Study on Control of a Smart Manipulator with Ultrasonic Motors

超音波モータを有するスマートマニピュレータの制御に関する研究

by

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Abstract

The utilization of robots for planetary exploration has reveled itself a promising way of understanding the history of the solar system. Scientists have already acquired precious data in the recent robotic missions to Mars and the Itokawa asteroid. Now, after forty years that man has first landed on the Moon, the efforts continue on understanding its formation. With forty years worth of technology development, robots are the key to a successful mission.

In the beginning of the robotic exploration, the idea was mainly to take the cameras closer to the surface so that images could be analyzed by scientists on Earth. In time, the role of the exploration robots has evolved into more sophisticated tasks requiring greater automation in navigation and the capacity to deploy instruments for in situ analysis. For future missions, the objective is quite the same and the main task of the exploration robots will be to collect and analyze samples of soil and regolith of the host planetary body. For that, and other purposes that require interaction with the environment, a robotic arm, or manipulator, is required.

Many researches presented manipulators for planetary exploration, but most of them are designed for a specific set of tasks or with limited application. Most of the times the arms would get too heavy if they were built to perform all the desired task. Recently, the Japanese Aerospace Exploration Agency, together with The University of Tokyo and Chuo University, has put some effort towards a general purpose manipulation technology for lunar exploration. The idea is to utilize lighter materials to fulfill the general purpose requirements and increase task capability. The resultant system is a light-weight six degrees-of-freedom (6-DOF) smart manipulator that is actuated by ultrasonic motors (USM).This master thesis describes and evaluates the developed system and proposes the necessary control scheme that better fits the system towards general purpose application.

The main challenge was to overcome all non-linearities presented by the USM system and also reduce the residual vibration caused when considerable load was

applied to the moving end. The solution that was studied and adopted was to combine a s-curve input shaper with a PID controller to track the desired velocity. Satisfying results were obtained with this method.

Acknowledgements

stand that I was victorious when I could only see defeat. Specially to my colleague and best friend Noriaki Mizukami who dedicated time and patience to teach and explain to me the Japanese culture and the ways of the Nichiren Buddhism.

<div align="right">Rodrigo Minghini</div>

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Chapter 1

Introduction

1.1 Motivation

The constant progress in robot technology have allowed mankind to reach places that some decades ago it was only imagined to be possible to reach. Motivated by the desire to understand where we came from, where we are now and to what part of the universe we are all going, scientists and engineers began to develop robots. These robots are supposed to investigate other planetary bodies and look for clues on how to answer those questions.

The first step towards achieving such knowledge is to understand the formation of the solar system. Once we can certainly explain the formation of our little space, perhaps the same logic can be applied to understand the mechanics of the entire universe. One of the points of interest to the scientists is to find out how the geological formation of planets and other celestial bodies differ from or resemble to each other. That could prove if the solar system was once a big galactic Pangaea for example.

Therefore the task to be accomplished at this stage is to collect and analyze soil samples from different planetary bodies and create a pattern throughout the solar system.

1.2 Background

After the success of NASA/JPL's MER and Phoenix missions that took robots to Mars and JAXA's Hayabusa and Kaguya(SELENE) missions that explored Itokawa Asteroid and surveyed the Moon respectively, both agencies plan to provide more scientific power to robots. As the American agency aims to send another rover to Mars, JAXA plans on exploring the surface of the moon to get prepared for a possible manned mission.

One of the intended goals for future missions is not only to provide robots with means of performing soil analysis in situ, but also to collect samples to be sent back to earth. Sending collected material back to earth means that a whole launching system should be provided in the first place. Considering all the required resources for that purpose, it is expected that sample return maneuvers would only happen a couple of times. Therefore, it is important that a large number of samples should be collected at each time. Meaning that rocks and regolith from several different places should be collected in the shortest time possible.

The idea then is to create smaller and simpler robots that would work together to reach a wider area of the host planet's surface. Another idea is to provide landers and bigger robots with a greater capacity of interaction with the environment. That also means to increase the degrees of freedom that a robotic manipulator can move to perform a desired task. For this purpose, The University of Tokyo and Chuo University, together with JAXA, have put some effort towards the development of small-sized, low-weighted robotic devices that would comply with that idea, considering that until now, more degrees of freedom meant more weight. One of the achieved results was a robotic arm actuated by ultrasonic motors [7].

1.3 Goals and Approach

Based on the novel manipulation idea explained in the previous section, the purpose of this thesis is to describe and analyze the responses of the robotic arm actuated by ultrasonic motors and propose a suitable control scheme that will provide a satisfactory performance of the system. During this process different methods of control were studied and, when necessary, put into test in the manipulator system. For being a light weighted system, it is expected for parts of it to present some flexibility when load is applied. In most cases, flexibility generates residual vibration. Depending on the amplitude of this residual vibration, the manipulator could present hazardous behavior or imprecision in movement and tasks. Besides the residual vibration problem, the USMs are also known by their non-linear behavior due to contact characteristics between rotor and stator. Therefore, all these characteristics of the smart manipulator system were evaluated and considered for the development of the controller. Another important point that had to be taken into consideration, is that the system is supposed to work in foreign unknown environment so robustness is essential. For that reason, control schemes that require training were studied but not considered. Also, for cost reduction matters, commercial off-the-shelf actuators and sensors were used. Finally, a simulation environment that can work as framework for the development of task algorithms was part of the goal of this work.

1.4 Related Work

In terms of controlling the USM there are several propositions that consider Fuzzy Logic, such as [1] and [11] and Artificial Neural Networks as shown in [12]. But as explained before this work focused in combining precise positioning with vibration suppression using robust methods that do not require neither training nor extra sensors. In terms of vibration suppression in end-to-end motion, the works related to feed forward input shaping techniques, such as [6], [13], [8] were considered. These

techniques rely on approximate models of the flexibility behavior of the system to provide considerable reduction on residual vibration. The point to be considered here was that for USM the shaped input must respect the timing of the controller response to compensate the dead-zone of the motor.

1.5   Thesis Organization

This document is devided in seven chapters each of which will address the following topics as it will be explained. Chapters 1 and 2 give a general view of space mission requirements and describe the robotic manipulator system in detail. The analysis and responses obtained from the system are addressed in Chapter 3. Chapters 4 and 5 show the study made on control methods and the suggested method that better fit the system and compare the results obtained using simulation models. Chapter **??** addresses the test results obtained using the suggested method and compares with the simulated results. Finally, conclusions and considerations about the results presented in this report are discussed in Chapter 6.

Chapter 2

Smart Manipulator

Since the beginning of the studies considering manipulators for planetary exploration, a 6-DOF manipulator (necessary to provide any attitude of the end-effector inside the working space) was avoided due to excess of required weight, as explained in [4]. Robots studied in JPL [3] and [10] also considered only 4-DOF.

In this chapter all the components of the manipulator system will be described. Details and their relevance to this work will be explained.

2.1 Robotic Arm

The robotic arm is a spherical wrist connected to an elbow manipulator. This means that there are six revolute joints, hence a 6-DOF robotic arm. Each part will now be explained in detail.

