Design and control of piezoelectric-driven handheld manipulator for tremor compensation in microsurgery

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Design & Control of Piezoelectric-Driven Handheld Manipulator for Tremor Compensation in Microsurgery

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Table of Contents

Acknowledgments	i
Table of Contents	iii
List of Figures	vii
List of Abbreviations	xi
Summary	xiii
1 Introduction	1
1.1 Background	1
1.1.1 Microsurgery and Cell Micromanipulation	1
1.1.2 Objectives	4
1.2 Technical Challenges	5
1.3 Scope	5
1.4 Organization	7
2 Literature Review on Control of Piezoelectric Actuator	8
2.1 Hysteresis Models	11
2.1.1 Polynomial	11
2.1.2 Preisach	12
2.1.3 Prandtl-Ishlinskii (PI)	14
2.1.4 Maxwell	14
2.1.5 Hysterons	15
2.2 Microscopic Theories	15
2.3 Electric Charge Control	17
2.4 Phase Control	17
2.5 Close-Loop Displacement Control	18
2.6 Conclusion	19
3 Singularity-Free Prandtl-Ishlinskii Model	21

3.1	Rate-Dependent Prandtl-Ishlinskii Model for Piezoelectric Actuators	23
3.1.1	Rate-Independent Model	23
3.1.2	Rate-Dependent Model	27
3.2	Singularity Problem	29
3.3	Modeling in a Different Domain	31
3.3.1	Intuition	31
3.3.2	Solution	32
3.3.3	Generation of the Inverse Model	35
3.3.4	Simulation	37
3.4	Experimental Results	37
3.4.1	Experimental Setup	39
3.4.2	Experimental Result	39
3.5	Discussion	43
4	Adaptive Controller	46
4.1	Adaptive Inverse Hysteretic Controller	46
4.2	Adaptive Weight-Control Mechanism	48
4.3	Algorithm	49
4.4	Simulation Results	50
4.4.1	Stationary Hysteretic Plant	50
4.4.2	Robustness: Sudden Change in Hysteretic Plant	52
4.5	Experimental Results	52
4.5.1	Experimental Setup	52
4.5.2	Experimental Results	53
4.6	Discussion	55
5	Design and Development of a Low-cost Handheld Mechanism for Micromanipulation	59
5.1	Background	59
5.1.1	Flexure-based Prismatic Joint	60

5.1.2	Parallel Mechanism	62
5.2	Design	62
5.2.1	Design 1	63
5.2.2	Design 2	65
5.3	Fabrication	69
5.4	Analysis	70
5.4.1	Degree of Freedom	70
5.4.2	Inverse Kinematics	72
5.4.3	Workspace	77
5.4.4	Finite Element Analysis	77
5.5	Experimental Results	77
5.5.1	Experiment Setup	78
5.5.2	Results	78
5.6	Discussion	82
6	Estimating Displacement of Periodic Motion with Inertial Sensors	85
6.1	Background	85
6.2	Extraction and Estimating Disturbance Motion	87
6.2.1	Weighted-Frequency Fourier Linear Combiner (WFLC)	88
6.2.2	Band-Limited Multiple Fourier Linear Combiner (BMFLC)	90
6.3	Discussion	93
7	Integrated Handheld Instrument	95
7.1	Integration	95
7.1.1	Design requirements	95
7.1.2	Design 1	96
7.1.3	Design 2	96
7.2	Experiments	99

7.3	Comparison between current instrument and work by previous re- searchers	101
7.4	Discussion	104
8	Conclusion and Contributions	106
8.1	Conclusion	106
8.1.1	Control of Piezoelectric Actuators	106
8.1.2	Design and development of Mechanism	107
8.1.3	Integrated Handheld Instrument	107
8.2	Contributions during Ph.D. Candidature	108
8.3	Future Works	111
	Appendix A	114
	Appendix B	117
	References	118

List of Figures

1.1	Overview of the active handheld instrument, Micron.	4
2.1	A Crystal Unit Cell of PZT Ceramic.	9
2.2	Polarization of a PZT Ceramic.	9
2.3	Hysteresis Path at different frequencies.	10
2.4	An illustration of the high tracking error when using PID controller on a PZT actuator.	10
2.5	Feedforward Controller.	12
2.6	Control Diagram used by Song <i>et al.</i> [24].	13
2.7	Maxwell Elasto-Slide Elements [33].	15
2.8	Hysteron Hysteresis Model [35].	16
3.1	Linerization of Hysteretic Plant using Inverse Feedforward Controller.	21
3.2	Illustration of an Ill-Conditioned Hysteresis.	22
3.3	The rate-independent generalized backlash operator.	24
3.4	Summing up the backlash operators.	25
3.5	Graphical Representation of Saturation Operator.	26
3.6	Weights of the hysteresis play operators against velocity obtained from piezoelectric actuator P885.50 from Physik Instrumente.	28
3.7	Signal flow of the Inverse Feedforward Controller.	29
3.8	Loading curve of an ill-conditioned hysteresis involving negative gra- dient.	30
3.9	Inverse loading curve of an ill-conditioned hysteresis to illustrate failure of the PI inverse operator when negative gradient is encoun- tered.	31
3.10	Transformation.	32
3.11	Method to obtain appropriate input voltage.	32

3.12	Graph of an ill-conditioned hysteresis with points x_0 to x_8 labeled. .	33
3.13	Relationship between y_1 (new domain) and y	35
3.14	Simulation to show that inverse after mapping is the reflection along the 45° line.	36
3.15	Simulation result of the feedforward linearization.	38
3.16	Simulation result of the feedforward linearization.	38
3.17	Experimental Architecture.	39
3.18	Triangular wave without mapping.	40
3.19	Triangular wave with mapping.	40
3.20	Exploded view of error of triangular wave without and with mapping respectively.	41
3.21	Non-periodic linear motion without mapping.	42
3.22	Non-periodic linear motion with mapping.	43
3.23	Superposition of a few different frequencies of sinusoidal waves. . . .	44
3.24	A hysteresis graph showing more than one maximum or turning points.	45
4.1	Signal Flow Diagram of the Adaptive Feedforward Controller. . . .	48
4.2	Simulation result of a stationary rate-dependent plant.	51
4.3	Simulation result of a rate-dependent plant with a sudden change in its parameters.	51
4.4	Tracking result of a 12Hz sinusoidal wave.	54
4.5	Convergence of the weights of the adapting mechanism in the actual experiment.	55
4.6	Experimental results of a randomly created non-periodic wave. The different non-periodic waves are created by passing random numbers through a low pass filter.	56
4.7	A section of Fig. 4.6 between time 5s to 8s.	57
4.8	Simulation result of the adaptive controller with real tremor data. .	57
5.1	Conventional prismatic joint.	60

5.2	Improved prismatic joint using double parallelograms.	61
5.3	Improved prismatic joint [66].	61
5.4	Prismatic joint making use of symmetrical deformation.	61
5.5	Lever used to amplify the actuator's stroke length.	63
5.6	Overlapping Individual Levers.	63
5.7	Design 1.	64
5.8	Comparison of Design 1 with a fifty cents coin.	64
5.9	Hysteresis like effect when driven at 10Hz.	65
5.10	Photo of the mechanism with actuator holder.	66
5.11	Exploded view of the mechanism.	66
5.12	Schematic of the Mechanism.	67
5.13	Deformation of Design 2 when actuated to move vertically up. . . .	68
5.14	Deformation of Design 2 when desired tip position is towards the left.	68
5.15	Part built layer by layer.	70
5.16	Orientation of the Mechanism in the Rapid Prototyping Machine. .	70
5.17	Example of a mechanism where calculation of the number of DOF via Grashof will fail.	71
5.18	Workspace of the manipulator.	77
5.19	Finite element analysis of the mechanism when all three actuators are actuating.	78
5.20	Experiment Setup.	79
5.21	3-D plot of the end effector when driven to draw a circle.	79
5.22	1-D plot of Fig. 5.21 in the y-axis component.	80
5.23	2-D plot of the end effector when driven to move along $y=x$	80
5.24	2-D plot of the end effector when driven to move along y-axis. . . .	81
5.25	2-D plot of the end effector when driven to move along x-axis. . . .	81
6.1	Integration drift of velocity and displacement given sinusoidal motion.	87
6.2	Block diagram of method using WFLC.	88

6.3	Convergence of the estimated disturbance frequency using WFLC. .	89
6.4	Experiment Setup.	92
6.5	Estimated displacement (solid) result from the accelerometers reading of a 100 μm peakpeak sinusoidal motion (dotted).	92
6.6	The error between actual displacement and estimated displacement.	93
7.1	Photo of first integrated instrument with respect to a fifty cents coin.	96
7.2	Photo of the Mechanism.	97
7.3	Photo of a hand holding the first design of the instrument.	97
7.4	Photo of a hand holding the second design.	98
7.5	Photo of a hand holding the second design.	98
7.6	Comparison between the two design.	98
7.7	Experiment Setup of the Bench Test.	100
7.8	Experimental Result of 10Hz sinusoidal Disturbance along x-axis. .	101
7.9	Experimental Result of 10Hz sinusoidal Disturbance along y-axis. .	101
7.10	Bench Test Experimental Result.	102

List of Abbreviations

BMFLC	Band-limited multiple Fourier linear combiner
PI	Prandtl-Ishlinskii
PSD	Position sensitive device
PZT	A solid solution of PbZrO_3 and PbTiO_3
RLS	Recursive least square
RMS	Root mean square
RMSE	Root mean square error
RP	Rapid prototyping
TVA	Tuned vibration absorber
WFLC	Weighted-frequency Fourier linear combiner

Summary

The problem of correcting imprecision due to physiological hand tremor while performing micromanipulation tasks such as microsurgery has received considerable attention. This results in the development of a hand-held instrument, Micron, that senses its own motion using an inertial measurement unit; distinguishes intended and undesired motion, and actively attenuates the undesired motion by an opposite but equal deflection of the tip through a piezoelectric-driven manipulator. This dissertation emphasizes an improved version of the aforementioned instrument with regards to the design and control of the piezoelectric-driven mechanism.

The hysteretic behavior of piezoelectric actuators makes control challenging. Hence, Prandtl-Ishlinskii (PI) hysteresis model is used to model this hysteretic effect. However, there is a limitation in the PI model. The inverse does not exist when the slope of the hysteretic curve is not positive definite. The author proposes overcoming this problem by mapping the hysteresis through a transformation onto a singularity-free domain, where the inversion can be obtained. The proposed solution brings along a number advantages to the instrument: 1) a stable controller as the limitation of the inverse model is removed; 2) better accuracy as smaller threshold values can be used; and 3) accelerometers will no longer pick up impacts caused by the jerks at the turning point due to the singularity problem. This solution is a general method and can be extended to model any hysteretic materials or systems.

The hysteretic behavior is dependent on the individual actuator and also environmental conditions like temperature. Hence, the actuator has to be modeled regularly. To overcome this, the author proposes closing the feedback loop to obtain an adaptive rate-dependent feedforward controller for piezoelectric actuators. The tracking performance of the adaptive controller is performed on a piezoelectric actuator and found to produce a smaller tracking error. In addition, since it is adaptive, experiments are no longer needed to be conducted to obtain the actuator's model and precious time is saved.

This dissertation also presents a new piezoelectric-driven 3-DOF flexure-based parallel mechanism. To reduce the cost and also to allow complexity in the design to reduce the size, a rapid prototyping machine (Objet) is used to build the mechanism portion as a single piece. Unlike previous work, the inverse kinematics is solved analytically and hence suitable for real-time implementation. In addition, the manipulator demonstrates an improved performance from previous designs. The absolute root mean square errors for 4 different trajectories driven at 10Hz are found to be less than $7\mu\text{m}$. Another strong reason for a flexure-based mechanism is because the motion of the instrument is sensed using accelerometers. Unlike the existence of small mechanical free play in pin joints, flexure joints eliminates the impacts between these free plays. These impact signals are difficult to filter out as this frequency is the same as the actuation frequency.

