard and soft surface in our 2 channel (P-P, P-F, F-P, F-F) control models.

5.3.1 P-P Control System

The main Simulink scheme we use in P-P channel control systems is shown in the **Figure 5-28**

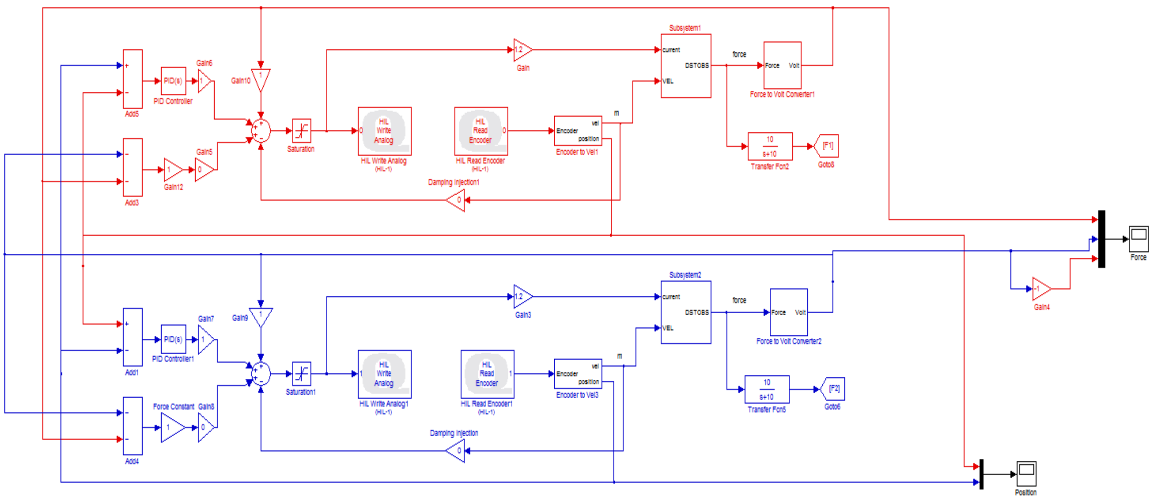

Figure 5-28: P-P Simulink Scheme

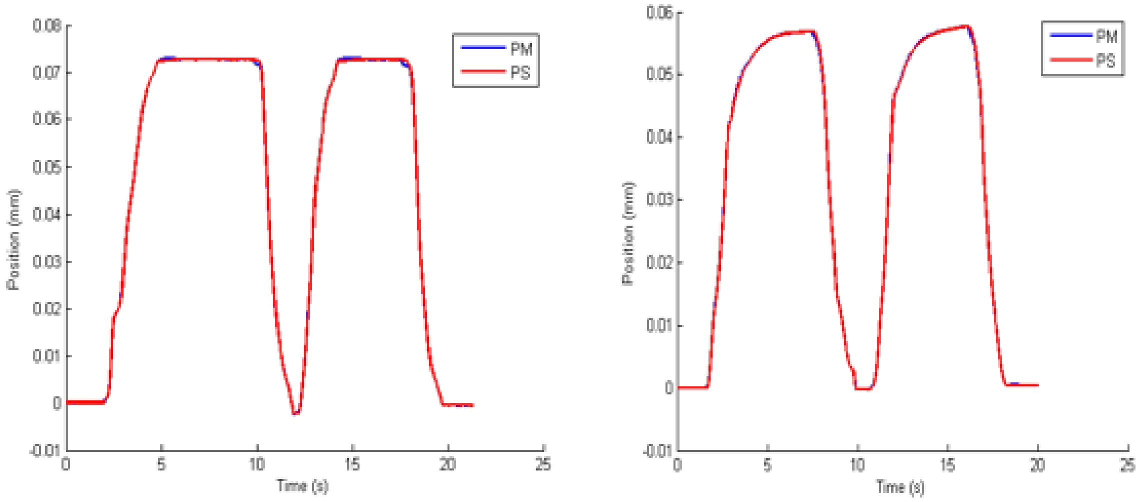

Figure 5-29: Position graphs for hard and soft surfaces, respectively.

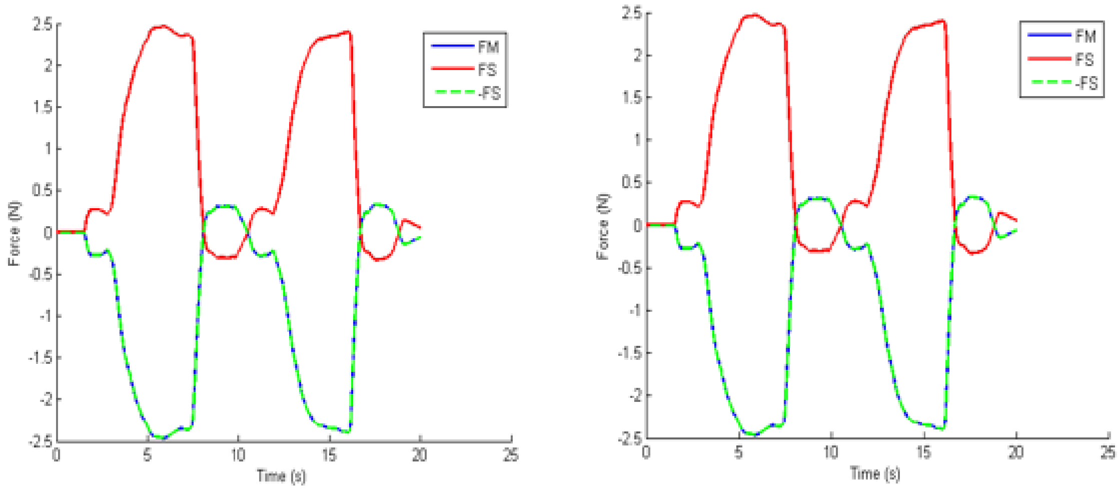

Figure 5-30: Force graphs for hard and soft surfaces, respectively.

When we look at the graphics we obtained as a result of our experiments using the P-P control system, we observed that our model performs position control and force feedback on hard and soft surfaces without any problems.

In the next step, we added 'Time Delay' to our system and repeated our experiments.