2.1.1 joint

The joint is a cylindrical case that lodges an ultrasonic motor, an optical encoder and a harmonic gear drive. The joints were designed in a way that there is no transversal between two joints. That means that all the joints will belong to the same plane no mater the configuration of the arm.
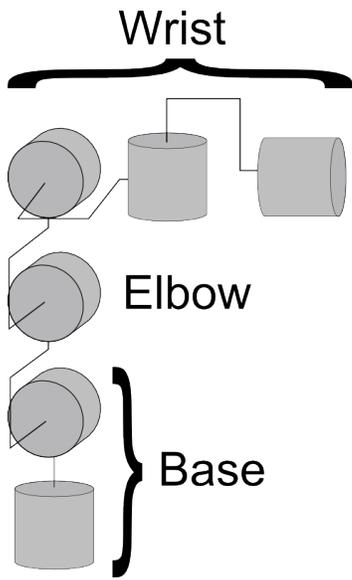
(a) Revolute Joints Scheme

(b) Smart Manipulator Deployed

Figure 2.1: The 6-DOF Smart Manipulator System

2.1.1.1 Ultrasonic Motors

The ultasonic motor is a device that converts electricity in mechanical energy by creating a traveling wave between to surfaces pressed together. The stator part of the motor is assembled on the top of a piezoelectric ceramic ring. By applying a pair of sinusoidal voltages fazed in 90^0, a traveling wave is generated. According to the properties of the ceramic used, a proper frequency is required so that the propagating velocity of the traveling wave will make rotor part of the motor run.

The motor used in the joint is a commercial, off-the-shelf, model. The USR30 made by Shinsei Motor. It is important to notice though, that this motor requires a special driving system that generates the proper signal. The commercial driver, made by the same company, was used to provide the signal to actuate to joint.

Table 2.1.1.1 summarizes the characteristics of the motor

There are a few reasons why the USM was chosen instead of a electromagnetic motor. When both motors are compared taking torque capacity as reference, the

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Rated Output Power	1.3W
Rated Speed	250rpm
Rated Torque	0.1Nm
Retention Torque	1.0Nm

Table 2.1: USR30 specifications

following advantages can be told about the USM.

- Compact and light-weighted

- Zero power self-retention
  (no free motiom)

- Lower speed
  (smaller reduction gear stage required)

- High responsiveness
  (motion inertia compensated by internal friction)

One important thing to consider is that when used with the commercial driver as a set, the operation of the motor changes compared to normal FEM motors. There are three different input signals required to operate a USM. A 0 3V analog input that controls the motor rotation speed and two TTL digital inputs that select direction and defines the on/off state of the motor. When both TTL signals are low, the motor is in its off state. That means that it is retained and no matter the amplitude in the speed control input, the motor will not operate. If one of the directional inputs is on its high level, the motor will operate to the direction determined by the chosen input port and the speed will be defined by the speed control analog input. In this case, even if the analog input level is 0 (zero) and the rotor is at rest, the phased sinusoidal voltages will still be applied to the stator, hence the current maximum torque will not be the retention torque.

2.1.1.2 Optical Encoder

The optical encoder converts pulses into angular displacement information. The model used here is the HEDS-9140 from Avago Technologies. The reasons to adopt this device are as follows.

- Resolution of 500 pulses per revolution

- No signal adjusment required

- Small sized

- -40°C to 100°C operating temperature

2.1.1.3 Harmonic Gear Drive

The harmonic gear drive is a coaxial reduction stage that offers high reduction in reduced space. Some of the advantages of its usage are as follows.

- 1:100 coaxial reduction

- Compact size

- No backlash

With the reduction obtained in this stage the joint angular displacement has a 50000 pulses per revolution of resolution.

2.1.2 Links

The links used in the proposed system are carbon fiber made tubes. A light but extreamily rigid material. Different lenghts of links were considered depending on the total payload of the wrist and the necessary torque for the tasks.

2.1.3   End-effector

The end-effector of the manipulator system, as the name already says, is the end part of the system that is supposed to interact will the environment, in other words, it will be the agent responsible for causing a desired effect. By the time that this study was made the end-effector had not been developed yet. Altought as its design was originally part of this research, some of the ideas will be presented in the appendix REF.

Chapter 3

System Response and Modeling

This chapter will describe the tests into which the manipulator system was submited. It was according to the results obtained at this stage that models of the system could be defined and a proper control scheme could be studied.

3.1   Testbed Setup

To obtain relevant information of the system to be modeled, it had to be submitted into different kinds of tests. It would be ideal if all the necessary data could be collected from the sensors already mounted on the manipulator. Unfortunately though, some of the tests required other kinds of sensors. Responses from motor input signals were measured through its optical encoder, but flexibility measures had to be undertaken with the assistance of an accelerometer.

To operate the system and capture the encoder response, the manipulator was attached to a DSP board that operates using a proprietary software. This system called dSPACE®and interface creator ControlDesk®can be used together with MatLab®Simulink®to operate input signals and capture sensor data.

3.2　Joint Response Analysis

The first step on understanding the functionality of the robotic arm is to analyze its actuator. Even though the motor itself is somehow understood, when combined with the other elements of the joint there might be other characteristics to be considered from controlling purposes. For that reason, the joint actuation unit was submitted to different kinds of tests.

3.2.1　Frequency Response

(a) 0.1 to 30 Hz chirp　　　　　　　　　　　　(b) Frequency domain
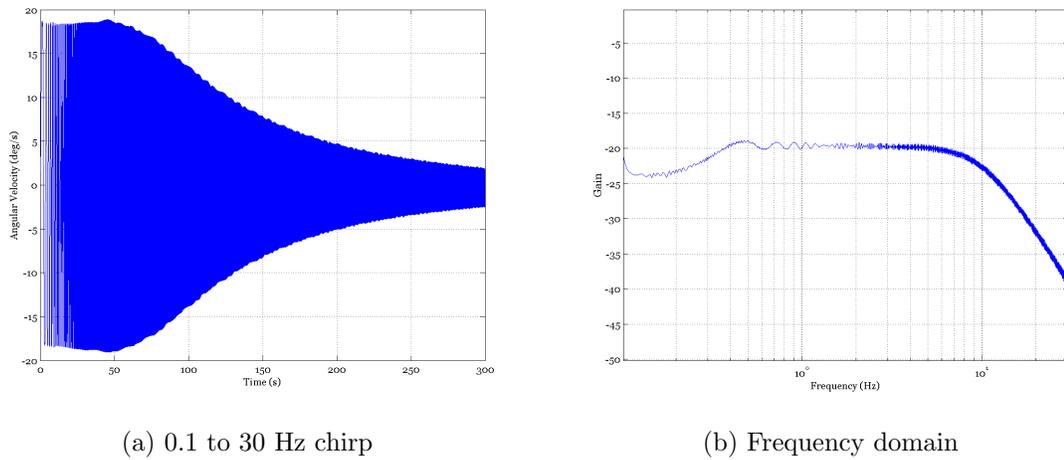
Figure 3.1: Frequency Response of the Joint with a 10Hz cut-off LPF

Figure 3.1a shows how the joint responds sinusoidal input varying from 0,1 Hz to 30 Hz. This result was actualy the signal from encoder passing through a low-pass filter with a 10hz cut-off frequency. Changing the frequency of the filter and rerunning the test showed that the high responsiveness of the motor surpasses its physical limits. The application of higher frequencies caused to motor to stop working. The frequency response analysis gives a approximate idea of the joint response. Ideally, this is the desired response to be used to model the system and develop a controller for it.