These are next integrated with an improved sensing module developed by the author's teammate. The new version of the handheld instrument is built and implemented. Experiments are then conducted to evaluate its performance.

Chapter 1

Introduction

All humans have inherent physiological hand tremor. Tremor can be considered as a form of noise and vibration problem and is undesired during micromanipulation like vitreoretinal microsurgery. Instead of going with the more familiar approaches like vibration absorber, real-time active disturbance compensation approach with minimal phase lag is illustrated in this dissertation.

1.1 Background

Physiological hand tremor, which is the result of the noise in the signals from the brain to the hand, causes humans to have limitation in positioning accuracy. The significance of these involuntary motion is amplified during micromanipulation like microsurgery and cell micromanipulation.

1.1.1 Microsurgery and Cell Micromanipulation

Microsurgery

In microsurgery, especially retina surgery, high accuracy is desired and tremor must be minimized. The retina is a thin tissue inside the eye that composed of layers of light-sensitive cells. These cells send visual information to the brain. In retina surgery, many delicate surgical procedures are involved and are limited to surgeons with very stable hands. One common procedure is epiretinal membrane peeling. With a microscope to give a high magnification, the vitreo-retinal surgeon uses a pair of extremely fine forceps to peel membranes as thin as $20\text{ }\mu\text{m}$ from the retina. Another example is the treatment of occlusions by injection of anticoagulants. As mentioned in [1], retinal artery and vein occlusions are among the most common

causes of severe vision loss. Mitchell *et al.* [1], in the Blue Mountain Eye Study, mentioned that the prevalence of retinal vein occlusion was found to be 1.6% in adults aged 49 years or older. Standard treatment like topical ocular hypotensive medications, pentoxifylline and laser chorioretinal anastomosis is generally not as effective in restoring blood flow. One example is shown in an 81 year old lady with visual loss due to a central retinal vein occlusion [2]. Thus, Weiss [2] and Tang *et al.* [3] proposed injection of anticoagulants using intraocular cannulation to treat retinal vein occlusions. However, this procedure is limited to very few surgeons, whose tremor is very low, as it is very difficult to insert a micropipette into a retinal vein and deliver the drug without risking tearing the vessel apart. Thus, a 3-DOF (degree of freedom) tremor compensating tool will improve the surgery performance greatly. In addition, this 3-DOF tremor compensating tool is applicable for similar surgeries that involve injection in neurological surgery and microvascular surgery.

Riviere *et al.* [4] found that the average rms error for an eye surgeon was 49 μm while the maximum error in the overall motion was found to be 133 μm . Singh *et al.* [5] discovered that during the most delicate portion of retinal microsurgery, the RMS (root mean square) error is 38 μm . As the surgeons get older, their noise signal get larger and their tremor motion increase. This forces many surgeons to retire at a relatively young age. With the high cost in training new surgeons and also the high demand for experience surgeons, it is beneficial to come out with a mechanism device that is attached to the medical instrument to compensate the erroneous tremor motion.

Non-contact surgery, like laser, is usually the preferred choice if they have the same effect as contact surgery. However, due to the complexity of human organs / bodies, contact surgeries are still needed for certain surgeries.

Robots are being applied in surgery by a number of groups [6,7]. The limitation of this method is robots are unable to make good judgments of many different cases. Robots also do not have good hand-eye coordination when compared to humans. They are limited to simple procedures. Robots are also expensive and require man-

power and time to debug and build. Master and slave methods were also proposed by researchers like Kwon *et al.* [8]. Desired motion, together with tremulous motion, is picked up at the master side. The undesired tremor is normally removed by either 1) filtering, or 2) scaling to increase the signal to noise ratio. Unfortunately, this approach is too costly. Two major systems have to be built and lots of time is wasted in debugging. In addition, surgeons are accustomed to treating the patient with their own hands using their “feel” and find this approach obtrusive. In addition, this approach cannot be extended to other industries, like nano-technology manufacturing sector, as it is unable to compensate natural vibrations. Taylor and Stoianovici [9] proposed using “Steady Hand”. This system, however, hinders the surgeons’ movement as the orientation of movement of the tools is constrained by the joints. In addition, this system takes up relatively more space.

Cell Micromanipulation

The technology used to solve the issue of tremor in cell manipulation is very similar to surgery. Like surgery, the methods used in cell manipulation can be broadly classified into contact and non-contact. In the category of non-contact, Ashkin *et al.* [10] proposed laser tapping. Another possible non-contact means is electro-rotation as proposed by Arai *et al.* [11]. However, the non-contact methods are limited to only certain procedures as the cells tend to get damaged due to the exposure of energy fields.

Presently, while there are commercially available telerobotic surgery systems like the famous da Vinci[®] surgical system from Intuitive Surgical Inc, there are bio-science companies like Harvard Apparatus offering systems like Nanoliter Injector Microinjection system with which the end effector is controlled via a joystick.

The joystick at the control unit for the micromanipulator acts as the “master” while the micromanipulator is the “slave”. The motion of the hand, inclusive of the tremor is captured by the master side. This motion is either filtered or scaled down to increase the signal to noise ratio before sending to the slave. Although this setup has removed the problem of tremor for most of the cell manipulation procedures,

there are some applications whereby this setup cannot be used. One example is the dissection of cells to transplant them to other cells to perform transgenic study. Amore *et al.* [12] and Hodor *et al.* [13] studied cell-cell interaction involving sea urchins.

Dissection is performed when the sea urchin embryonic cells are at their 16-cell stage. The 4 micromeres, which are responsible for the growing of spines, are removed and transplant to other cells to identify key cell-cell interactions in the early embryo.

Dissection of cells requires the dexterity of human hands and the telerobotic system cannot be used. Due to tremor, most of the cell biologists ended up wasting much time and patience to perform the dissection. In addition, only those biologists with very stable hands are able to dissect small cells. This is one of the limiting factors of cell-cell interaction study. Thus, a 3-DOF handheld tremor compensating tool will enhance the research on cells.

1.1.2 Objectives

To deal with the problem due to tremor, Ang *et al.* [14] proposed an intelligent active handheld instrument for microsurgery named Micron (Fig. 1.1).

Figure 1.1: Overview of the active handheld instrument, Micron.

This instrument senses its motion and distinguishes between desired and tremor

motion through advanced filtering techniques. The tremor is next compensated by an equal but opposite deflection of the surgical tip. The core objective of this dissertation is to improve the performance of this handheld instrument, with greater emphasis on the design and control of the piezoelectric-driven mechanism to compensate the tremulous motion. To achieve that, there are two main objectives:

1. To control the piezoelectric actuators, and
2. To design a manipulator.

1.2 Technical Challenges

To meet the requirements of a handheld instrument to compensate hand tremor, there are a number of challenging technical issues:

1. High accuracy ($5\mu\text{m}$) is required;
2. The bandwidth of tremor is relatively high (around 8-12Hz) and is beyond most actuators;
3. Compensation must be performed in real time. This is because compensation after a phase difference will mean large tracking error;
4. In order to be a handheld instrument, the mechanism must be small and light.

1.3 Scope

The work of this research project is generally split between the author and his teammate, who researched into the filtering and compact arrangement of the sensors. The main research focus of the author's dissertation is on the research and development of the piezoelectric-driven handheld manipulator and the scope is as follows:

Singularity-Free Prandtl-Ishlinskii Model

First is the control of the piezoelectric actuators. Prandtl-Ishlinskii (PI) operators are used to model the hysteretic piezoelectric actuators. However, the inverse of the PI operator does not exist when the slope of the hysteretic curve is not

positive definite. Hence, in order to solve the ill-conditioned problem, a solution by mapping onto another domain is proposed with experiments conducted to show its effectiveness.

Adaptive Controller

The hysteretic behavior is dependent on individual actuator and also on environmental conditions like temperature. It is troublesome and costly to model the hysteresis regularly. In addition, the hysteretic behavior of the actuators also changes with age. Hence, the author closed the control feedback loop and an adaptive rate-dependent feedforward controller using PI hysteresis operators for piezoelectric actuators is proposed and evaluated with experiments.

Design and Development of a Flexure-based Hand-held Mechanism

A 3-DOF handheld manipulator driven by 3 piezoelectric actuators is also designed and fabricated. Traditional pin and ball joints are replaced by flexure-based joints because of its non-existence of backlash and assembly errors. Parallel manipulator design is the proposed choice as compared to a serial mechanism because of its rigidity and compactness. To reduce the cost of fabrication and also to allow more complex designs to reduce the size, Objet (a rapid prototyping machine) is proposed to be used to build the mechanism.

Estimating Periodic Displacement using Inertial Sensors

While the focus is on the piezoelectric-driven mechanism, a method to estimate the displacement of a periodic motion using inertial sensors is also proposed during the course of the Ph.D. candidature years. In this instrument, accelerometers are used to sense the tremor motion. Inertial sensors, like accelerometers and gyroscopes, are rarely used alone to infer information of a lower order Laplace domain like displacement as the accuracy is greatly handicapped by the notorious integration drift. Hence, a method to provide a good estimate of the inferred information is proposed for period motion.

Integrated Handheld Instrument

The manipulator is then built and integrated with the author's teammate's sensing component. Experiments are also conducted. The tremor compensation performance, together with its advantages and improvements over previous work, is shown.

1.4 Organization

After this chapter of introduction, the remaining chapters of the dissertation are organized as follows.

Chapter 2 provides a literature review on the different methods that are proposed by researchers all over the world on how the piezoelectric actuators can be controlled. These methods include different hysteresis models using feedforward control, microscopic theories, electric charge control, phase control, closed-loop displacement control and hybrids of the methods mentioned.

Chapter 3 proposes the solution to the ill-condition problem of Prandtl-Ishlinskii model. A rate-dependent Prandtl-Ishlinskii (PI) model is first introduced. This is followed by an illustration of the ill-conditioned problem and the proposed solution. Chapter 4 presents an adaptive rate-dependent model.

Chapter 5 presents the design and development of the low-cost flexure-based handheld mechanism while Chapter 6 covers how readings from inertial sensors can be used to infer lower Laplace domains like displacement for periodic motions.

Chapter 7 illustrates the integration of the new handheld instrument and also its experimental results. Chapter 8 concludes the dissertation.

Chapter 2

Literature Review on Control of Piezoelectric Actuator

Hysteresis is a common phenomenon in applications involving issues like magnetic fields and smart materials, such as piezoelectric actuators. In recent years, with the development in precision engineering and micro-positioning applications, there is an increasing demand in high frequency high precision actuators. Piezoelectric actuators are extremely popular not only because of its high output force, rapid response and compactness; piezoelectric actuators also do not produce magnetic fields and are thus compatible with many instruments. Piezoelectric actuators also do not have backlash and this enable the positioning precision to reach nanometer level.

Garmon *et al.* [15] demonstrated how piezoelectric actuators could be used for microsurgical tool while Chang *et al.* [16] used piezoelectric actuator to compensate vibration. Dong *et al.* [17] drove their precision compliant parallel positioner using piezoelectric actuators. Other applications include cell manipulation, scanning tunneling microscopy and diamond turning machines.

One common example of piezoelectric ceramic is PZT ceramic. PZT is a solid solution of PbZrO_3 and PbTiO_3 and the general formula is $\text{Pb}(\text{Zr}_y\text{Ti}_{1-y})\text{O}_3$. PZT has the perovskite ABO_3 structure (Fig. 2.1).

When a voltage is applied across the ceramic, the atom at the center (Zr or Ti) will displace (Fig. 2.2). A pole is induced and the net polarization in the PZT ceramic changes. This results in the deformation of the material. The usage of deformation as actuators is a solution for precise actuation as no mechanical backlash is involved. A reverse observation will occur when the ceramic is loaded.