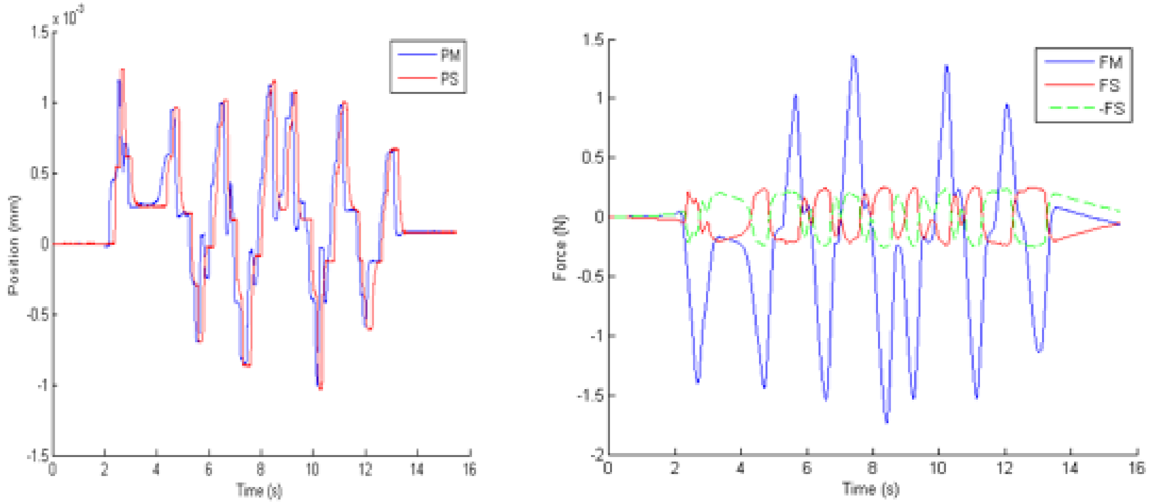

Figure 5-31: Position and force graphs for hard surface, respectively, at the 'Time Delay' effect.

As a result of our experiments on our 'Time Delayed' model, we encountered high levels of oscillation and rebound while moving our 'master' and observed almost no force feedback. To overcome this problem, we removed the 'disturbance observer' in our model and repeated our experiments.

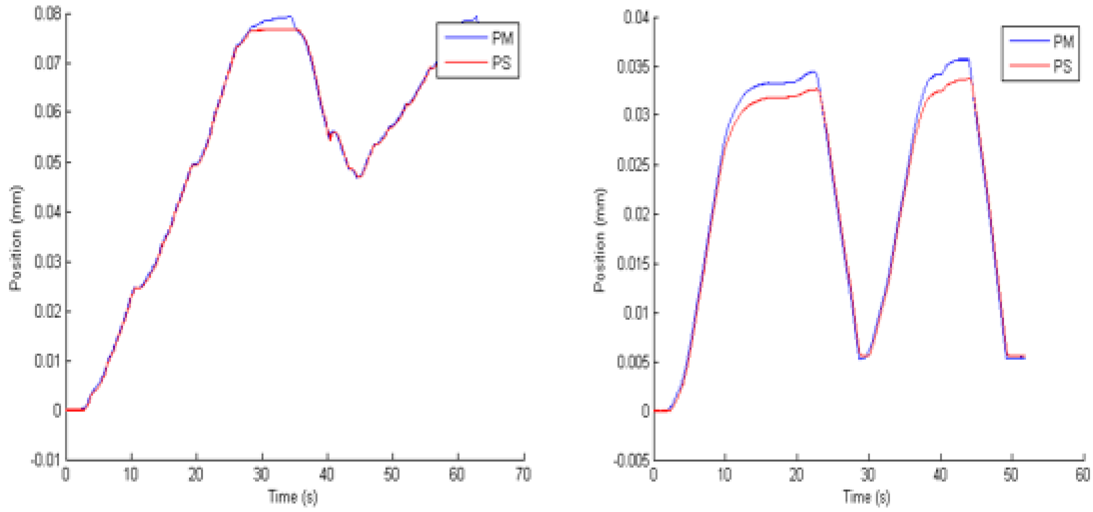

Figure 5-32: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect and without D.O.

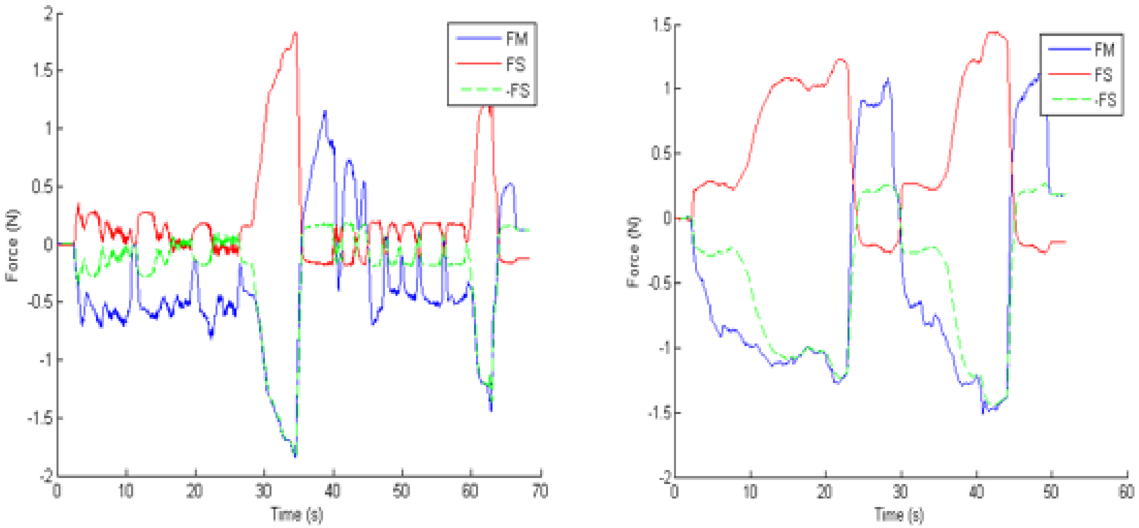

Figure 5-33: Force graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect and without D.O.

If we look at the results we obtained from the experiments we made with our new model, we observe that the oscillation, which is high in position tracking, is reduced, and we see that the movement of our master is not blocked at the time of contact with the surfaces.

If we look at the force feedback, we can talk about an efficient feedback in contact moments while it is inefficient in free motion.

As a result, the P-P control system is very stable and efficient when there is no 'time delay', but the opposite is the case when there is a 'time delay'.