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Although, according to results presented by different authors [2] [5] [11] the non-linearities originated in the mechanical contact between stator and rotor of the USM, considerably change the response of the system in time.

3.2.2 Constant Response in Time

The joint response in time to a constant input also presented some considerable variation. Most of the effects are from the USM, but it might also be caused by imperfections in the joint assembling. Due to this characteristics that it was decided not to use the rated speed of the USM as the maximum speed. It was decided to leave a small margin that could be compensated by the controller in case the motor parameters change in time. To get a better idea of the signal response in time, a low-pass filter with a 10Hz cut-off frequency was applied to the capturing interface.

(a) Angular velocity in time   (b) Output X Input
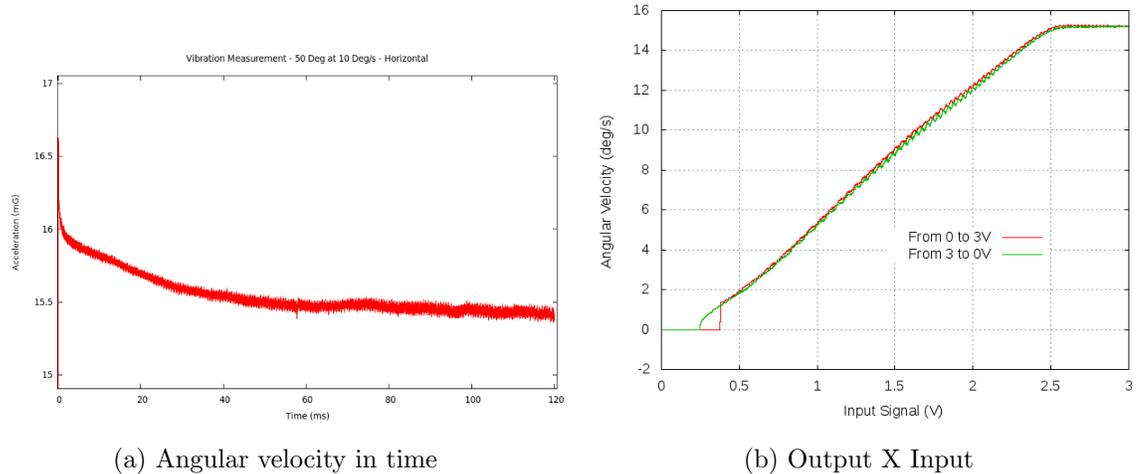
Figure 3.2: Residual Vibration

Figure ?? shows what could be imperfections in the coupling of the joint elements. Perhaps an inclination in the motor axis that leads the harmonic gear drive. But more than that reveals the extream non-linearity near 0V. Dead-zone and output off-set

are expected as motor response.

3.2.3   Flexibility

The smart manipulator system is a light-weight robotic arm with rigid links, but when submitted to a end-to-end motion with heavy load in the moving end it produces what is called residual vibration. According to its mechanical characteristis is could be observed that the vibration is originated in the harmonic gear reduction stage. The flexible cup that is connected to the link bends in a torsional way causing vibration. The oscillaation is naturally damped due to mechanical hysteresis. But as observed in the modeling section, there might also be coulumb damping due to friction in some amount.

(a) Vertical   (b) Horizontal
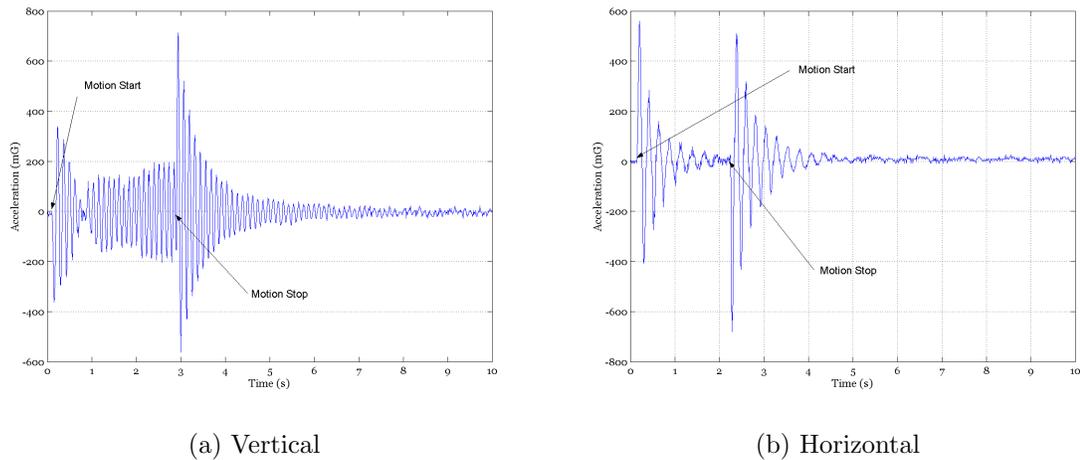
Figure 3.3: Residual Vibration

Considering that the optical encoder is only sensitive to the motor output, to measure the flexibility of the arm accelerometers were used. Vibrations were then measured as the output of the angular acceleration impulse, i. e. the angular velocity step. Figures 3.3a and 3.3b show the resultant residual vibration from both vertical

and horizontal motions.

3.3 Modeling

3.3.1 Motor

Considering the complexity of the functionality of the ultrasonic motor, it is quite a challenge to model it with fidelity, or at least some approximation. Some authors have proposed physical models or ways to represent it in a more practical way. But to use a reliable model would mean to increase the complexity of the control system. Besides, it would require more sensors just to acquire the necessary data to confirm the validity of the model since its parameters depend on time, temperature and so on.

For that reason, only the most relevant characteristics of the motor were considered in a approximate way to create a model. That model was only used during simulation stage to represent the high non-linearity of the system.

Basically the most relevant characteristics of the motor are:

- Input dead-zone between 0 0.3 V

- Off-set speed at 0.3V

- Speed varies according to the applied load

- Frequency response in the linear interval.

3.3.2 Vibration

For modeling the flexibility of the arm it was assumed a second order (spring-damper) system. Normally, the equation that describes the motion of a spring-mass-damper system of a mass m connected to a spring of constant k and damper constant c is written as follows.

$$\ddot{y}m + c\dot{y} + ky = u(t) \tag{3.1}$$

with $u(t)$ as the system's input. Although, as shown in Figure 3.4, the motion is an angular motion and the mass is submitted to a momentum of inertia. Hence, the new equation becames

$$\ddot{\theta}j + c\dot{\theta} + k\theta = u(t) \tag{3.2}$$

in which j is defined as $j = m.l$ with l being the distance from the center of rotation to the center of mass.

Considering that the manipulator has an elbow, the distance of the mass to the center of rotation will also depend on the current angle of the elbow and the total residual vibration in the wrist will be the sum of all the residual vibrations of each previous joint. Nevertheless, in this study it was only considered the resultant vibration of the shoulder joints. That is because the residual vibration originated in the wrist due to the elbow joint is not as significant as the vibration due to the flexibility in the shoulder.