Figure 2.1: A Crystal Unit Cell of PZT Ceramic.

Figure 2.2: Polarization of a PZT Ceramic.

This is why piezoelectric materials are able to function as both actuators and sensors.

However, due to the nature of polarization, such materials exhibit non-linear multi-path hysteresis that makes control challenging, especially if precise tracking is required.

A piezoelectric ceramic is an excellent choice because of its ability to output a large force, large operating bandwidth and fast response time. Unfortunately, the hysteretic effect of piezoelectric materials increases the difficulty in controlling piezoelectric actuators. The hysteretic error is about 15%. To make matters worse, the hysteresis path changes according to rate (Fig. 2.3).

Traditional PID controller is easy to build and implement, and also produce good positioning accuracy. However, a PID controller produces high error when it is used to perform tracking control of a certain profile. An example is shown in Fig.

Figure 2.3: Hysteresis Path at different frequencies.

Figure 2.4: An illustration of the high tracking error when using PID controller on a PZT actuator.

2.4, which is driven at 8Hz.

Hence, researchers around the world have been exploring more advance models and controllers. While there has been a lot of work done on rate-independent control, little research has been done and very few people have been successful in controlling the actuator at varying frequency.

More details of current methods to model or control the actuators are covered in

the subsequent sections. Current research in hysteresis modeling and compensation can be broadly classified into the following categories:

1. Linear control with feed-forward inverse hysteresis model;
2. Microscopic theories;
3. Electric Charge Control;
4. Phase Control;
5. Closed-loop displacement control.

The more recent methods comprise a hybrid of the methods. The following sections will be a review of the work done in each category in greater detail. There are different models like Preisach, Prandtl-Ishlinskii (PI), Maxwell and Hysterons and section 2.1 covers how these models are used as feed-forward controller. A brief description of how microscopic theories are used to control piezoelectric actuators is shown in section 2.2. Section 2.3 is about controlling the actuator through controlling the electric charges. A description on how phase controls were used is shown in section 2.4. Section 2.5 consists of the different types of control like adaptive, sliding-mode, neural network, repetitive, H_∞ and fuzzy logic.

2.1 Hysteresis Models

The main idea of this section is to obtain a mathematical model that describes the complex hysteretic motion of the piezoelectric actuator. Phenomenological approach is about obtaining a model base on the behavior of the actuator. A phenomenological approach is more commonly used because the underlying physics on the relationship of the piezoelectric actuator's hysteretic path with rate is not well understood yet. As shown in Fig. 2.5, after obtaining the model, the inverse is then used as a feed-forward controller to linearize the actuator motion.

2.1.1 Polynomial

There are a number of existing models. Among the simplest method is to utilize two polynomials. Two sets of polynomial are used to model the forward and

Figure 2.5: Feedforward Controller.

backward paths. This method will fail when the turning point is changed as it is not continuous. Hence, Sun *et al.* [18] proposed a new mathematical model by modifying the polynomials.

2.1.2 Preisach

The Preisach hysteresis model is a popular phenomenological model that has mathematical generality. Thus, the Preisach model is being used in many different applications like situations involving piezoelectric ceramics, magnetization and backlash. Mathematically, the classical Preisach model can be written as

$$f(t) = \int \int_{\alpha \geq \beta} \mu(\alpha, \beta) R_{\alpha\beta}[u(t)] d\alpha d\beta \quad (2.1)$$

where $f(t)$ is the output, $\mu(\alpha, \beta)$ are the weights, $R_{\alpha\beta}[u(t)]$ is the hysteresis operator with an output either 0 or 1 and α and β are the switching values up and down respectively. A discrete Preisach model is obtained by summing the outputs from the entire individual α s and β s.

Hu and Mrad [19,20] found that the Preisach model was accurate in applications where the load function was relatively small and the range of frequencies was limited. Some of the constraints were wiping out and congruency properties must be satisfied. Hughes *et al.* [21,22] illustrated the implementation of the classical Preisach model and also its inverse model and had also shown that the wiping property holds for piezoelectric ceramic actuator. The use of higher-order reversal curves for hysteresis modeling would help the model to adapt to arbitrary variation of signal amplitude as the congruency property was not satisfied for operation along the minor hysteresis loop. To obtain the Preisach distribution, numerical differentiation had to be done. Unfortunately, this was a process whereby the noise would be amplified. In addition, the inverse of Preisach was also not easy

to compute. Gorbet *et al.* [23] discussed the passivity of Preisach model and the stability of velocity feedback control for hysteretic actuators.

A number of people like Song *et al.* [24] and Ge *et al.* [25] have also proposed tracking control of a piezoelectric ceramic actuator by using the inverse Preisach model and a feedback controller. Song designed the closed loop controller by first using least squares method through comparing the step response of the identified model and the piezoelectric ceramic actuator system step response. Fig. 2.6 shows the control diagram.

Figure 2.6: Control Diagram used by Song *et al.* [24].

Unfortunately, the operating frequency is kept constant. As the frequency of the input signal increases, the hysteresis non-linearity becomes more severe and the classical Preisach model would fail. Like most models, Preisach model is also unable to model the hysteresis phenomenon when the largest displacement does not occur at the highest input signal. Thus, when such situations are encountered, the author proposed to model the hysteresis in a different domain which will be covered in chapter 3.

Attempts to use Preisach model to model the rate-dependence hysteresis were made on magnetostrictive actuators. Fuzzi [26] and Tan *et al.* [27–29] coupled the Preisach operator with an ordinary differential equation. The ODE was based on energy balancing principles. That was possible for the topic relating magnetism as physicians had discovered more details on topics like magnetic field and eddy currents, but not on piezoelectric ceramics. In the identification of the parameters, Tan proposed using least square method. Even though the weighting masses could be computed theoretically from the first order reversal curves, least square method

was used because signals were never noise free.

Preisach model were also used in shape memory alloy (SMA). Majima *et al.* [30] proposed to use Preisach model with modification to model the material. The temperature was considered as input and the detwinned martensite fraction as output. Thus, the parameters taken into consideration included austenite start temperature, austenite finish temperature, martensite start temperature and martensite finish temperature. Majima carried out a few experiments with different controllers and again, the controller consisting of PID with the inverse SMA model proved to be the best.

2.1.3 Prandtl-Ishlinskii (PI)

Prandtl-Ishlinskii (PI) is another hysteresis model that is able to model hysteresis. The author had decided to use this model and more details are given in the following chapter.

2.1.4 Maxwell

Maxwell model is another hysteresis model commonly being used. Goldfarb and Celanovic [31, 32] proposed a generalized Maxwell resistive capacitor as a lumped-parameter representation of hysteresis. The model is made up of a number of elasto-slide elements, which consists of a massless linear spring and a massless block that is subjected to Coulomb friction (Fig. 2.7).

Choi *et al.* [33] had shown that the tracking was improved when a PID controller was used with feedback linearization loop and repetitive controller. When compared to open loop, PID + feedback linearization controller reduced error by 72% while PID controller without feedback linearization controller could only reduced the error by 15%. This again illustrated the importance of feed-forward linearization as it should be added to compensate the hysteresis. The tracking error of a sinusoid input for the controller with repetitive controller was not periodic. The error decreased as the number of cycles increased as the system used the periodic

Figure 2.7: Maxwell Elasto-Slide Elements [33].

error signal to improve tracking performance.

2.1.5 Hysterons

Sain *et al.* [34] suggested 4 models for hysteresis. They were namely Hysteron, Bouc-Wen, Chua-Stromsmoe and Preisach model. Fig. 2.8 shows the graphical model for Hysteron. The model is made up of two half-lines and two line segments. Tao [35] proposed to use hysterons to model the hysteresis. The inverse of the hysteresis was developed. Adaptive controller with adaptive hysteresis inverse was also proposed for plants with unknown hysteresis.

2.2 Microscopic Theories

The models shown in previous section are all phenomenological approaches and do not take the underlying physics into consideration. This section illustrates some of the attempts to control piezoelectric actuators by understanding piezoelectric ceramics' microscopic theories.

Smith *et al.* [36] showed that hysteresis is rate dependent, even at low frequencies. Landauer *et al.* [37] discussed the dependence of the polarization, in barium

Figure 2.8: Hysteron Hysteresis Model [35].

titanate, on the rate at which the field is cycled. This reference illustrated that the coercive field at which the polarization switches direction was dependent upon the time allowed for switching. The rate at which the field cycles also affected the shape of the polarization curve, with the maximum polarization attained at a fixed field strength decreasing with increasing frequency.

Smith *et al.* [36] proposed that the hysteretic polarization for both quasi-static and dynamic regimes could be modeled through the balance of electrostatic and thermal energy using Boltzmann principles by considering the dipole p in the electric field with the thermal energy at temperature T . Smith *et al.* proposed a rate dependent model by considering the probability of one cell switching into the field direction and also the probability that a dipole switches in the opposite direction due to thermal excitation. At equilibrium, these two rates are equal and using this knowledge, the rate dependent model was derived.

2.3 Electric Charge Control

From the knowledge of the linear relationship between charge and displacement, Furutani *et al.* [38] proposed combining induced charge feedback with inverse transfer function compensation. The hysteresis of the displacement of the actuator to the applied voltage is about 15% while the displacement to induced charge is 2%. As it was difficult to use the charge amplifier for a time longer than the time constant, the inverse transfer function was proposed to compensate. The inverse transfer function was placed in series after the induced charge amplifier in the feedback loop. This was similar to a feed-forward control. In this paper, the charge amplifier was assumed to be a second order system. The parameters were obtained through experimental data. Due to the error in the identified parameters and the drift of charge amplifier's output, the displacement could only be controlled for a limited amount of time, in this case 10s.

Yi and Veillette [39] proposed an inverting charge control circuit to linearize the stack actuator hysteresis motion. Yi incorporates an operational amplifier to provide high loop gain, a high-voltage amplifier to drive the stack actuator and a lead compensator to ensure stability. Yi also mentioned that the charge control produced better result than voltage control.

However, with the hysteresis still in existence, although at much smaller percentage, the displacement of the actuator cannot be tracked to sub micron level with the hysteresis of the induced charge not being modeled.

2.4 Phase Control

Cruz-Hernandez and Hayward [40] introduced the idea of interpreting the Preisach hysteresis model in terms of phase shift. The notion of apparent phase shift between the input and output gave Cruz-Hernandez and Hayward [41,42] the idea to consider phase as a control approach to design a compensator to reduce hysteresis. The general idea was to add a phaser as a compensator before the plant to get a

linear output. The compensator shifted the phase of the periodic signal, but keeps its magnitude unchanged.

As the angle varies with the magnitude of the input signal, a variable phaser is placed before the phaser. This variable phaser, which can be termed a nonlinear phaser, changes the angle according to the input. As the phaser is non-causal, an approximation is needed and Cruz proposed 3 different methods: 1) Hilbert Transform, 2) PD controller and 3) phase lead implementation (filters).

The ways the author quantified his work is by checking the arc length of the loop and also the area inside the loop, instead of checking the error between desired and actual output. This type of measurement of performance can be studied to see if these are better ways of quantifying a work involving hysteresis.

Cruz *et al.* [43] next proposed the Hysteron unit model to be used. The Hysteron is much simpler than the Preisach model. Filters were proposed as the compensator as filters introduce phase shift in this paper too.

2.5 Close-Loop Displacement Control

There are many different approaches to closed-loop displacement control. Some proposed incorporating inverse hysteresis model with a controller while some proposed advance controllers like adaptive, fuzzy logic, sliding mode and H_∞ control. Researchers like Ku *et al.* [44] and Hwang [45] had proposed the ideal of using Neural Network to control the piezoelectric actuators while Stepanenko [46] proposed implementing an approximation function to compensate the hysteresis effects by using fuzzy logic methods.