5.3.2 P-F Control System

The main Simulink scheme we use in P-F channel control systems is shown in the **Figure 5-34**

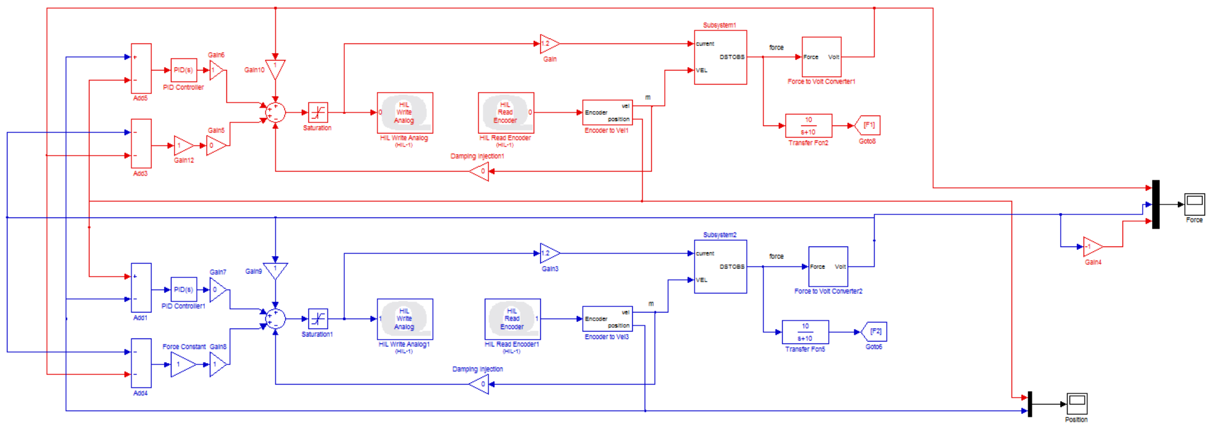

Figure 5-34: P-F Simulink Scheme

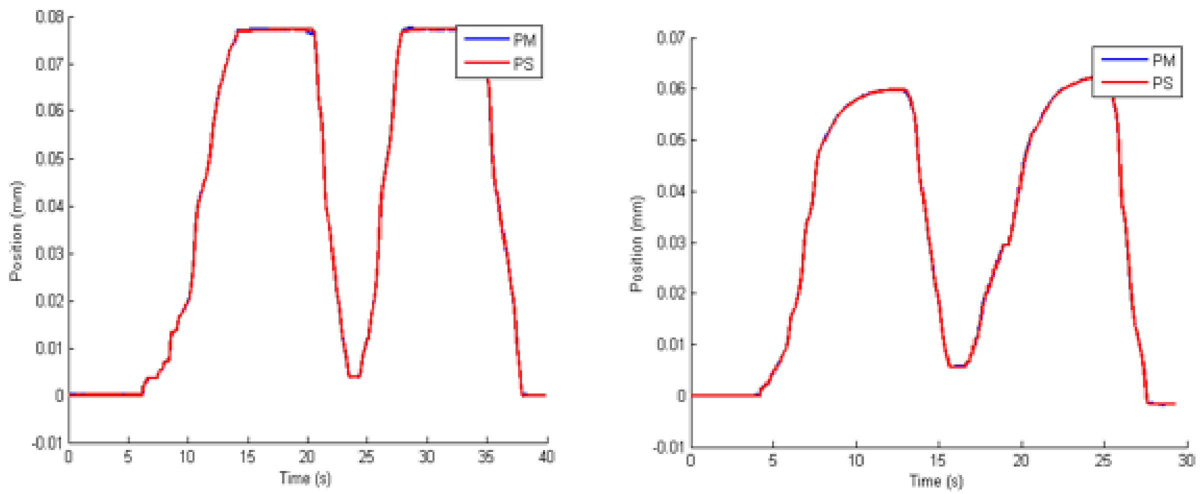

Figure 5-35: Position graphs for hard and soft surfaces, respectively.

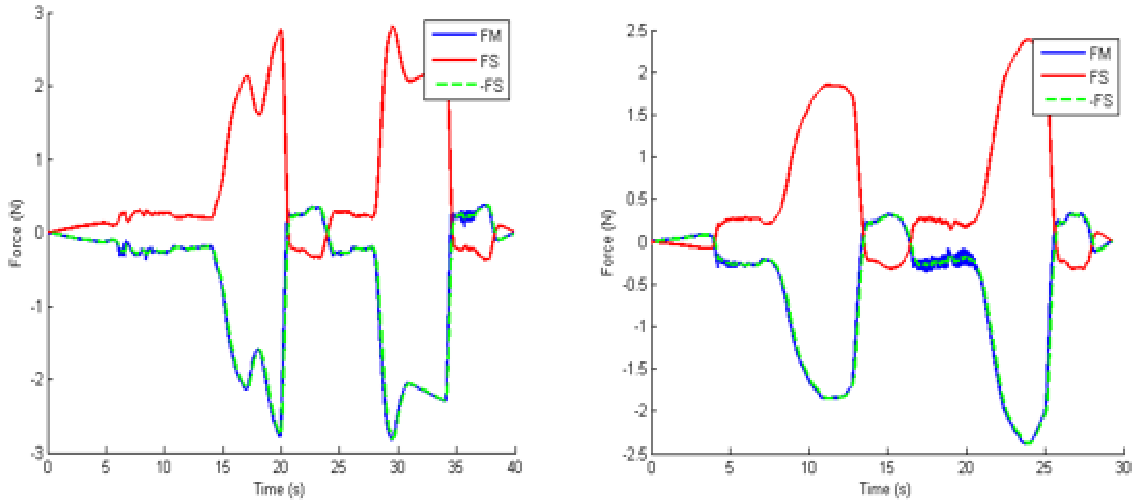

Figure 5-36: Force graphs for hard and soft surfaces, respectively.

If we look at the graphics we obtained from the experiments we made with the model we created for the P-F control system, we observe that although our system works at the desired level during contact, there is oscillation in our system in free motion. To overcome this problem, we add 'Damping Injection' to our model and repeat our experiments.

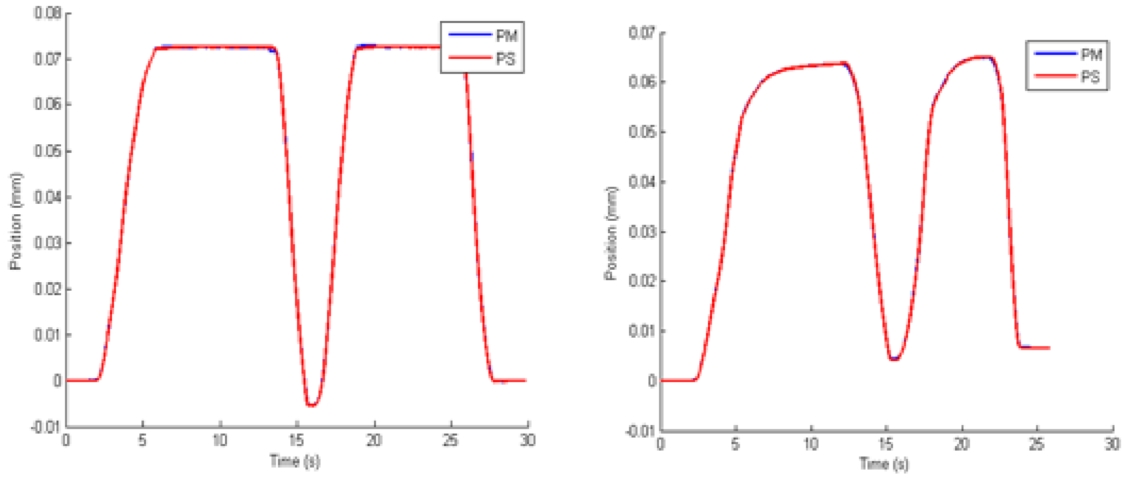

Figure 5-37: Position graphs for hard and soft surfaces with D.I., respectively.