To determine the constants of the equation 3.2 two parameters had to be acquired from the response analysis of the system. The natural damped frequency ω_d and the damping ratio ζ. With those parameters, c and k can be obtained using 3.3, 3.4 and 3.5 as explained in [9].

$$\omega_d = \omega_n\sqrt{1 - \zeta^2} \tag{3.3}$$

$$\zeta = \frac{c}{2sqrtkm} \tag{3.4}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{3.5}$$

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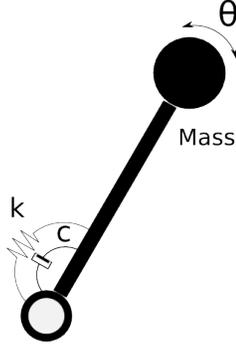
Figure 3.4: Vibration Modeling Schematics

(a) Vertical - 9Hz

(b) Horizontal - 4.7Hz
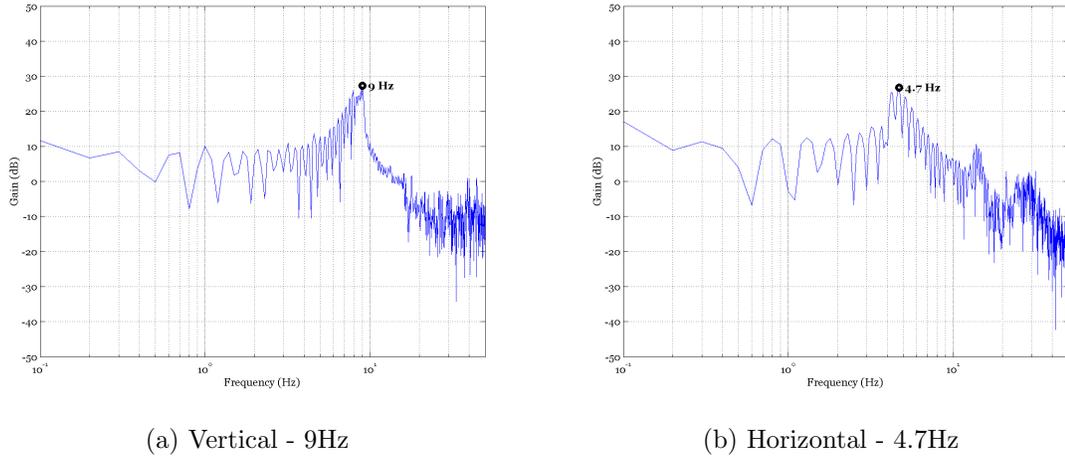
Figure 3.5: Natural damped frequency on the shoulder joints

From the measurements obtained before, the natural damped frequency was measured in a frequency analysis, as shown in Figure 3.5, and the damping ratio ζ was obtained according to the exponential decay of the resultant vibration and calculated using equation 3.6.

$$\zeta = \frac{\frac{1}{n-1}\left(\ln\frac{x_1}{x_n}\right)}{\sqrt{4\pi^2 + \left[\frac{1}{n-1}\left(\ln\frac{x_1}{x_n}\right)\right]}} \tag{3.6}$$
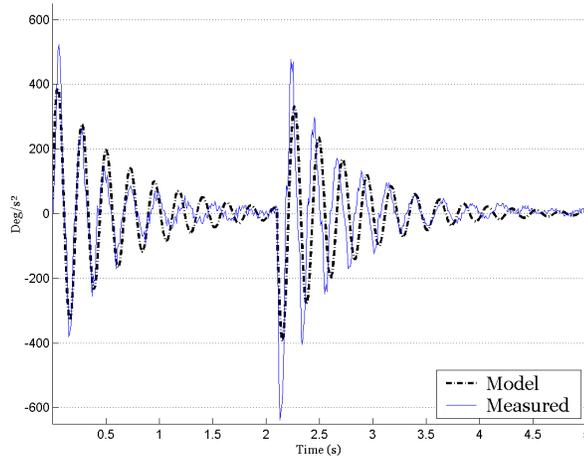
Figure 3.6: Vibration model and measured

Looking at Figure 3.6 it is possbible to observe that the measured vibration changes frequency along the settlement. It is possible that at some level there is a superposition of damping effects. It could happen that for very small angles a coulumbian damping effect takes place changing the damped vibration frequency near settlement. Considering that the elastic properties of the system is the same even with extra damping, the modelled frequency was kept.

Chapter 4

Proposed Control Method

4.1   Control Analysis

4.1.1   Response Evaluation and Signal Feedback

In control theory, using response feedback is a common way to automatically adjust input for achieving a desired response of the system. The most common usage is with PID controllers. Those actually consider the error between input and output as a reference for changing the input of the controlled system.

PID response for position control

The control design for controlling robotic arms has being studied since the first robot was invented. It depends on what kinds of disturbances and the effects caused by those disturbances that have to be reduced, nulled or compensated. Some of the most common purposes for controlling robotic arms are precise positioning, force/torque matching and residual vibration suppression. There is also somewhat of a common sense of the order to be followed when designing control systems. The first step is to ensure that motor and sensors respond efficiently to provide the desired motion and positioning. If this is the only problem to be solved, the controller mainly focus in

the optimization of the time taken and the reduction of the final position error. The PID controller would probably suffice for such case. As seen in Chapters 2 and 3, the USM has a peculiar response to the input. Normally, servo systems also present similar non-linearity as response as well, mostly due to friction between gears and so on. Although, different from electromagnetic motors that the voltage input has a direct relation to the output torque, and that angular velocity is a result between the balance of forces, USMs provide angular velocity as output instead of torque. Of course as any other physical system, it will present losses according to the applied load, but it is a much more complicated relationship in which torque depends mostly on the contact friction between stator and rotor. In [2] a circuit analogy to the USM for control purposes was proposed, but it is still a time dependent set of parameters. For such reason, even though the use of a simple PID controller could provide a way for positioning the motor, it was not enough to compensate the non-linearities of the USM.

PID response for velocity control

In the other hand of the results obtained using a PID for positioning of the robotic arm, it served as a great tool for compensating most of the non-linear problems to stabilize the angular velocity. The USM is not an unstable system, but due to its intrinsic mechanics and also some imperfections in the kinematic design of the joints, the motor output presented a harmonic oscillation in constant speed. Figure 3.2b shows how is the angular velocity output of the joint.

Using a PID to control the output considerably reduced that effect. Also, as will be explained in this chapter, the angular velocity control is a key part of the controller design. Another thing that could be observed latter during the experiments, is that the same controller could compensate possition error by using a double integrator. In that case, instead of using the whole position error as input, it just considerd the instantaneous error due to the time response of the velocity controller.

4.1.2 Response Estimation and Signal Feed-Forward

When there is confidence in the model of a determined system, it is possible to estimate its response before the input signal is actually applied. In such cases it becomes useful to change the input signal previously according to the expected response. For example, flexible beams, robotic arms and so on, might produce residual vibration. If a model of the vibratory oscillation is obtained, the input of the system can be shaped to nearly null the effect. Based on the oscillation model obtained in Chapter 3 it is possible to establish a acceleration profile that if respected will reduce the amount of residual vibration in the end-to-end motion.

Input Shaping

In the case of reducing the amount of residual vibration in an end-to-end motion, one has to reduce the amount of energy in the spectrum band in which the natural frequency of the system and its multiples are located. Considering that most of the actual robotic systems are controlled in a discrete time basis, most of the changes in the input signal becomes a step like signal. As its known, this kind of signal produces frequency components in a wide range of the spectrum. If the stimulus to vibration is the derivative of this signal it becomes even worse. As suggested by [6], the proper train of steps with the right amplitude of the input signal in the proper allocation in time, cancels out the effects of residual vibration in optimum systems. For situations when there is uncertainty about the model of the system to be controlled, there must have be some compensation of this uncertainty. Nevertheless, recent studies concerning these methods do not take into consideration what kind of actuator that is being used. Unfortunately, the difficulty to predict the output of a USM makes it almost impossible to use such a method.