Jan and Hwang [47] proposed a control system consisting of a feedback linearizing control with a reference model and a sliding-mode control with an equivalent control and a switching control. The reference model was obtained through learning and was rate independent. Problems would surface if the actuator were to be operated at variable non-periodic speed. In addition, this paper consisted purely of simulation only. Other sliding modes attempts were done by Abidi *et al.* [48]

and Yu *et al.* [49]. Yu *et al.* [49] proposed incorporating neural network to model the hysteresis and its inversion and a sliding mode controller augmented with inverse hysteresis model to compensate the hysteretic behaviour, modeling error and disturbance.

2.6 Conclusion

This chapter has given a brief overview of a couple of different methods proposed by different groups of researchers in controlling of piezoelectric actuators. As the hysteretic behavior of such materials are not that well studied at the atom level yet and the equipments to study the movement of the atoms is expensive, microscopic theoretical methods are not commonly used. Electric charge control requires expensive equipments as they are the amount of charges stored at the actuators have to be monitored accurately. Phase control is able to perform tracking control, but up to today is limited to periodic signals. Close-loop displacement control is able to give excellent position control, but they tend to have high tracking error due to the phase difference introduced. One popular method that is suitable of this application is the usage of the phenomenological inverse feedforward controller.

In real time applications, Preisach model is not preferred because there is no closed form expression to obtain the inverse. Hence, heavy numerical computation has to be performed to obtain the inverse. Although Maxwell resistive capacitor is efficient in modeling, it does not have an analytical inverse model too. Another model is the Prandtl-Ishlinskii model. Kuhnen [50–52] demonstrated that the

Table 2.1: Summary of the various hysteresis models in obtaining the inverse model

Model	Method to obtain inverse model
polynomial	yes, but input is limited to periodic signal
Preisach	numerical method is needed
Prandtl-Ishlinskii	close-form analytical solution is available
Maxwell	numerical method is needed

classical Prandtl-Ishlinskii operator, which is less complex and its inverse can be computed analytically, is more suitable for real-time applications that requires as little mathematical computation time as possible. Hence, Prandtl-Ishlinskii (PI) model is proposed to be used. A summary among the models in obtaining the various inverse models is in table 2.1.

Chapter 3

Singularity-Free Prandtl-Ishlinskii Model

The phenomenological approach discussed in chapter 2 is used in this project to control the piezoelectric actuator and Prandtl-Ishlinskii (PI) model is the proposed model. The hysteretic behavior of the actuator is first modeled. The inverse model is then used as a feedforward controller to predict and linearize the relationship between the input and output as illustrated in Fig. 3.1. The desired displacement is input into the feedforward controller to obtain the estimated required input voltage. This voltage is next generated and input into the hysteretic plant. Ideally, the output is a linearized relationship between desired input and actual output.

Figure 3.1: Linearization of Hysteretic Plant using Inverse Feedforward Controller.

The Prandtl-Ishlinskii (PI) operator, while being able to model the hysteresis be-

havior of a piezoelectric actuator well, has one major inadequacy: the inverse of the operator does not exist when the slope of the hysteretic curve is not positive definite, i.e. singularity occurs when the sum of the PI weights is ≤ 0 . Most systems can be explained using a spring mass damper system. When driven at high velocity, the actuator/mechanism has a high momentum at the turning point, especially if a rapid change is made. The large momentum tends to keep the system in motion and the large momentum results in the convex curve. Similar explanation is applicable for large loads. Prandtl-Ishlinskii model is unable to be used as a feed-forward controller for such hysteresis phenomenon when the largest displacement does not occur at the highest input signal (see Fig. 3.2).

Figure 3.2: Illustration of an Ill-Conditioned Hysteresis.

Thus, the author proposes to transform the ill-conditioned hysteresis onto another domain. This chapter presents an extension to the Prandtl-Ishlinskii operator to overcome the singularity problem. The author proposes to map the ill-conditioned hysteresis curve onto another domain that gives a well conditioned hysteresis graph to model.

This chapter first gives an overview of a rate-dependent Prandtl-Ishlinskii forward

controller, followed by an explanation of the ill-condition problem and the proposed solution. Experimental results are then shown while the last portion discusses the significance of the results.

3.1 Rate-Dependent Prandtl-Ishlinskii Model for Piezoelectric Actuators

This section first introduces the rate-independent PI model, followed by the rate-dependent model proposed by Ang *et al.* [53].

3.1.1 Rate-Independent Model

This subsection introduces the Prandtl-Ishlinskii (PI) hysteresis model and demonstrates the modified PI operator proposed by Kuhnen *et al.* [50–52]. This section also includes a slight modification proposed by Ang *et al.* [53] to account for the one sided characteristic, which is normally needed for piezoelectric actuators, as the operating region of piezoelectric actuators is only on the positive region. An explanation on the parameters needed to be found to use as a feedforward controller is also shown.

Prandtl-Ishlinskii (PI) Play Operator

The elementary play operator in the PI hysteresis model is a rate-independent backlash or linear-play operator. The play operator, which is commonly used to model the backlash between gears with one degree of freedom, is defined by:

$$\begin{aligned} y(t) &= H_r[x, y_0](t) \\ &= \max\{x(t) - r, \min[x(t) + r, y(t - T)]\} \end{aligned} \quad (3.1)$$

where x is the control input, y is the actuator response, r is the control input threshold value or the magnitude of the backlash, and T is the sampling period.

If the hysteretic actuator starts in its de-energized state, initial Condition of (3.1)

is given by:

$$y(0) = \max\{x(0) - r, \min[x(0) + r, y_0]\} \quad (3.2)$$

where y_0 is a real number which is usually initialized to 0. To change the gradient, a weight value w_h is multiplied to the play operator H_r . A graphical representation of the operator is shown in Fig. 3.3. By summing a number of such operators with

Figure 3.3: The rate-independent generalized backlash operator.

different threshold values and weights, a hysteresis model is obtained:

$$y(t) = \vec{w}_h^T \vec{H}_r[x, \vec{y}_0](t) \quad (3.3)$$

where weight vector $\vec{w}_h^T = [w_{h_0} \dots w_{h_n}]$ and $\vec{H}_r[x(t), \vec{y}_0] = [H_{r_0}[x(t), y_{0_0}] \dots H_{r_n}[x(t), y_{0_n}]]^T$ with the threshold vector $\vec{r} = [r_0 \dots r_n]^T$ where $r_n > \dots > r_0, r_0 = 0$, and the initial state vector $\vec{y}_0 = [y_{0_0} \dots y_{0_n}]^T$.

As describe in chapter 2, the Preisach model consists of a number of step changes and is like a stairs of steps. Unlike the Preisach model, another advantage of the PI operator is that the PI operator is a more efficient mathematical model as it is a first order gradient and it is also mathematically simpler. To account for the one sided characteristics of piezoelectric actuators, Ang *et al.* [53] proposed setting the value of r_n to be half of the maximum control input. This is due to the fact that the threshold width of each piecewise linear segment is actually $2r$. Fig.3.4 shows the PI hysteresis for one-sided hysteresis using what is proposed.

It is a useful information to note that the gradient of each piecewise linear segments is actually the sum of the weights up to that particular point.

Figure 3.4: Summing up the backlash operators.

Modified Prandtl-Ishlinskii

The nature of PI operator is symmetrical about the center point of the loop, but this is not really true in the phenomena observation. To overcome this restriction, Ang *et al.* [53] and Kuhnen *et al.* [50] proposed using a one-sided dead zone operator:

$$S_d[y](t) = \begin{cases} \max\{y(t) - d, 0\} & , \quad d > 0 \\ y(t) & , \quad d = 0 \end{cases} \quad (3.4)$$

$$z(t) = \vec{w}_s^T \vec{S}_d[y(t)] \quad (3.5)$$

where weight vector $\vec{w}_s^T = [w_{s_0} \dots w_{s_m}]$, $\vec{S}_d[y(t)] = [S_{d_0}[y(t)] \dots S_{d_m}[y(t)]]^T$, d is the threshold value in the dead-zone operator and z is the actuator's displacement response. The general idea of the one-sided dead zone operators is to bend the graph and make it not symmetrical. As shown in Fig. 3.5, the one-sided dead zone operator bends the graph according to the operator to obtain a non-symmetry model. Fig. 3.5a consists of only the dead zone operator while Fig. 3.5b consists a sum of 3 dead zone operators.

Figure 3.5: Graphical Representation of Saturation Operator.

Inverse Parameters

The inverse PI model is commonly expressed using the stop operators. Kuhnen [50] showed that the inverse PI model can be expressed by PI play operators too. Thus, the inverse of the PI model can be easily computed by the inverse of the PI operator:

$$\Gamma^{-1}[z(t)] = \vec{w}_{h'}^T \vec{H}_{r'} \left[\vec{w}_{s'}^T \vec{S}_{d'} [z], \vec{y}'_0 \right] (t) \quad (3.6)$$

where $\vec{w}_{h'}^T$ and $\vec{w}_{s'}^T$ are the inverse parameters of $\vec{w}_h^T$ and $\vec{w}_s^T$ respectively and $\vec{H}_{r'}$ and $\vec{S}_{d'}$ are the $\vec{H}_r$ and $\vec{S}_d$ operators with the inverse of $\vec{r}$ and $\vec{d}$ as the input respectively.

The graphical representation of finding the inverse is to find the mathematical model that describes the hysteresis path after a reflection along the 45° line. Using the inverse as a feedforward controller gives a linear response as shown in Fig. 3.1. Mathematically speaking,

$$\begin{aligned} z(t) &= \Gamma [\Gamma^{-1}[x(t)]] \\ &= x(t) \end{aligned} \quad (3.7)$$

Kuhnen [50] showed that the inverse model parameters can also be calculated by:

$$\begin{aligned}
 w'_{h_0} &= \frac{1}{w_{h_0}}; w'_{h_i} = \frac{-w_{h_i}}{\left(\sum_{j=0}^i w_{h_j}\right) \left(\sum_{j=0}^{i-1} w_{h_j}\right)}, i = 1 \dots n; \\
 r'_i &= \sum_{j=0}^i w_{h_j} (r_i - r_j); y'_{0_i} = \sum_{j=0}^i w_{h_j} y_{0_i} + \sum_{j=i+1}^n w_{h_j} y_{0_j}; \\
 r_0 &= 0; i = 0 \dots n; \\
 w'_{s_0} &= \frac{1}{w_{s_0}}; w'_{s_i} = \frac{-w_{s_i}}{\left(\sum_{j=0}^i w_{s_j}\right) \left(\sum_{j=0}^{i-1} w_{s_j}\right)}, i = 1 \dots m; \\
 d'_i &= \sum_{j=0}^i w_{s_j} (d_i - d_j), i = 0 \dots m
 \end{aligned} \tag{3.8}$$

Parameter Identification

The behavior of the actuator is repeatable and the resolution is very good. A phenomenological approach is to model this repeatable behavior of the actuator using mathematical expressions. Experimental values are obtained to model the hysteresis behavior. After obtaining the experimental data, least square minimization of the error function, $E[x, y]$, is performed to the weights $\vec{w}_h$ and $\vec{w}_s$ using

$$E[x, y](\vec{w}_h, t) = \vec{w}_h^T \vec{H}_r[x, \vec{y}_0](t) - \vec{w}_s^T \vec{S}_d[z(t)] \tag{3.9}$$

The inverse parameters can be obtained by (3.8). This error function, obtained from Kuhnen *et al.* [50], is recommended over position error because the error will be linearly dependent on the weights.