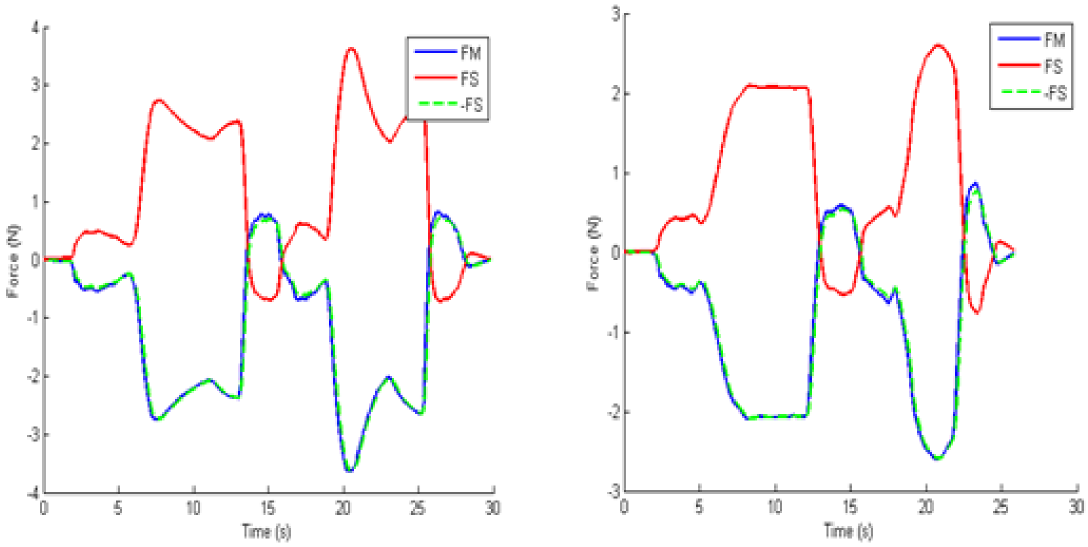

Figure 5-38: Force graphs for hard and soft surfaces with D.I., respectively.

If we look at the work we have done with our model that we have added 'Damping Injection', we observe that we have completely removed the oscillation problem in our system. Our system works seamlessly on both surfaces.

In the next step, we added 'Time Delay' to our model and repeated our experiments.

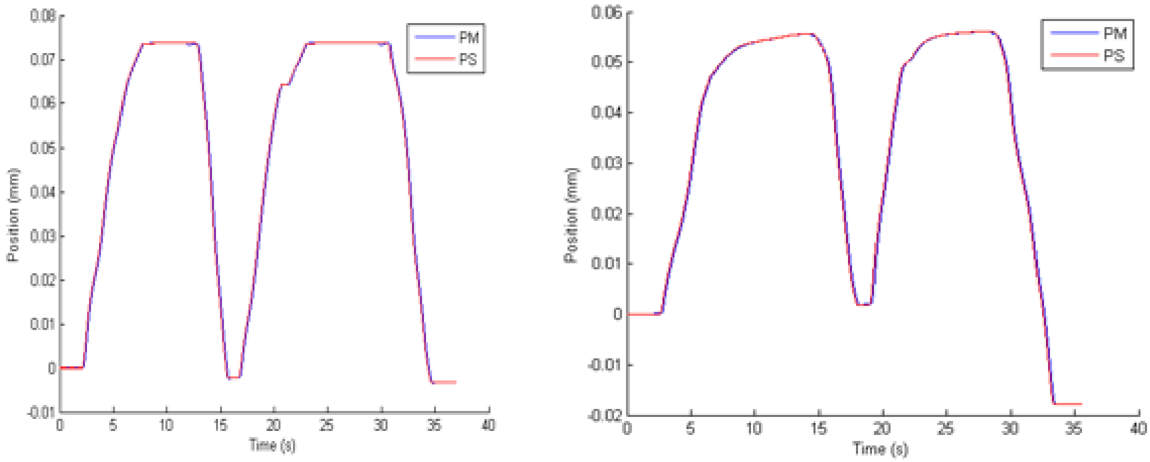

Figure 5-39: Position graphs for hard and soft surfaces, respectively, at the 'Time Delay' effect.

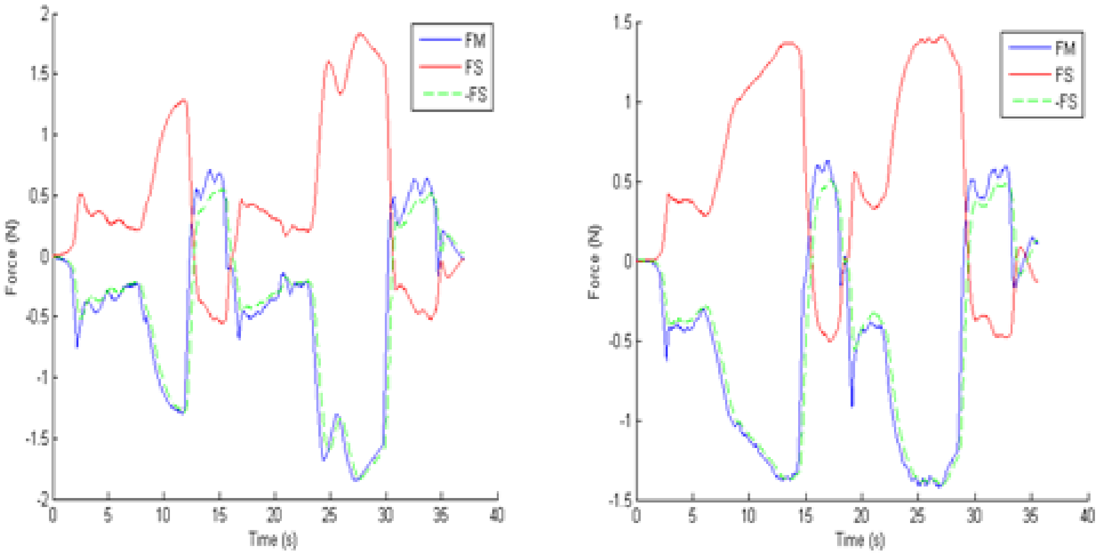

Figure 5-40: Force graphs for hard and soft surfaces, at the 'Time Delay' effect respectively.