For the present study, the alternative for the controller was to use a continuous-like input shape approach to compensate the limitations of the USM. In this case a PID controller was used to ensure that the motor would track the desired input

according to the desired profile.

(a) Trapezoidal Curve   (b) S-curve
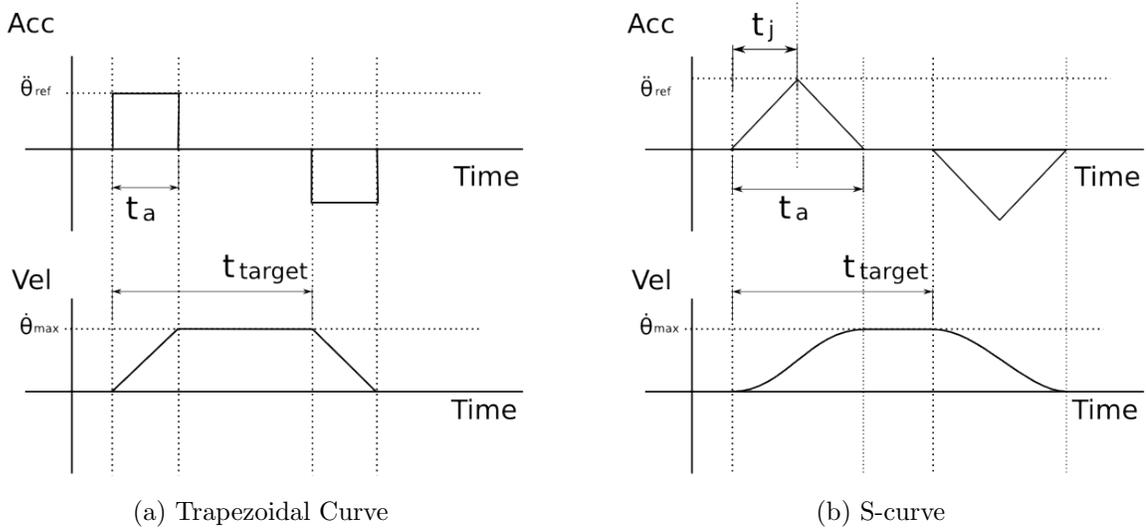
Figure 4.1: Acceleration and Velocity Profiles for Input Shaping

Determination of the input profile

Given a target position and the constraints of the system, it is possible to create a end-to-end motion profile that discribes the desired system response. An end-to-end motion requires the final velocity to be zero. Consequently, all its derivatives should be zero as well. In such a case, one could either consider a constant acceleration segmented motion or even create more segments of the motion by considering the derivatives of the acceleration. Figure 4.1a show the trapezoidal velocity profile that is obtained when constant acceleration is used. When the acceleration derivative, i. e. the jerk is taken as the reference, the result is the s-curve as shown in Figure 4.1b, a more refined profile that reduces stimulations caused by jerk impulses like in the previous example.

Another point to be considered in the determination of the input profile is the symmetry of the input references. according to what paramenter and maximum

values that must be respected, different results of speed and position can be obtained during the motion. This characteristic is used to make position adjustments when required. One example was proposed by engineers at Toyota [8]. For them, it was assumed that the maximum physical velocity of the system is never reached so there is no considerable no-jerk or no-acceleration time.

If the time reference to accelerate and decelerate from the symmetric profile is used as reference for an asymmetric acceleration shape, having the maximum values of velocity and acceleration fixed, the position reached at the end of the motion can be changed. Based on that idea that it was decided to put it into test to be used as fine position control. This method uses both response analysis and estimation. That is because the maximum amplitude of the variable position in the end depends on the shaping time references and the position correction will depend on the response of the system.

4.2   Input Shaper

As mentioned before, the purpose of the input shaper stage is to reduce the residual vibration in the end-to-end motion by limiting the the band of input frequencies according to the natural frequency of the manipulator system. Although, another characteristic of input shaping was examined. That is the capability of adjusting the position error by changing the input profile.

4.2.1   Symmetric Profiling

Basically, to create the desired velocity shape to be followed by the controller in a end-to-end motion, a symmetric motion profile is calculated. Figure 4.1b shows the basic steps to determine the times and maximum values. The first step is to calculate the time to reach the target displacement t_{target} when the angular velocity is ω_{max} and constant. Next, a trapezoidal curve of the velocity is created by applying a

constant acceleration to reach ω_{max}. The maximum acceleration is determined based on the maximum angular velocity and the period of the natural damped frequency T_ω obtained in the vibration model. The time t_{vmax} is then obtained. Applying the same logic to the acceleration profile, using a constant jerk, the jerk time t_j is obtained. Summing up all the times along the motion curve, the s-curve velocity profile can be determined. With this technique of input shaping, the residual vibration can be considerably reduced, but there is no guaranty for precise positioning.

4.2.2 Asymmetric Profiling

So the idea is to redefine the jerk values and times according to the evaluation of the output to provide a fine tune in the position control. Since there is no way to estimate the position error before the motion starts, the only possible way to change the input profile is to calculate the error estimative during the motion for as long as it is possible. This means that only the deceleration part of the input gets to be changed. Another important point that has to be considered, is that there is a limit of how much the final position can be shifted. Furthermore, the position shift comes with the cost of smoothness in one point of the stop motion. To calculate how much can be shifted in the final position, firstly it is required to know the displacement variation during the deceleration period as shown in Figure 4.2. Normally the jerk time during acceleration and deceleration periods are $1/4T_\omega$ for each jerk, but here it had to be calculated as two different times.

$$\theta_{dec} = \dot{\theta}_{max}t_{j1} + \frac{\ddot{\theta}_{max}}{t_{j1}} + \left(\dot{\theta}_{max} - \frac{\ddot{\theta}_{max}t_{j1}^2}{2t_{j1}}\right)t_{j2} - \ddot{\theta}_{max}t_{j2}^2 + \frac{\ddot{\theta}_{max}t_{j2}^3}{6t_{j2}} \qquad (4.1)$$

after some algebraic reductions it becomes

$$\theta_{dec} = \frac{\ddot{\theta}_{max}t_a^2}{3} - \frac{\ddot{\theta}_{max}t_a t_{j2}}{6} \qquad (4.2)$$

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Using $t_{j2} = T_\omega/4$ the displacement during deceleration in a symmetric profile is obtained. Varying t_{j2} from 0 to $T_\omega/2$, the limits of variation of the final displacement are obtained. The adjustments will always fit inside these limits. From Equation 4.2 one can understand that the maximum variation of the final displacement also depends on T_ω.