3.1.2 Rate-Dependent Model

Mathematical hysteresis models are commonly mathematically defined as rate-independent as velocity is not one of the inputs. However, the phenomenological hysteretic behavior of most smart materials changes with rate. In most literature, a smart material actuator is commonly modeled using a cascade of rate-independent hysteresis operator and a dynamical system. However, the inertial dynamics of the structure is not the only contributing factor to the overall rate-dependent

behavior. As mentioned in Landauer *et al.* [37] and Smith *et al.* [36], the nature of the polarization is dependent on rate too. As the rate-dependent portion of the model was not completely accounted, most of the signals used in most of the papers are limited to periodic signals. As a complete model will be quite complex, a phenomenological rate-dependent hysteresis model is used here.

The phenomena response of the piezoelectric actuator is dependent on the velocity. Thus, experiments are carried out on piezoelectric actuators to obtain a rate-dependent phenomenological model. Ang *et al.* [53] proposed a rate-dependent model by modeling the weights of the PI operator with respect to rate. The author used this method and actuated the actuator to achieve a desired triangular (to have constant speed) wave using an adaptive feedforward controller similar to [54]. Experiments are carried out and plotted in Fig. 3.6. Up to a certain velocity, (this limit depends on the length of the piezoelectric ceramic), weights of the play operators of the piezoelectric actuator can be modeled linearly to the velocity input with good approximation.

Figure 3.6: Weights of the hysteresis play operators against velocity obtained from piezoelectric actuator P885.50 from Physik Instrumente.

Thus, based on the phenomenological hysteretic behavior with rate, the equation to approximately relate the weights with rate is presented as follows:

$$w_{h_i}(\dot{z}(t)) = a_i + b_i \dot{z}(t), i = 0 \dots n \quad (3.10)$$

where b_i is the slope of the best-fit line through the a_i 's and the referenced slope a_i is the intercept of the best-fit line. It is also interesting for the readers to note that the gradient of rate dependent relationship equation (3.10) is only significant for the first few weights as shown in Fig. 3.6.

Thus, the rate-dependent PI model becomes:

$$\begin{aligned} z(t) &= \Gamma[x(t), \dot{z}(t)] \\ &= \vec{w}_s^T \vec{S}_d \left[\vec{w}_h^T (\dot{z}(t)) \cdot \vec{H}_r[x, \vec{y}_0](t) \right] \end{aligned} \quad (3.11)$$

The inverse rate-dependent modified PI operator is also of the PI type:

$$\Gamma[z](t) = \vec{w}_{h'}^T (\dot{z}(t)) \vec{H}_{r'} \left[\vec{w}_{s'}^T \vec{S}_{d'}[z(t)], \vec{y}'_0 \right](t) \quad (3.12)$$

Unfortunately, there is a limitation to this model. From Fig. 3.6, one can see that the first weight goes into the negative region (ill-conditioned) when the velocity is high. The inverse will fail and thus, a method to map the hysteresis onto a singularity-free domain is proposed in the following section.

3.2 Singularity Problem

Figure 3.7: Signal flow of the Inverse Feedforward Controller.

Fig. 3.7 shows the signal flow diagram of the inverse feedforward controller. The desired displacement, $z(t)$, is first passed through the inverse dead zone operators, followed by the inverse play operators to obtain the required voltage. This voltage is then passed through the hysteretic plant, which is modeled by the play operators followed by dead zone operators. However, there is a limitation when finding the inverse parameters of the play operators. Linearization of the boxed area in Fig. 3.7 will fail. The equations to find the inverse parameters of the play operators (3.8) fail when negative gradient is encountered. The inverse parameters

of the play operators were derived by Kuhnen *et al.* [50] under the consideration of the following linear inequality constraints (equation 8 of [50]):

$$\mathbf{U}_H \cdot \vec{w}_h - \mathbf{u}_H \leq 0 \quad (3.13)$$

where

$$\mathbf{U}_H = \begin{pmatrix} -1 & 0 & \dots & 0 \\ 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & -1 \end{pmatrix}, \mathbf{u}_H = \begin{pmatrix} -\varepsilon \\ 0 \\ \vdots \\ 0 \end{pmatrix} \quad (3.14)$$

and ε is a very small positive number. This linear inequality means that the slope is assumed to be positive during the derivation and the inverse of the play operator will fail when negative slope is encountered. An example is illustrated here. Given the weights $w_h^T = [-0.2 \ 0.1 \ 0.2 \ 0.2 \ 0.2 \ 0.2]$ and $\vec{r} = [0 \ 1 \ 2 \ 3 \ 4 \ 5]$ for an application where the amplitude of the periodic input voltage is 10V, the loading curve obtained is shown in Fig. 3.8.

Figure 3.8: Loading curve of an ill-conditioned hysteresis involving negative gradient.

Applying (3.8) to get the inverse PI parameters, the parameters obtained are $\vec{w}_h'^T = [-5 \ -5 \ 20 \ -6.6667 \ -1.333 \ -0.5714]$ and $\vec{r}' = [0 \ -0.2 \ -0.3 \ -0.2 \ 0.1 \ 0.6]$. Fig. 3.9 illustrates the inverse curve that is obtained using (3.8). It can be seen that

inverse curve obtained is not a reflection of the loading curve along the 45° line. This simple example clearly illustrates that (3.8) fail to find the correct inverse weights when negative gradient is encountered. Zero gradient is not demonstrated in this example as it is clear that the reciprocal of 0 is a singular point.

Figure 3.9: Inverse loading curve of an ill-conditioned hysteresis to illustrate failure of the PI inverse operator when negative gradient is encountered.

3.3 Modeling in a Different Domain

This section proposes a method to deal with situations when negative gradient is encountered and the inverse of the PI operator cannot be evaluated properly. This section begins with the intuition, followed by the method and simulation.

3.3.1 Intuition

With the singularity problem, the idea to model the hysteresis in an alternative domain, which is always well conditioned, is proposed. A transformation is used to map y to y_1 , which has no singular points as shown in Fig. 3.10. The inverse model can now be obtained in the new domain. If the relationship between y and y_1 is known, the appropriate input voltages can be obtained using the inverse model found in the new domain as shown in Fig. 3.11.

Figure 3.10: Transformation.

Figure 3.11: Method to obtain appropriate input voltage.

The desired value displacement y is first passed through the transformation function to obtain the corresponding new domain y_1 value. This y_1 value is then passed through the inverse model obtained in the new domain to get the appropriate input voltages.

3.3.2 Solution

Although the inverse of the PI model fails, the PI model can still describe the phenomena path like Fig. 3.2. The weights of the play operators for the ill-conditioned hysteresis can be obtained as shown in section 3.1.1. by performing least square error to (3.9). To obtain the relationship between the two domains (y and y_1), 9 points (x_0 to x_8) are identified as labeled in Fig. 3.12. a_0 to a_8 are points associated with x_0 to x_8 in the y -axis, respectively.

Figure 3.12: Graph of an ill-conditioned hysteresis with points x_0 to x_8 labeled.

The region between x_0 and x_1 is for the negative gradient while 0 gradient is between x_1 and x_2 . In the hysteresis loop, region between x_3 to x_4 and x_6 to x_7 has negative gradient while x_4 to x_5 and x_7 to x_8 contain gradient value 0. The labeled points x_0 to x_8 can be calculated using:

$$x_0 = 0;$$

$$\text{If } \sum_{j=1}^i w_{h_j} = 0 \text{ exists, } x_1 = r_i; x_2 = r_{i+1};$$

$$\text{otherwise, } x_1 = x_2 = r_{\max} \text{ where } \sum_{j=1}^{\max} w_{h_j} > 0$$

$$x_3 = 2r_{\max};$$

$$x_4 = x_3 - 2x_1;$$

$$x_5 = x_3 - 2x_2;$$

$$x_6 = 0;$$

$$x_7 = x_6 + 2x_1;$$

$$x_8 = x_6 + 2x_2; \quad (3.15)$$

Next, a transformation function to map y domain onto a new domain y_1 , which has no singular point, has to be proposed. The transformation function should be one that is able to obtain the relationship between y and y_1 easily. The author proposed to keep the slope's amplitude of y_1 against voltage to be the same as y against voltage, except for region where the gradient is near 0. Negative slope is

reflected along the horizontal axis to obtain a positive, but equal amplitude slope. In this way, the gradient of the relationship between y_1 vs y is either 1, -1 or infinite. This makes the formation of the relationship between the two domains easy to establish.

Thus, the following transformation function to obtain the new weights is proposed:

$$w_{2h_i} = \begin{cases} -\sum_{j=1}^i w_{h_j} - \sum_{j=1}^{i-1} w_{2h_j} & , \sum_{j=1}^i w_{h_j} < 0 \\ c - \sum_{j=1}^{i-1} w_{2h_j} & , \sum_{j=1}^i w_{h_j} = 0 \\ \sum_{j=1}^i w_{h_j} - \sum_{j=1}^{i-1} w_{2h_j} & , \sum_{j=1}^i w_{h_j} > 0 \end{cases} \quad (3.16)$$

where c is a positive non-zero constant. The objective of this transformation is to ensure that the gradient of the hysteresis in the new domain is positive throughout. The first expression will reflect all the negative gradient to become positive. The second expression will force a 0 gradient to become a positive non-zero number. The third expression will allow the positive gradient to remain the same value. In addition, the new domain is of a PI type. Notice that with this transformation, the amplitude of the gradient at all points is maintained. This makes the relationship between y and y_1 easy to be expressed. Fig. 3.13 shows the relationship between the two domains. The constants a_i and b_i are the corresponding y and y_1 values respectively to input voltage x_i .

Figure 3.13: Relationship between y_1 (new domain) and y .

As the amplitude of the slope is maintained, all the gradients of the lines relating y_1 and y are 1, -1 or infinite. Points b_0 to b_8 can be obtained using (3.17).

$$\begin{aligned}
 b_0 &= 0; \\
 b_1 &= -a_1; \\
 b_2 &= b_1 + c \times [x_2 - x_1]; \\
 b_3 &= b_2 + [a_3 - a_2]; \\
 b_4 &= b_3 - [a_4 - a_3]; \\
 b_5 &= b_4 - 2c \times [x_2 - x_1]; \\
 b_6 &= b_5 + [a_6 - a_5]; \\
 b_7 &= b_6 - [a_7 - a_6]; \\
 b_8 &= b_7 + 2c \times [x_2 - x_1];
 \end{aligned} \tag{3.17}$$

With these points, the relation between y_1 and y can be expressed in table 3.1.

3.3.3 Generation of the Inverse Model

This section demonstrates that the inverse model obtained is indeed the reflection along the 45° line. The y value is first obtained from the desired displacement, z ,

Table 3.1: Relation Between the two Domains

y value	corresponding y_1 value
a_0 to a_1	$y_1 = -y$
a_1 to a_2	$y_1 = b_2$, any value between b_1 and b_2
a_2 to a_3	$y_1 = y + b_2 - a_2$
a_3 to a_4	$y_1 = -y + b_3 + a_3$
a_4 to a_5	$y_1 = b_5$, any value between b_4 and b_5
a_5 to a_6	$y_1 = y + b_5 - a_5$
a_6 to a_7	$y_1 = -y + b_6 + a_6$
a_7 to a_8	$y_1 = b_8$, any value between b_7 and b_8

by passing it through the inverse dead zone operator. The corresponding y_1 value is then obtained from y using table 3.1. The y_1 value is then passed through the inverse model obtained in the new domain to get the appropriate input voltage. The final inverse graph is plotted with the ill-conditioned hysteresis in Fig. 3.14.

Figure 3.14: Simulation to show that inverse after mapping is the reflection along the 45° line.

As shown in Fig. 3.14, the final inverse graph (dotted) is a reflection of the

hysteresis graph along the 45° line. This section has illustrated the ability of the transformation function to obtain the inverse of the ill-conditioned hysteresis curve. The transformation function has no effect on well-conditioned hysteresis as $x_2 = x_1 = x_0 = 0$.