When we look at the graphics we obtained with the model we created for P-F with time delay, we observe that the position control works stably and efficiently. On the other hand, although our force feedback is partially efficient at contact, it produces an inefficient result in free motion.

5.3.3 F-P Control System

The main Simulink scheme we use in F-P channel control systems is shown in the **Figure 5-41**

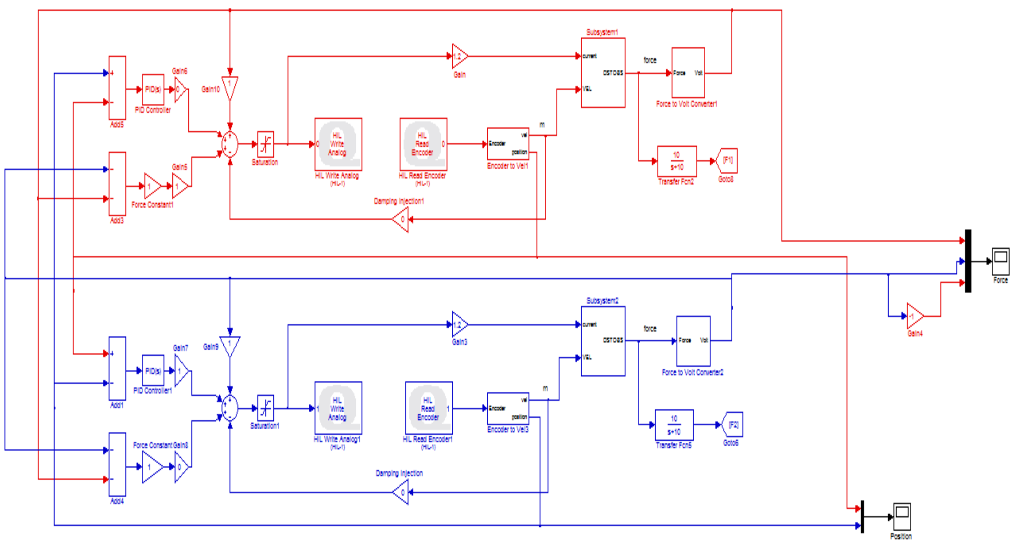

Figure 5-41: F-P Simulink Scheme

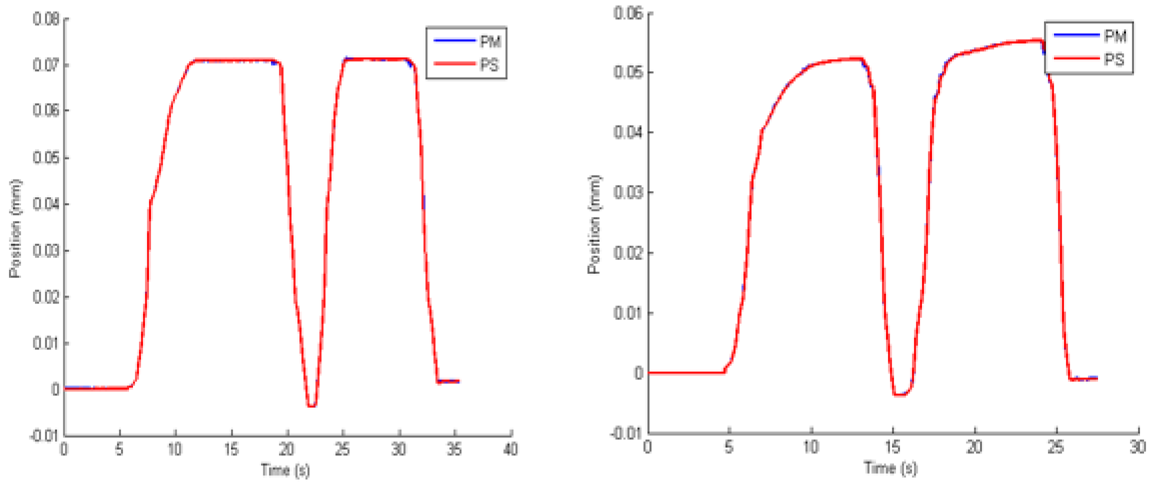

Figure 5-42: Position graphs for hard and soft surfaces, respectively.

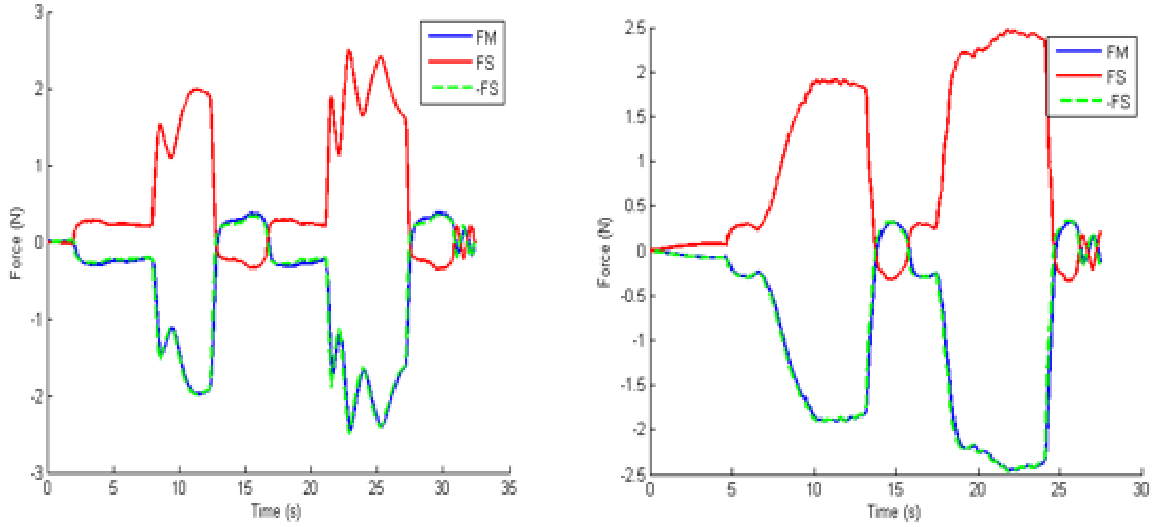

Figure 5-43: Force graphs for hard and soft surfaces, respectively.