(a) Angular Displacement and Velocity

(b) Angular Acceleration and Jerk
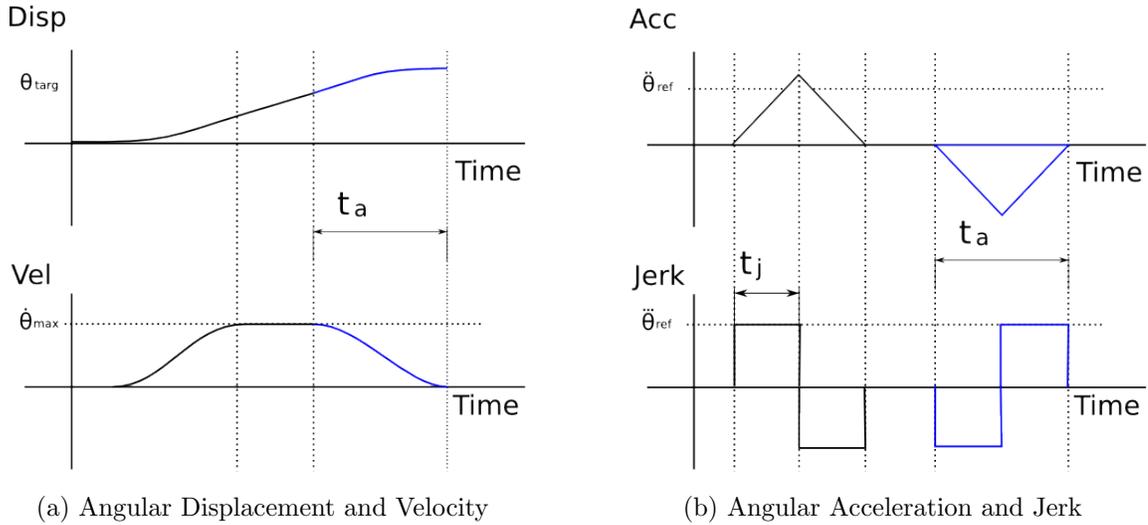
Figure 4.2: Angular displacement during deceleration

4.2.3 Angular Velocity PI controller

It is according to the error between the actual angular velocity ω and the desired shaped angular velocity ω_m that the controller will actuate. The challenge here is to determine the proper controller gains so that the actuation of the joints will not generate undesired vibration. Figure 4.2.3 shows the whole controller scheme.

As explained in chapter 3 the frequency response of the motor observed by the controller will depend on the filter used to reduce noise generated by both motor and encoder. The choice of a low cut-off frequency allows the usage of higher controller gains. The desire to increase controller gains is explained not only by the necessity
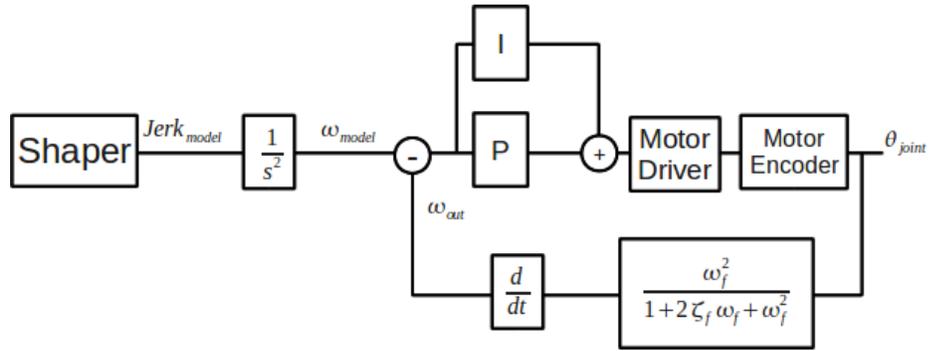
Figure 4.3: Controller diagram

of a rapid response but also because the PI controller alone does not compensate the position error once the angular velocity is stabilized. The greater the integrative gain is, the smaller the position error until velocity stabilization. On the other hand, the increment of the controller gains might generate oscillations in the input until settlement. If these oscillations enter the band of frequencies that stimulates the natural oscillation of the arm, forced vibration will be generated. Hence, all this has to be considered for stablishing a proper set of gains for the controller.

One proposed solution to compensate position error during motion was to add a second integrative stage to the PI controller. Naturally, the output of the first integrator will represent the position error during motion. This error tends to be compensated in the end of the motion. Nevertheless, if the the gain is too small the input signal might fall under the dead-zone limits and the position error will never be compensated. That is why it should be compesated eighter using higher gains to the controller or some other way during motion. The extra integrative gain balances the stabilized input signal between integrator and the proportional controllers.

Chapter 5

Simulation Results

5.1   Vibration Suppression

Simulation tests were conducted firstly to analyse the effect of the input shaping according to the acceleration time in a symmetric acceleration basis. The acceleration time period was decided according to the natural vibration frequency of the arm. Normally for the optimum system, the minimal time to apply and remove force with provoqueing any vibration is the period of the damped vibration frequency. The times $t_a = T_\omega$, $1.5T_\omega$, and $2T_\omega$. Naturally, the chosen time will directly influence the applied jerk. The standard motion adopted to conduct the simulation was 50 degrees of horizontal movement of the shoulder joint. Maximum velocity of 15 deg/s and PI gains of 1 and 10 respectively. Gains were defined by system response observation.

Figure 5.1 shows the effectiveness of the preshaping technique compared to the no-controlled result. Nevetheless, one of the purposes of this research was to find ways to reduce the necessary power to perform all the manipulation tasks, and that includes computer power. To understand the consequences of adapting the algorithm to lower computational capable systems, the results using $t_a = 2T_\omega$ were compared to the same procedure under biger time sampling steps.

Though it is possible to understand that no considerable change in the residual fre-
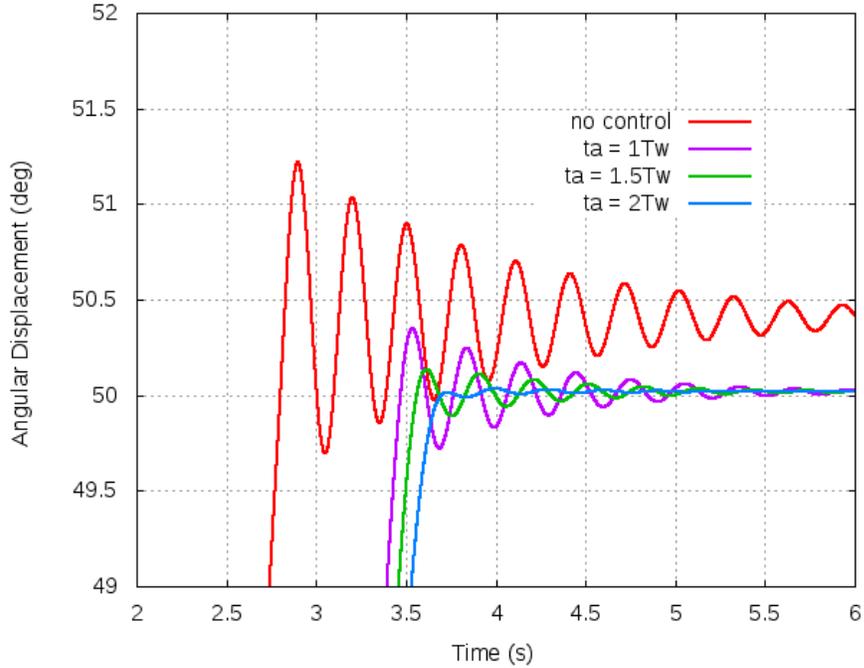
Figure 5.1: Comparison of vibration suppression results according to maximum jerk

quency was observed, there is a clear statement that the final position error increases with the increment of the sampling time. For that reason a model error compensator algorithm is proposed as following.