3.3.4 Simulation

Next, a feedforward linearization simulation is performed on an ill-conditioned hysteretic plant with the following parameters: $\vec{r}=[0 \ 0.05 \ 0.1 \ 0.2 \ 0.4 \ 0.8 \ 1.2 \ 1.6 \ 2.4 \ 3.2 \ 4 \ 5]$, $\vec{w}_h^T=[-1.6030 \ 2.1478 \ 4.3923 \ -3.2764 \ 0.7664 \ 0.1845 \ 0.2283 \ 0.3222 \ 0.3515 \ 0.2176 \ 0.1358 \ -0.3989]$, $\vec{d}=[0 \ 8 \ 12]$ and $\vec{w}_s^T=[0.48538 \ -0.02548 \ -0.01384]$. These parameters were obtained from an actual actuator. Experiments were conducted on a PZT actuator (PICMA P885.50) to obtain the individual points in Fig. 3.6 using equation (3.9). A best-fit line is then obtained from these points to obtain the parameters in equation (3.10). These parameters are then used in the simulation to have a more appropriate simulation. The simulation is performed with and without the proposed method and the results are compared. Fig. 3.15 shows the output result while Fig. 3.16 shows the input output linearization effect. Residual error can be clearly seen if mapping is not used.

3.4 Experimental Results

In this section, the behavior of the piezoelectric actuator P885.50 from Physik Instrumente is modeled. PICMA P885.50 is a stack of multi-layered piezoceramic with a stroke length of $15 \mu\text{m}$ at 100V and a resonant frequency of 70KHz. The actuators is modeled using the rate-dependent model proposed by Ang *et al.* [53]. Experiments are performed to show the improvements of the PI model by mapping onto a singularity-free domain. A brief description of the experiment setup is first given, followed by several experiments. The first experiment is a 20 Hz triangular wave. This is followed by varying amplitude linear motion with varying velocity to demonstrate the capability to model the rate-dependent model. The

Figure 3.15: Simulation result of the feedforward linearization.

Figure 3.16: Simulation result of the feedforward linearization.

last experiment is a varying frequency with varying amplitude sinusoidal wave.

3.4.1 Experimental Setup

As seen in Fig. 3.17, a 16-bit D/A card is used to generate the necessary voltage, which is then passed through the amplifier (the gain is approximately 10). Given the voltage, the actuator will deform and the interferometer will detect the displacement and convert it to analog voltage signal. The interferometer used is Philtec RC12 with a resolution of $0.08\mu\text{m}$, meaning the peak-peak noise can be up to $0.16\mu\text{m}$. Using a 16-bit A/D card, the PC reads in the displacement.

Figure 3.17: Experimental Architecture.

3.4.2 Experimental Result

The actuator is first modeled. The same model is used for both with and without mapping. The first experiment's desired displacement is a triangular wave with the velocity high enough for the first weight to go into the negative region while the second experiment's desired displacement is non-periodic linear motion. Fig. 3.18-3.20 shows the results of the triangular wave while Fig. 3.21 and Fig. 3.22 shows the outcome of the non-periodic motion.

From Fig. 3.18 and Fig. 3.20, it can be seen that the error has a general shape of a square wave. It has a general offset of overshoot when the desired displacement is increasing and an offset of undershoot when the displacement is decreasing. With mapping, this overshoot or undershoot are removed. Thus it can be clearly seen that the error in Fig. 3.18 (without mapping) is higher than the error in Fig. 3.19

Figure 3.18: Triangular wave without mapping.

Figure 3.19: Triangular wave with mapping.

(with mapping). The RMS error is greatly reduced by 40.1%. This proved that it is the singularity problem in the inverse expression that is creating the problem and not the hysteresis model.

Figure 3.20: Exploded view of error of triangular wave without and with mapping respectively.

Similar findings were obtained with non-periodic linear motion. Fig. 3.21 and 3.22 show the result of without and with mapping respectively. As seen from Fig. 3.21, like Fig. 3.18, there is also a constant overshoot or undershoot in the error depending on the direction of actuation. With mapping, the offsets are removed and the RMS error, calculated over the 200ms is reduced by 41.4%. Table 3.2 summarizes the result.

Figure 3.21: Non-periodic linear motion without mapping.

Table 3.2: Experimental Results

	Triangular Motion		Non-Periodic Linear Motion	
	Without	With	Without	With
RMSE (μm)	0.2580	0.1544	0.2267	0.1328
RMS error reduction	40.1%		41.4%	
max. error (μm)	0.5478	0.4222	0.4959	0.3473

This table summarizes the experimental results. A comparison between without mapping and with mapping can be made from this table.

Fig. 3.23 is an experiment to show that the proposed model is also valid for non-periodic varying sinusoidal waves and the rms error obtained is $0.14436\mu\text{m}$. These figures demonstrate that the model is able to model non-periodic motion.

Figure 3.22: Non-periodic linear motion with mapping.

3.5 Discussion

Prandtl-Ishlinskii model is the proposed method because models like Preisach model can only model continuously increasing gradient while Prandtl-Ishlinskii is able to model hysteresis like Fig. 3.2. In addition, Prandtl-Ishlinskii is the preferred method because the gradient of each segment can be obtained easily without any numerical differentiation needed. The inverse PI model can also be computed easily.

In this singularity-free Prandtl-Ishlinskii model, the formulas are based on one assumption. The assumption made is the existence of only one maximum and one minimum turning point. Some modifications will have to be made if there are two or more maximum or minimum turning points like Fig. 3.24. However,

Figure 3.23: Superposition of a few different frequencies of sinusoidal waves.

there is not much need to bother about this factor as very few systems have such irregular hysteresis. Having more than one maximum turning point will mean that the displacement of the actuator will decrease and suddenly increase while one has been lowering the input voltage. Even if such situation arises, the reader can use the proposed method with similar modification to account for the ill-shaped hysteresis.

Although Prandtl-Ishlinskii model is being used here, the idea of transformation can be extended to other models and the authors intend to do that in the near future because there are different advantages in each model to suit different situations.

From Fig. 3.20, it can be clearly seen that the error has a general shape of a

Figure 3.24: A hysteresis graph showing more than one maximum or turning points.

square wave. It has a general offset of overshoot when the desired displacement is increasing and an offset of undershoot when the displacement is decreasing. The reason to this error is due to the singularity-problem in the inverse PI hysteresis model. By mapping the hysteresis model onto a singularity free domain, the rms error was decreased by 48% (from $0.2\mu\text{m}$ to $0.1109\mu\text{m}$).

Although the application here is with piezoelectric actuators, this singularity-free hysteresis model transformation is a general model and is applicable to any hysteretic materials (applicable to most smart materials) or systems.

Chapter 4

Adaptive Controller

When using the open-loop feedforward controller, the hysteretic behavior of the actuator must be first modeled by sensing the relationship between the input voltage and output displacement. Unfortunately, the hysteretic behavior is dependent on the individual actuator and also environmental conditions like temperature. It is troublesome and costly to model the hysteresis regularly. In addition, the hysteretic behavior of the actuators also changes with age. Hence, an adaptive feedforward controller is proposed in this chapter. The adaptive feedforward controller is first given. The adapting mechanism, which is recursive least square, is next implemented with a slight modification. An algorithm for the adapting mechanism is next shown for ease in implementation. This chapter ends with experiments followed with discussions.

4.1 Adaptive Inverse Hysteretic Controller

A complete model is very complex. Thus, a phenomenological model of the actuator within the specification of the project's requirement was used. Experiments on the actuators were performed according to the application's specification. Based on the phenomenological hysteretic behavior of the actuator, equation (3.11) is able to model the hysteretic actuator well when within the specification. Hence, an assumption that the hysteretic behavior of a piezoelectric actuator can modeled using (3.11) is made. Substituting (3.10) into (3.11):

$$z(t) = \vec{w}_s^T \vec{S}_d \left[\vec{a} \cdot \vec{H}_r [x, \vec{y}_0] (t) + \dot{z}(t) \vec{b} \cdot \vec{H}_r [x, \vec{y}_0] (t) \right] \quad (4.1)$$

Thus, given the desired displacement, the required voltage can be obtained via:

$$y_d(t) = \vec{w}_{s'}^T \vec{S}_{d'} [z_d(t)] \quad (4.2)$$

$$x(t) = \vec{w}_{h'}^T (\dot{z}(t)) \vec{H}_{r'} [y_d, \vec{y}'_0] (t) \quad (4.3)$$

where $z_d(t)$ is the desired displacement, $y_d(t)$ is the desired displacement after passing through the inverse saturation operator and $x(t)$ is the estimated required voltage.

Given the input voltage, the actual output displacement from the hysteretic actuator is modeled as:

$$z_a(t) = \vec{w}_s^T \vec{S}_d \left[\vec{w}_{h_p}^T (\dot{z}(t)) \cdot \vec{H}_r [x, \vec{y}_0] (t) \right] \quad (4.4)$$

where $z_a(t)$ is the actual displacement, $\vec{w}_{h_p}^T$ are the actual weights of the play operators. The actual displacement of the actuator is also the measured displacement. Equation (4.4) can also be rewritten as:

$$\begin{aligned} y_a(t) &= \vec{w}_{s'}^T \vec{S}_{d'} [z_a(t)] \\ &= \vec{w}_{h_p}^T (\dot{z}(t)) \vec{H}_r [x, \vec{y}_0] (t) \\ &= \vec{a}_p \cdot \vec{H}_r [x, \vec{y}_0] (t) - \dot{z}(t) \vec{b}_p \cdot \vec{H}_r [x, \vec{y}_0] (t) \end{aligned} \quad (4.5)$$

where $\vec{a}_p$ and $\vec{b}_p$ are the vectors of the vertical-axis intercept and gradient of the plant's best fit lines that is described in Fig 3.6.

The error of the model is obtained as:

$$\begin{aligned} e_m(t) &= y_a(t) - y_d(t) \\ &= \vec{w}_{s'}^T \vec{S}_{d'} [z_a(t)] - \vec{w}_h^T (\dot{z}(t)) \vec{H}_r [x, \vec{y}_0] (t) \\ &= \vec{w}_{s'}^T \vec{S}_{d'} [z_a(t)] - \vec{a} \cdot \vec{H}_r [x, \vec{y}_0] (t) \\ &\quad - \dot{z}(t) \vec{b} \cdot \vec{H}_r [x, \vec{y}_0] (t) \end{aligned} \quad (4.6)$$

To adapt the vectors $\vec{a}$ and $\vec{b}$, least squares is performed with the cost function:

$$V(t) = \frac{1}{2} \sum_{i=0}^t [e_m(i)]^2 \quad (4.7)$$

Figure 4.1: Signal Flow Diagram of the Adaptive Feedforward Controller.

Assuming the hysteretic behavior of a piezoelectric actuator can be modeled accurately using equation (3.11), the vectors $\vec{a}$ and $\vec{b}$ will adapt as close to the behavior of the plant as possible. In other words,

$$\lim_{t \rightarrow \infty} e_m(t) \approx 0 \quad (4.8)$$

$$\lim_{t \rightarrow \infty} a_i \approx a_{i_a} \text{ and } \lim_{t \rightarrow \infty} b_i \approx b_{i_a} \text{ for } i = 1, \dots, n \quad (4.9)$$

if the input signals satisfy the persistent excitation condition. With the adapted vectors $\vec{a}$ and $\vec{b}$ that can closely model the plant, $\vec{w}_h^T(\dot{z})$ can be obtained. Thus, the inverse $\vec{w}_{h'}^T(\dot{z})$ can also be obtained using equation (3.8) and the desired-actual error will be minimized. The signal flow diagram of the adaptive feedforward controller is given in Fig. 4.1.