If we look at the graphs we collected with the model we created for our F-P control system, we observed that there is a high level of recoil at contact with the hard surface. For this reason, we could not get an efficient force feedback. However, if we look at the tests we made on the soft surface, we observe that our system works without any problems. We added 'Damping Injection' to our model so that our system can work efficiently on hard surfaces, and we repeated our experiments.

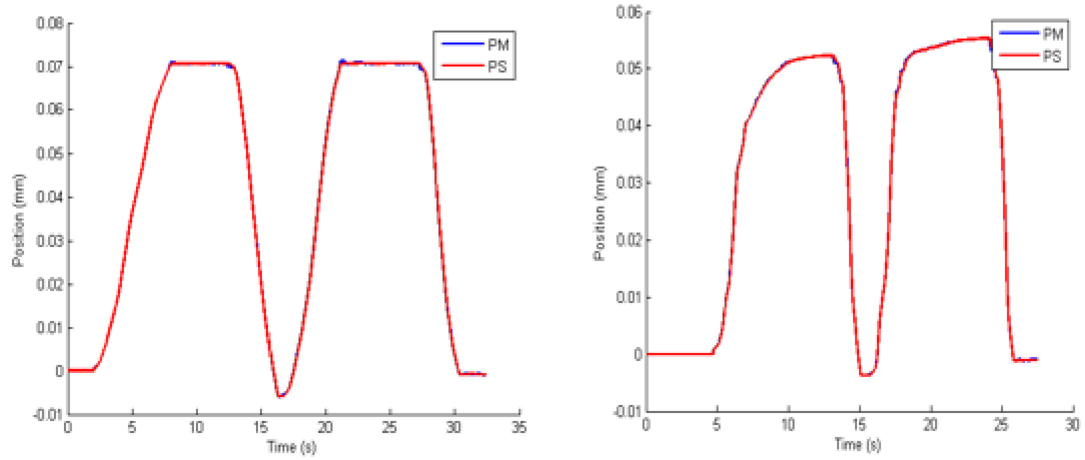

Figure 5-44: Position graphs for hard and soft surfaces with D.I., respectively.

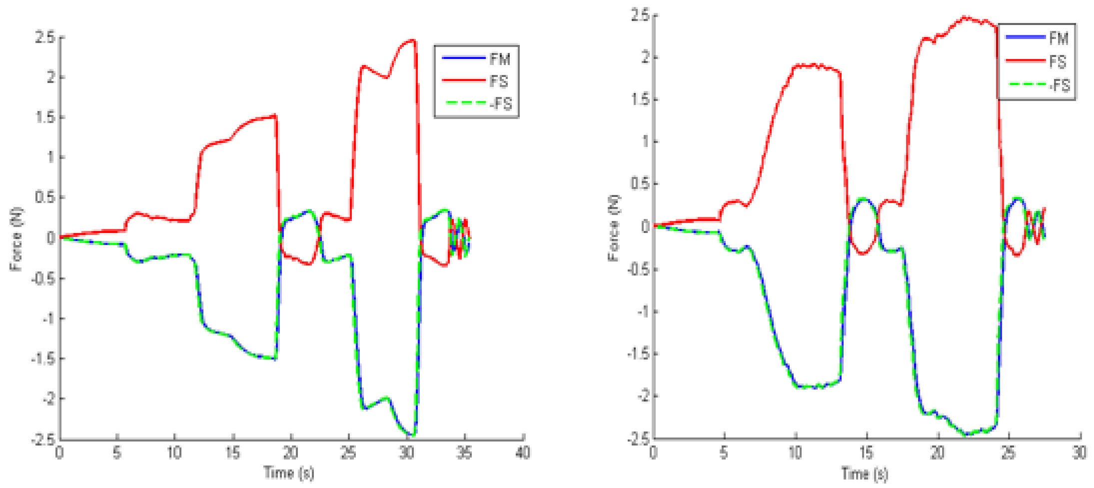

Figure 5-45: Force graphs for hard and soft surfaces with D.I., respectively.

If we look at the graphics we have obtained from the experiments we have done with the model we have added 'Damping Injection', we observe that we have made our system stable and efficient. Our model has become stable for both surfaces.

As a next step, we added 'Time Delay' to our model and repeated the experiments.

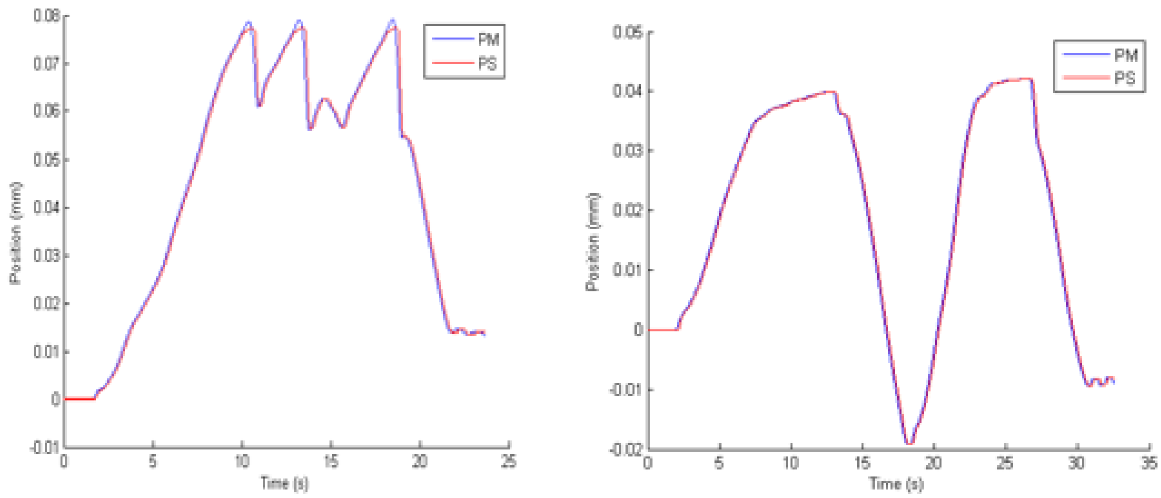

Figure 5-46: Position graphs for hard and soft surfaces, at the 'Time Delay' effect respectively.