5.2   Compensation of Numerical Errors

As showed in the last section, the bigger is the time step to conduct the input profiling and the control of the system, the greater the final position error. Observing the behavior of changing acceleration symmetry in the input profile, it could be observed that it is possible to change the final displacement by adjusting both or one of the to acceleration profiles.

figure 5.2 shows that all the constraints of the system can be kept and yet refine the final position by deducing the error during motion and re-profiling the final ac-
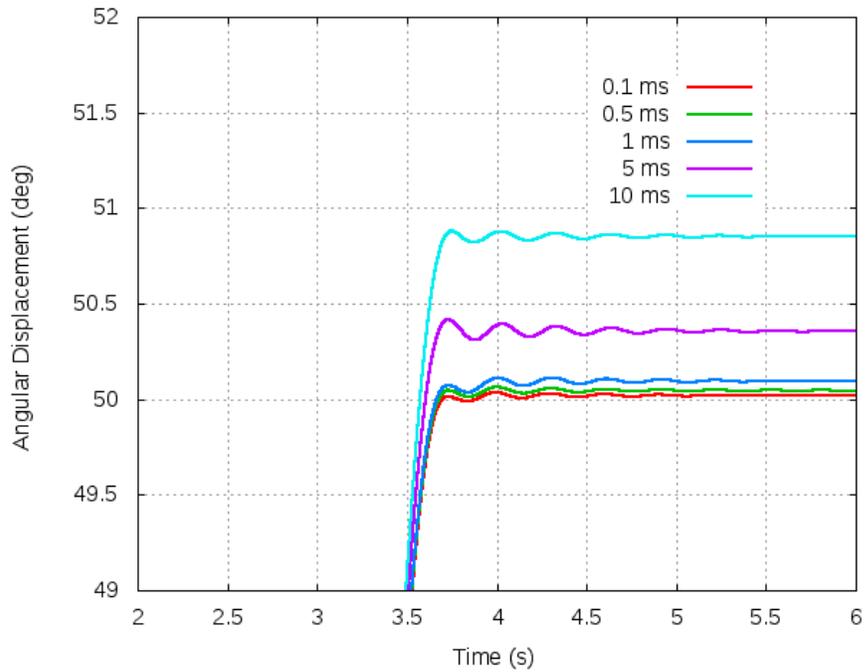
Figure 5.2: Comparison of vibration suppression results according to sampling time

celeration period. There is off course a limit of how much change can be done to the final position in the modeled input. Figure 5.2 explains how this logic works.

5.3   Comparison of Results

Here the results of applying the modeling error compensator will be presented for sampling times from 0.1 ms to 10 ms.