4.2 Adaptive Weight-Control Mechanism

The input vector to the recursive least square (RLS) is:

$$\vec{I}(t) = [H_{r_0}, \dot{z}(t)H_{r_0}, \dots, H_{r_n}, \dot{z}(t)H_{r_n}]^T \quad (4.10)$$

where H_{r_i} is $H_{r_i}[x(t), y_0]$. It is more important to adapt the a_i values to the hysteretic behavior than b_i . This is because as seen in Fig. 3.6 that the gradient of

the first few weights are more significant. Thus, the terms in the input vector, $\vec{I}(t)$, is multiplied with the terms in a priority vector, $[c_{a_0}, c_{b_0}, \dots, c_{a_n}, c_{b_n}]^T$, to obtain:

$$\mathbf{u}(t) = [c_{a_0}H_{r_0}, c_{b_0}\dot{z}(t)H_{r_0}, \dots, c_{a_n}H_{r_n}, c_{b_n}\dot{z}(t)H_{r_n}]^T \quad (4.11)$$

In this case, c_{a_i} is set to 1 and c_{b_i} is set to 0.007 if the unit of $\dot{z}(t)$ is in $\mu\text{m/s}$.

The weight vector to be adapted is defined as:

$$\vec{w}(t) = [a_0, b_0, a_1, b_1, \dots, a_n, b_n]^T \quad (4.12)$$

The remaining derivation steps to obtain the algorithm are very similar to the derivation of adaptive filters using RLS and can be found in books like [55]. Other available adaptive laws found in adaptive control textbooks may be implemented, with some modification if needed.

4.3 Algorithm

Initialization of the weights is first performed as shown in (4.13). Note that the first weight must again be set to be a positive non-zero number. The matrix $\mathbf{P}$ is also initialized. After that, for each sample loop, the parameters are computed as described in (4.14).

Initialization:

$$\begin{aligned} \vec{w}(0) &= [5, 0, \dots]^T \\ \mathbf{P}(0) &= \delta^{-1}\mathbf{I} \end{aligned} \quad (4.13)$$

where δ is a positive real number called the regularization parameter and is set to be a small positive constant for high signal to noise ratio (SNR) and set to be a large positive constant for low SNR.

For each instant of time, $n = 1, 2, \dots$, use

$$\begin{aligned}
 \vec{\pi}(n) &= \mathbf{P}(n-1) \cdot \mathbf{u}(n), \\
 \vec{\mu}(n) &= \vec{\pi}(n) / [\lambda + \mathbf{u}^H(n) \cdot \vec{\pi}(n)], \\
 \vec{w}(n+1) &= \vec{w}^T(n) + \vec{\mu}(n) \cdot \mathbf{u}(n) e_m(n), \\
 \mathbf{P}(n) &= \lambda^{-1} \mathbf{P}(n-1) - \\
 &\quad \lambda^{-1} \vec{\mu}(n) \cdot \mathbf{u}^H(n) \cdot \mathbf{P}(n-1).
 \end{aligned} \tag{4.14}$$

where λ is the forgetting factor which is a positive constant close to, but less than 1. When λ is set to 1, it implies infinite memory. Thus, set λ to be near unity if you want a controller that will remember most of the historical result, but it means it will adapt slower to a changing plant.

4.4 Simulation Results

In this section, simulation is performed using the proposed adaptive controller. The weights of a real piezoelectric actuator is first obtained through experiments. A few randomly created waves are then sent into the controller through simulation. The first portion shows the performance for a hysteretic plant that does not change while the second portion introduced a sudden change in the hysteretic plant at time 2.5sec to show its ability to adapt to changes. A number of simulation with different random input waves were performed for both portions. White noise with the amplitude of the interferometer's noise is also introduced in all the simulations to make it more similar to real environment condition.

4.4.1 Stationary Hysteretic Plant

In the first simulation test, the rate-dependent hysteretic behavior of the actuator is kept constant. In other words, the plant/actuator is consistent. In order to make the simulation nearer to real life applications, a piezoelectric actuator is modeled and the parameters are obtained. Assuming that the parameters are not known, the weights are initialized as (4.13). Fig. 4.2 shows the simulation result of the

controller.

Figure 4.2: Simulation result of a stationary rate-dependent plant.

Figure 4.3: Simulation result of a rate-dependent plant with a sudden change in its parameters.

4.4.2 Robustness: Sudden Change in Hysteretic Plant

In the second simulation test, the controllers are subjected to a sudden change in the hysteretic behavior at time 2.5 sec to test its robustness. Fig. 4.3 shows the result. a_p was changed from $[8.4 \ 1.3 \ 0.92 \ 0.7 \ 0.88 \ 0.74 \ -2.6 \ 1.12]$ to $[7.8 \ 1.3 \ 0.95 \ 0.5 \ 0.8 \ 0.8 \ -2 \ 1.6]$ while b_p was change from $[-0.9 \ 1.03 \ -0.244 \ 0.1 \ 0 \ 0 \ 0 \ 0]$ to $[-0.8 \ 1.1 \ -0.2 \ 0.1 \ 0 \ 0 \ 0 \ 0]$ at time $t=2.5$ sec. The percentage change in each parameter is summarized in table 4.1. As seen in the figure, the controller is able to adapt to changes in the plant.

Table 4.1: Summary of the change in parameters

initial a_p	8.4	1.3	0.92	0.7	0.88	0.74	-2.6	1.12
updated a_p	7.8	1.3	0.95	0.5	0.8	0.8	-2	1.6
percentage change (%)	7.1	0	-3.2	28.6	9.1	8.1	23.1	-42.9
initial b_p	-0.9	1.03	-0.244	0.1	0	0	0	0
updated b_p	-0.8	1.1	-0.2	0.1	0	0	0	0
percentage change (%)	11.1	6.8	18.0	0	0	0	0	0

4.5 Experimental Results

In this section, a brief description of the experiment setup is first given, followed by the results. The behavior of the piezoelectric actuator P885.90 from Physik Instrumente is used to demonstrate the adaptive rate-dependent feedforward controller.

4.5.1 Experimental Setup

Similar to the experimental setup in the previous chapter (Fig. 3.17), a 16-bit D/A card is used to generate the necessary voltage, which is then passed through the amplifier (the gain is approximately 10). Given the voltage, the actuator will deform and the interferometer will detect the displacement and convert it to analog voltage signal. Using a 16-bit A/D card, the PC reads in the displacement.

To perform tracking control, real-time operating system QNX Neutrino is used. The sampling rate of the DAQ card is set at 10 kHz. A timer interrupt is set at an interval of 0.5 ms (2 kHz) to average the data collected and update the parameters. The averaging acts a form of filtering.

4.5.2 Experimental Results

Experiments are conducted to demonstrate the performance of the adaptive feed-forward controller. The objective of the actuator is to actuate according to a desired motion. In all the experiments conducted for this chapter, the parameters of the actuator are treated as unknown. The first term of vector $\vec{a}$ is initialized as 5 whilst all the remaining terms in the vectors $\vec{a}$ and $\vec{b}$ are all initialized as 0.

The first experiment is to actuate the actuator in a periodic sinusoidal motion. Fig. 4.4 shows the outcome and table 4.2 summarize the result. The RMSE is found to be 0.1211 μm from 0.75s to 1s. The RMSE will continue to drop if more adaptation time is permitted. The RMSE from time 10s to 20s is 0.0584 μm , which is near to the interferometer's noise level. Using a sensor with lower noise and better resolution might be able to reduce the RMSE.

Table 4.2: Measured Performance of the Adaptive Rate-Dependent Controller in Tracking Sinusoidal Waveforms

	4 Hz	8Hz	12Hz
RMSE(μm)	0.0638	0.0619	0.0584
RMSE / actuator's stroke length	0.0028	0.0026	0.0027

The RMSE and max errors are the results taken from over a span from 10s to 20s.

In the first experiment, the desired motion is a periodic motion. However, the desired motions in many industrial applications are random and non-periodic. Thus, the adaptive feedforward controller was tested with a number of randomly created desired waveform motions. These waveforms are created by first generating random numbers using a Matlab function (rand), which can be assumed to be uniformly distributed random numbers. These values are then passed through a

Figure 4.4: Tracking result of a 12Hz sinusoidal wave.

low pass filter, with a cutoff frequency of 20Hz, to remove the higher frequency components and smoothen out the points. Random numbers are used to ensure that the waveform is not periodic. This is where the rate-dependent phenomena play a role in the adaptive feedforward controller.

Five different waves were randomly created. Fig. 4.5 shows how the weights converge while Fig. 4.6 shows the tracking performance of the adaptive feedforward controller for one of the waveforms. A section between time 5s and 8s is shown in Fig. 4.7. The result is summarized in Table 4.3. A wide time span of 10s to 20s is used to calculate the result for better representation. The mean RMSE of the 5 non-periodic motions is found to be $0.0943 \mu\text{m}$ with $\sigma = 0.0159$. The mean of the maximum errors is $0.3899 \mu\text{m}$ with $\sigma = 0.0291$.

Figure 4.5: Convergence of the weights of the adapting mechanism in the actual experiment.

Table 4.3: Measured Performance of the Adaptive Rate-Dependent Controller in Tracking Randomly Created Waveforms

Adaptive Rate-Dependent Controller	
RMSE $\pm \sigma(\mu\text{m})$	0.0943 ± 0.0159
RMSE / peak-peak (%)	0.33
max error $\pm \sigma (\mu\text{m})$	0.3899 ± 0.0291
max error / peak-peak (%)	1.35

The RMSE and max errors are the mean results over a set of 5 different random non-periodic waveform experiments. The error is calculated from time = 10s to 20s. The waveforms are created by passing random numbers through a low-pass filter. The peak-peak is obtained as the difference between the maximum and minimum during this 10s interval of the random non-periodic waveforms.

4.6 Discussion

Most controllers like PID controllers introduce phase difference. Phase difference comes with higher tracking error. The proposed adaptive hysteresis feedforward controller is suitable for tracking purpose as no phase difference is introduced.

In this chapter, the actuator is actuated in accordance to the randomly created non-periodic waveform. Thus, there is no prior knowledge of the desired motion

Figure 4.6: Experimental results of a randomly created non-periodic wave. The different non-periodic waves are created by passing random numbers through a low pass filter.

and the motion is non-periodic. The purpose of choosing non-periodic waveform is to illustrate the rate-dependent ability of the adaptive feedforward control. As illustrated in the experiments, although the hysteretic plant (actuator) is treated as unknown, the adaptation speed of the feedforward controller is less than a second. The convergence speed is dependent on the waveform. A good learning waveform at the beginning will shorten the convergence time. Different adapting mechanism/law can be used too. In this chapter, RLS is used as it is a simple and good algorithm with fast convergence time to implement. The author had also implemented least mean square (LMS) as the adapting mechanism. Although LMS is more robust to sudden changes, the steady state error is not as low and also the environmental conditions do not often change abruptly.

Figure 4.7: A section of Fig. 4.6 between time 5s to 8s.

Figure 4.8: Simulation result of the adaptive controller with real tremor data.

In the simulations and experiments, the excitation signal is treated as not known before hand. Each point is treated to be known only at each instant. The idea of these tests is to show that the controller is able to perform tracking control of motion that are not known before hand, which is the case for real-time control.

However, there is no perfect controller. There is one major limitation in the proposed controller. The input signals to the adapting mechanism must satisfy the persistent excitation condition because RLS is used. It is difficult to prove the order of satisfying the persistent excitation condition because of the operators involved. Hence, real tremor data were collected from healthy subjects performing a pointing task using M2S2 developed by Win *et al.* [56]. These data were then input into the simulation and the controller was found to be stable. An example is shown in Fig. 4.8.