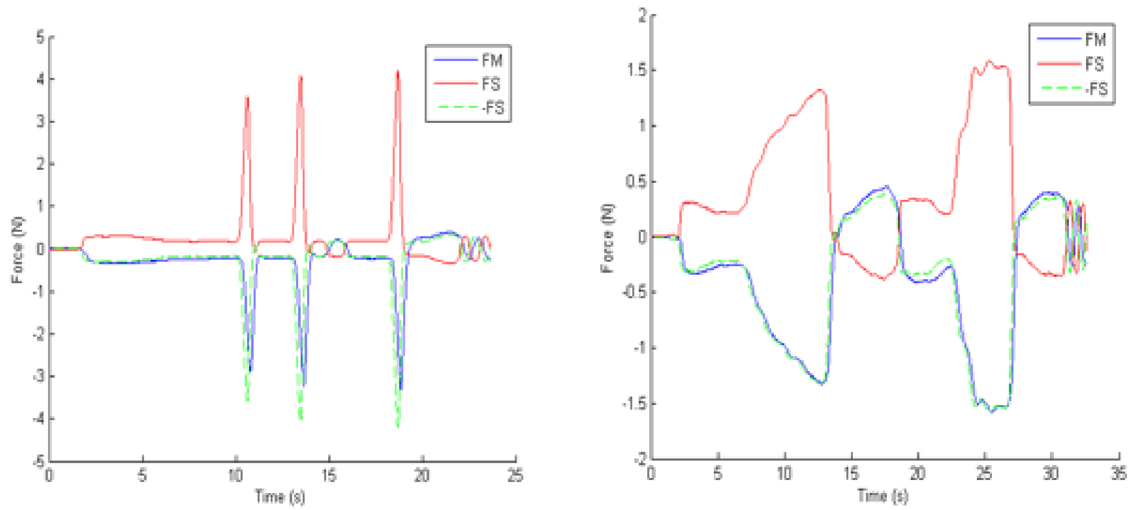

Figure 5-47: Force graphs for hard and soft surfaces, at the 'Time Delay' effect respectively.

When we look at the graphics that came out as a result of the tests we made with our model to which we added time delay, we observe that our system recoils at the moment of contact with the hard surface, so the desired force feedback cannot be made. On the other hand, in our tests with the soft surface, we can say that the position and force graphs are much more stable than the hard surface.

5.3.4 F-F Control System

The main Simulink scheme we use in F-F channel control systems is shown in the **Figure 5-48**

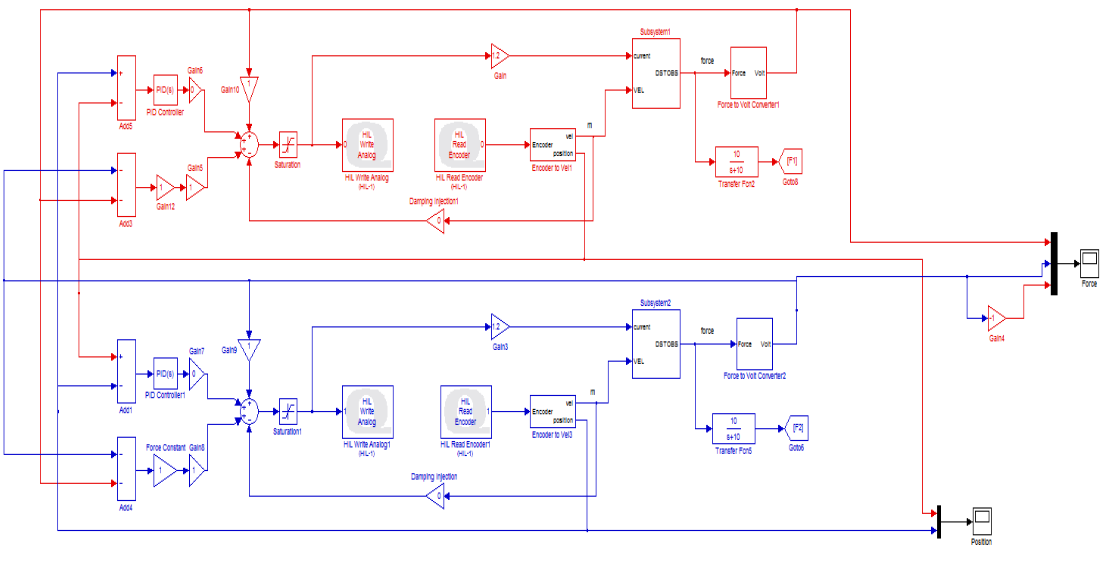

Figure 5-48: F-F Simulink Scheme

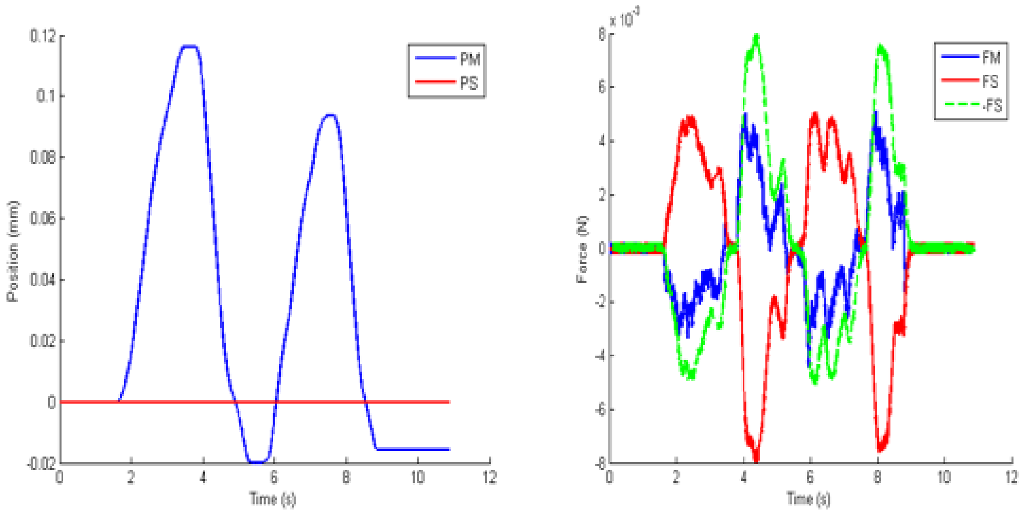

Figure 5-49: Position and Force graphs, respectively.

When we examine the graphics, we observe that the position control is not transmitted from our master to our slave. Therefore, it is not possible to talk about a healthy force feedback. We added 'Time Delay' to our model, as we thought it might change this situation, and repeated our tests.