For all the considered cases the logic promoved great compensation of the error and increase precision in the positioning of the joints.
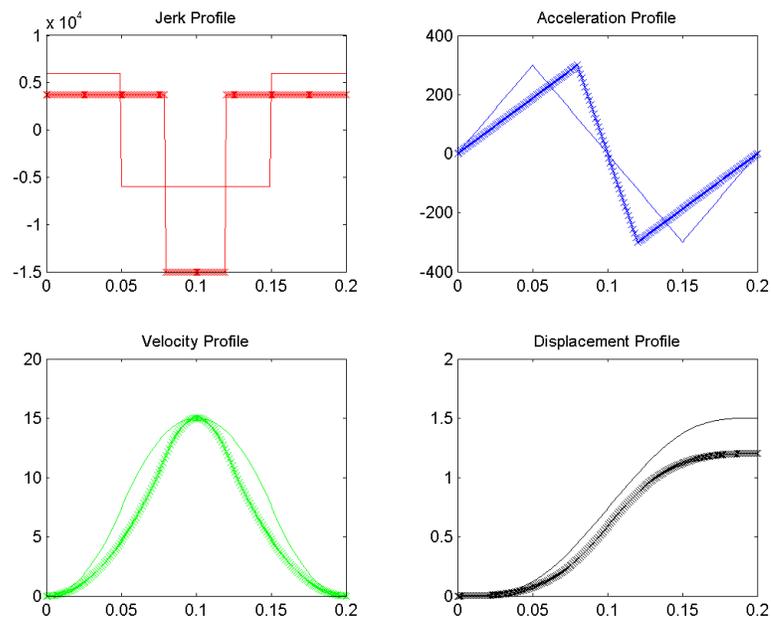
Figure 5.3: Changing the final target position by changing acceleration profile
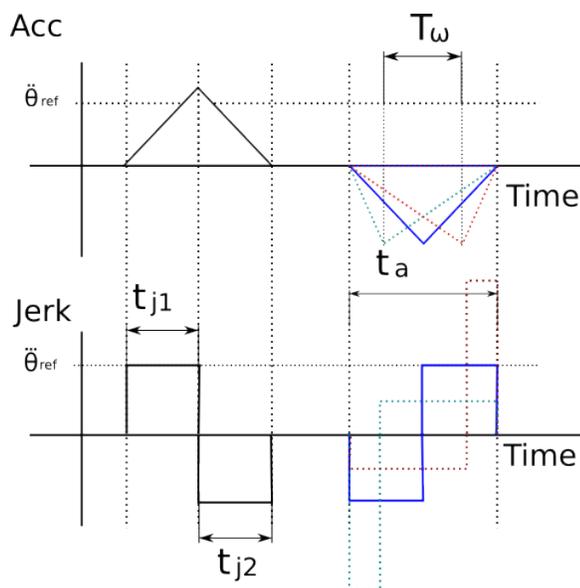
Figure 5.4: Limits in the variations of jerk time and amplitude
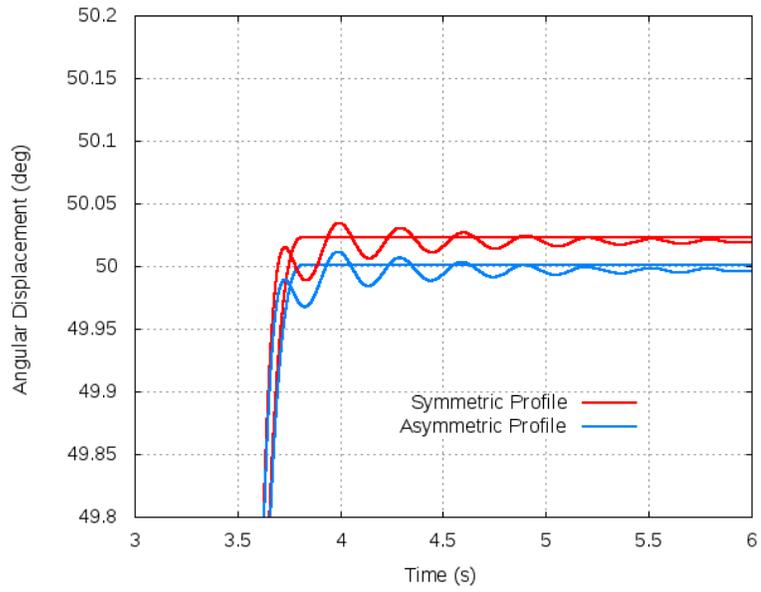
Figure 5.5: Normal and error compensated results for 0.1 ms sampling time
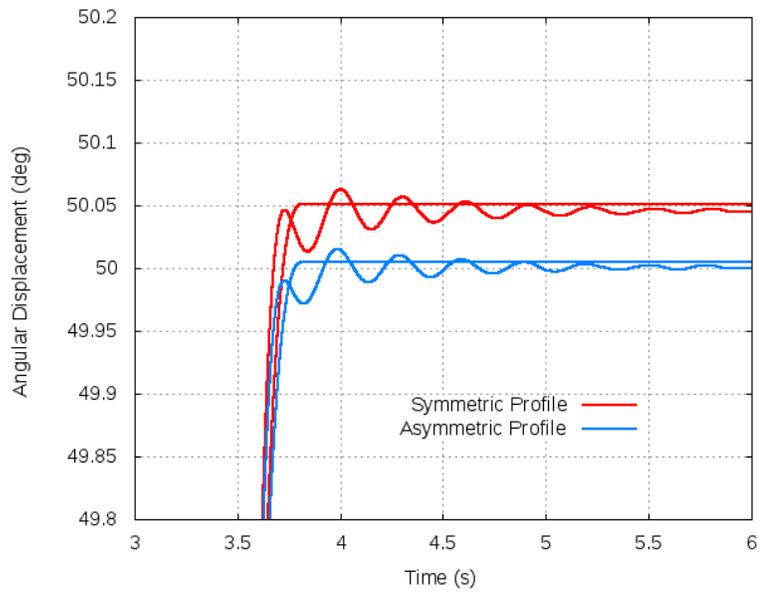
Figure 5.6: Normal and error compensated results for 0.5 ms sampling time
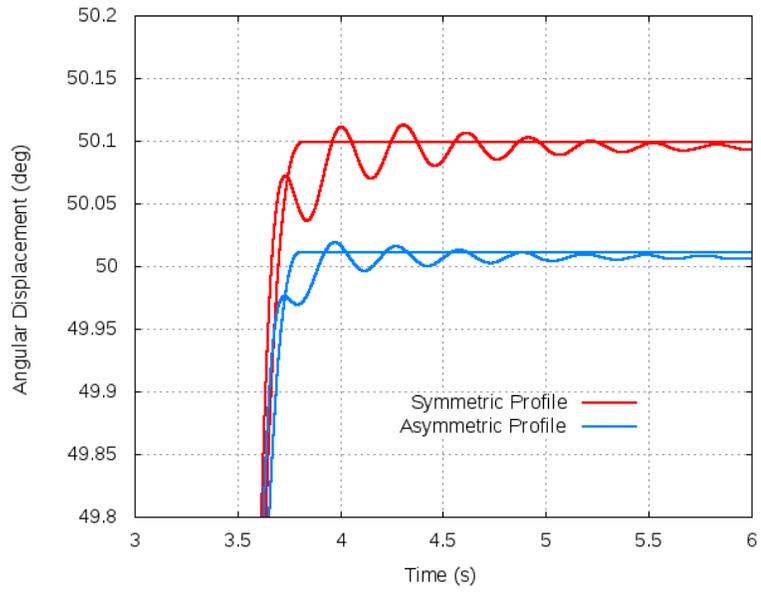
Figure 5.7: Normal and error compensated results for 1.0 ms sampling time
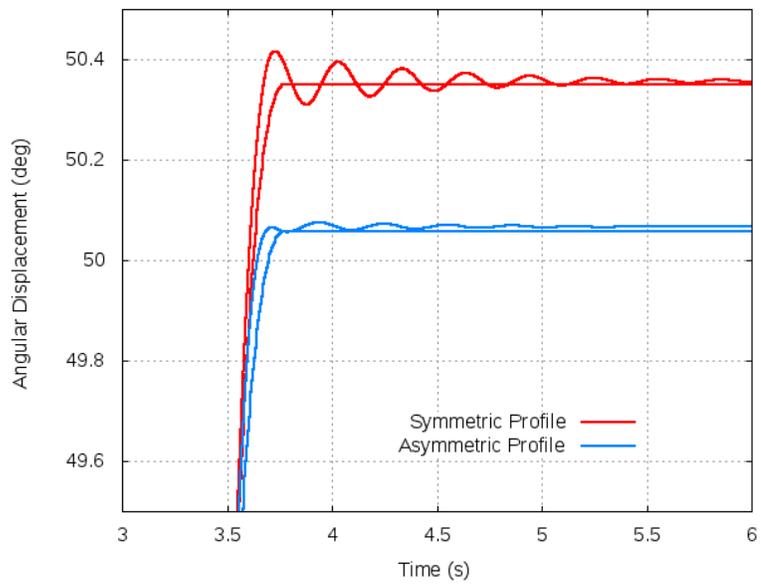
Figure 5.8: Normal and error compensated results for 5.0 ms sampling time
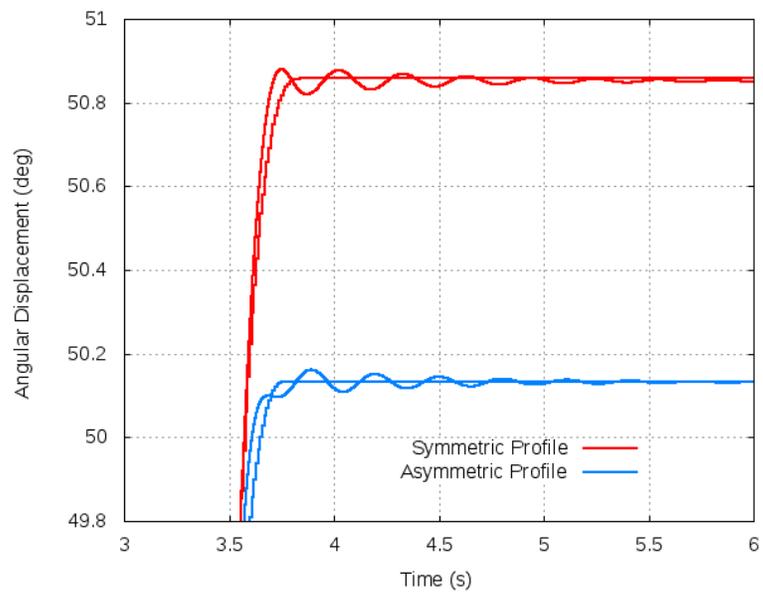
Figure 5.9: Normal and error compensated results for 10.0 ms sampling time

Chapter 6

Conclusions

This work has presented a study of a smart manipulator system that was developed to be applied to remote planetary exploration. This is a novel system because it allows a grater number of joints to be used so consequently a greater number of degrees-of-freedom. This was only obtained by using ultrasonic motors. Although it has many advantages, controlling the ultrasonic motor with simplicity, as is required by space missions, is still a challenge. This thesis showed that it is possible to provide a control system to the smart manipulator. That was done by using an asymmetric s-curve velocity profile combined with a PID controller to follow the desired velocity. The results also allow the possibility of improvement of the idea in cases where estimation can be used to calculate how the profile of motion should change. Finally, as part of the initial goal of this research, a visual simulator was developed to assist in the creation of task algorithms.

The work realised in this thesis allows the continuity of the development of the Smart Manipulator. As future work it is expected to extend the logic presented here to all six joints of the arm considering any type of motion. Futhermore, it will be required to develop a compatible end-efector that complies with the multiple task capability requirement.

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