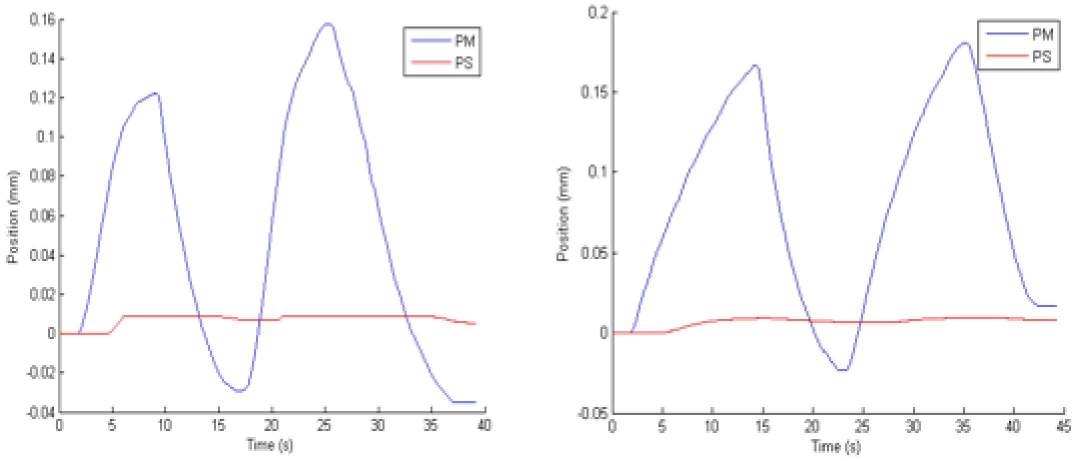

Figure 5-50: Position graphs for hard and soft surfaces, at the 'Time Delay' effect respectively.

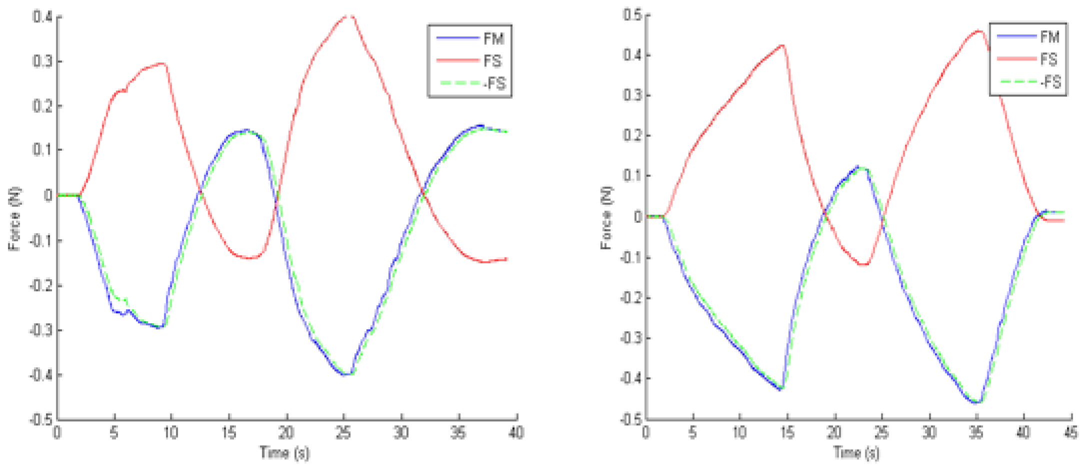

Figure 5-51: Force graphs for hard and soft surfaces, at the 'Time Delay' effect respectively.

After adding 'Time Delay' to our model, we were able to move our slave a little, but there is still very inefficient position tracking. On the other hand, despite this low position tracking, we received efficient force feedback.

6 CONCLUSION AND RECOMMENDATIONS

In this thesis, 4 channel, 3 channel and 2 channel control systems in haptic telerobotic systems are examined with and without 'Time Delay'. We carried out our experiments on linear motors with the MATLAB Simulink model we designed.

For 4 channel control systems, the control system without time delay works more stable and is more preferable.

All systems work stably when there is no time delay in 3 Channel control systems. In models using time delay, the most desired results were obtained from the P-PF control system.

In 2 Channel control systems, P-F control systems gave the most stable results in both cases. In the F-F control system, there is no position feedback from the master to the slave.

As a result, we were able to operate all other control systems stably and efficiently without time delay, except for the F-F control system.

The Development of Haptic Telerobotic System will provide great convenience in many areas, especially health, in the world industry. This technology should be given the value it deserves and the development process should proceed faster.

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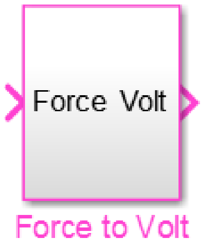
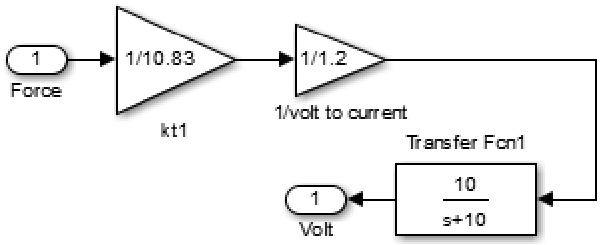
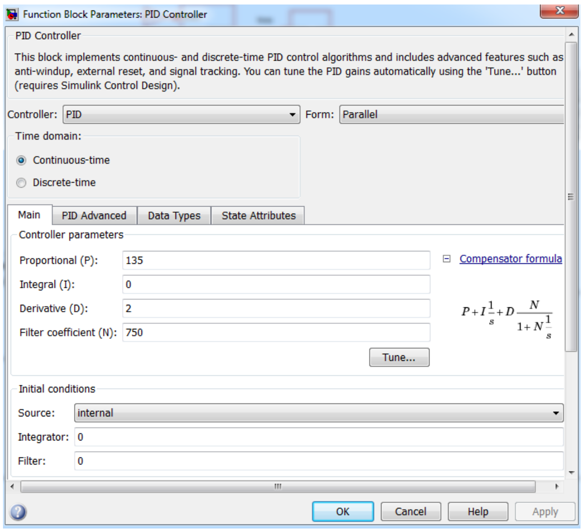
8 APPENDIX



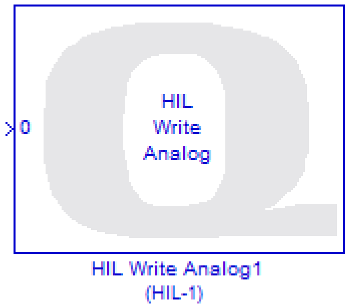
Force to Voltage Convertor

Input : Force (N)
Output : Volt (V)

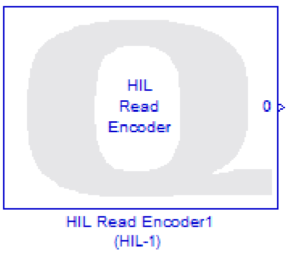




PID Controller Values



Write Analog Block to transfer data from Matlab to Daq Card



Read Encoder Block to transfer data from Daq Card to Matlab