Chapter 5

Design and Development of a Low-cost Handheld Mechanism for Micromanipulation

A parallel manipulator is designed and developed for the piezoelectric actuators to actuate and compensate the tremulous motion. The first few prototype developed by Dr. Riviere and Dr. Ang were not totally flexure-based. In the later days, Choi and Riviere [57] designed a flexure-based mechanism to remove any backlash issue. A similar design was built and discovered that it has hysteresis-like behavior when driven at high frequency. Hence, a new 3-DOF flexure-based handheld manipulator is designed, developed and tested. The chapter begins with some background information on flexure-based mechanism.

5.1 Background

There is a need for manipulators with high accuracy and rapid response in many applications. Conventional mechanisms with traditional motors, gears and revolute joints are not able to meet the requirements. Their coarse accuracy is caused by the existence of backlash and friction between moving parts. Hence, flexure joints are more popularly used.

Flexure joints have been used in precision instruments like watches and clocks since many years ago. Ever since the seminal work of Paros and Weisbord [58], there has been an increase in usage of flexure-based mechanism in new applications, such as optical systems and micro-robots, where precision is of great importance.

Flexure joints offer several significant advantages [59, 60] and are typically manu-

factured monolithically. Hence, errors due to assembly can be avoided. In addition, no sliding parts are required in flexure-based mechanism. Thus, lubricant is not needed making it suitable for applications like medical surgery which require clean and sterile environment. More importantly, flexure joints generate smooth displacement without backlash. As long as the flexure joints are not pushed into their plastic region, the joints are able to produce predictable and repeatable motions. These advantages make flexure-based mechanism attractive in applications involving micro-scale precision motion [61–64].

5.1.1 Flexure-based Prismatic Joint

One of the joints used in the final design is a flexure-based prismatic joint. An ideal prismatic joint is defined as one that is able to generate pure linear motion when actuated, without having cross-axis effect on other axis. There should neither be any rotation nor any motion generated in any of the other axis. There are a couple of flexure-based prismatic joints. The most conventional prismatic joint, which uses a parallelogram, is shown in Fig 5.1.

Figure 5.1: Conventional prismatic joint.

This conventional parallelogram prismatic joint is simple, but it has a cross-axis effect. The prismatic joint generates a linear motion with parasitic motion in the other axis. To overcome that, the idea of using double parallelograms (Fig. 5.2) was used [65].

The main disadvantage of Fig. 5.2 is that it is not symmetrical and changes due to temperature will not be uniform. Hence, Tang and Chen [66] proposed a prismatic joint as shown in Fig. 5.3.

Figure 5.2: Improved prismatic joint using double parallelograms.

Figure 5.3: Improved prismatic joint [66].

As space constraint is a major consideration for our handheld instrument, the mentioned designs were not suitable. Hence, the idea of symmetry for symmetrical deformation was used and the prismatic joint to be used in the final design is shown in Fig. 5.4. The deformation of the prismatic joint can be seen in Fig. 5.13 later.

Figure 5.4: Prismatic joint making use of symmetrical deformation.

5.1.2 Parallel Mechanism

In order to meet the handheld requirement, size is a concern. Thus, parallel mechanism is preferred over serial mechanisms because of its compactness. In addition, parallel manipulators have advantages such as no accumulative error and high rigidity over serial mechanisms. Tang and Chen [66] proposed an XYZ-flexure parallel mechanism with large displacement and decoupled kinematics structure. Dong *et al.* [64] proposed a wide-ranged flexure hinge-based parallel manipulator while Yi *et al.* [67] focused on $XY\theta_Z$ stages.

However, it is expensive and difficult to make a compact parallel micromanipulator using traditional machining methods. Processes like electro-discharge machining (EDM) are able to produce precise cutting, but the cost is expensive. In addition, machining methods are limited to simple designs. Complicated 3-D designs are not allowed as there must be space available for the cutting tool to reach.

To save cost, a rapid-prototyping machine is proposed to be used. Objet, a rapid-prototyping machine, is used to build the part and the material used is VeroWhite. The part is built layer by layer. The supports used in the building is a gel-like material, which can be easily removed. Thus, complicated designs are permitted.

The remaining portion of the chapter presents the 3-DOF low-cost handheld manipulator for micromanipulation.

5.2 Design

The function of the manipulator is to provide an equal, but opposite displacement to the tip of the intraocular shaft to cancel the physiological tremor in realtime and the design specifications are as follows:

1. Actuation bandwidth of 8-12Hz,
2. Actuation force of more than 15.0mN,
3. Manipulator workspace $\geq 70\mu\text{m}$ sphere, and
4. Diameter of instrument $\leq 30\text{mm}$.

5.2.1 Design 1

In the first design, which is similar to the design by Choi and Riviere [57], the author wanted to use short actuators so as to keep the instrument short. As the stroke length of the short actuator is insufficient, levers were used to amplify the stroke as shown in Fig. 5.5

Figure 5.5: Lever used to amplify the actuator's stroke length.

Since there was a need to make the mechanism slim, the author used the idea of overlapping levers. The three overlapping levers are shown in Fig. 5.6.

Figure 5.6: Overlapping Individual Levers.

Initially, the design of the mechanism is made up of different parts. Each lever is a part itself. The author realised that the assembly error incurred in the mechanism is significant. Hence, the author decided to make the mechanism as a single piece as shown in Fig. 5.7 while Fig. 5.8 shows a photo of the prototype.

Figure 5.7: Design 1.

Figure 5.8: Comparison of Design 1 with a fifty cents coin.

However, the first design is able to function well only for low frequency motion. At higher frequency of 10Hz, hysteresis like effect comes in. Fig. 5.9 shows the result when the mechanism is driven to move in a line alone x-axis at 10Hz.

The hysteresis like effect is due to the overlapping levers. This is because when driving the mechanism at a higher frequency, the moment acting on the lever in-

Figure 5.9: Hysteresis like effect when driven at 10Hz.

creases and thus, the levers start to bend accordingly. One way of solving this problem is by increasing the moment of inertia. However, due to the space constraints, the moment of inertia cannot be increased by too much. Hence, a second design was proposed.

5.2.2 Design 2

Fig. 5.10 shows a photo of the manipulator of the second design. There are two portions. The upper portion is the mechanism while the lower part houses the piezoelectric actuators. The two parts are connected via screws. Fig. 5.11 shows the mechanism while Fig. 5.12 is the schematic of the mechanism.

The mechanism used is a parallel mechanism. There are three limbs connecting the moving platform to the base platform. Each limb consists of a prismatic joint in series with a pin joint and a ball joint. The main function of the prismatic joint is to provide a spring like effect to keep the actuators in contact with the base. The mechanism is designed in such a way that the actuator is pre-stressed when the mechanism is attached to the holder.

Figure 5.10: Photo of the mechanism with actuator holder.

Figure 5.11: Exploded view of the mechanism.

Figure 5.12: Schematic of the Mechanism.

As the length of the ball joint in the axial direction is not relatively long enough, it is not an ideal ball joint as the bending stiffness along the axial direction is greater than along the two radial directions. However, this design can still be used because the designed workspace is small and the axial direction of the joints is along the global z-axis when at zero position. Hence, very little bending needed along each axial direction.

Fig. 5.13 shows how the joints will deform when the mechanism is actuated to move vertically upwards while Fig. 5.14 shows the deformation when the desired tip position is towards the left.

The size of the manipulator is small enough for handheld purpose. The diameter of the mechanism (excluding the holder) is 27mm and the height from the mechanism's base to the moving platform is 17mm. The diameter of the holder is 22mm and the height of the holder actually depends on the length of the actuator, which is dependent on the stroke length required for the application. In this thesis, the

Figure 5.13: Deformation of Design 2 when actuated to move vertically up.

Figure 5.14: Deformation of Design 2 when desired tip position is towards the left.

height of the holder is 57mm.

A male luer connector is also built on the moving platform. A needle is attached to the moving platform via tight fit with the male luer connector. For a wider range of usage, the design of the connector can be changed to other type of connectors accordingly to suit the required tool to be used.

5.3 Fabrication

The cost of building the lower and upper part is SGD \$100 in Singapore Dollars (approximately USD\$ 71.8) each, making the total cost to be SGD\$200 (USD\$143.6), which is less than USD\$150. Designing the upper portion (mechanism) for traditional machining easily involve more than 20 parts and will cost more than SGD\$2000. In addition, errors due to assembly, backlash and friction will come into play. Thus, it is proposed that the mechanism to be built as a single piece using rapid prototyping. No assembly will be required for the mechanism portion. In addition, the cost of rapid prototyping is less than 10% of the traditional machining cost.

To save cost, the lower portion is fabricated using traditional machining. As for the complicated upper portion, Objet (by Objet Geometries Ltd) is used to build the part. Objet Geometries Ltd manufactures and markets ultra-thin-layer, high-resolution 3 dimensional printing systems that utilize PloyJet™ Polymer Jetting technology to print. The material that is used here is VeroWhite, whose mechanical properties can be found in Appendix B. VeroWhite is jetted onto the build tray in thin layers of $16\mu\text{m}$. The part is built layer by layer till the whole part is completed. Each layer is cured by UV light immediately after it is jetted onto the build tray. This results in a fully cured model and can be used immediately. No post-curing is required. The supports that are used in the building is a gel-like material. The gel-like support material can be easily removed by hand and water. In addition, certain solvent can be used to dissolve those support material that cannot be reached by hand. Thus, complicated mechanism can be easily built and available for use within a day.

There is one major issue to note when using rapid prototyping machine for flexure-based mechanism. The part is built layer by layer as shown in Fig. 5.15 and the side is not very smooth. As flexure joints involve bending, there is higher stress concentration on the sides. In addition, the bonding strength between layers is weaker than the material's tensile strength.

Figure 5.15: Part built layer by layer.

To avoid the mechanism failure due to the layers' issues, instead of building from the bottom of the mechanism to the top, the mechanism is built from left to right. The mechanism is configured to be built in the manner shown in Fig 5.16. In this way, the stress due to most of the bending will be taken up by the material, and not by the bond between layers.

Figure 5.16: Orientation of the Mechanism in the Rapid Prototyping Machine.

5.4 Analysis

This section first analyzes the mechanism. This is followed by the inverse kinematics that is used to calculate the required actuation input. The workspace and finite element analysis is presented next.

5.4.1 Degree of Freedom

In a parallel mechanism, it is usual to have similar constraints among the joints. Hence, reciprocal screws are used over Grashof criterion to determine the degree of freedoms, and at the same also to analyze the wrenches by the limbs on the

platform. For example, given a mechanism as shown in Fig. 5.17, the link can move up and down. However, the number of DOF obtained using Grashof is not 1. This is because of the similar constraints in the two prismatic joints. In a parallel mechanism, similar constraints among the joints is common. Hence, reciprocal screws are used.

Figure 5.17: Example of a mechanism where calculation of the number of DOF via Grashof will fail.

In general, given a parallel mechanism with m limbs and l joints per limb, the net twist motion system of limb i is $\xi_{1,i} \cup \xi_{2,i} \cup \dots \cup \xi_{l,i}$. The net wrench of limb i are the screws that are reciprocal to the twist motions and the number of independent wrenches is given by:

$$\begin{aligned}
 &= \text{rank}[(\xi_{1,1} + \xi_{2,1} + \dots + \xi_{l,1}) \cap (\xi_{1,2} + \xi_{2,2} + \dots + \xi_{l,2}) \cap \dots \cap (\xi_{1,m} + \xi_{2,m} + \dots + \xi_{l,m})] \\
 &= 6 - \text{rank}[(W_{1,1} + W_{2,1} + \dots + W_{l,1}) \cap (W_{1,2} + W_{2,2} + \dots + W_{l,2}) \cap \dots \cap (W_{1,m} + W_{2,m} + \dots + W_{l,m})]
 \end{aligned} \tag{5.1}$$

where $W_{j,i}$ is the j^{th} wrench of limb i . The basics and screw convention used in this paper to analyze the mechanism can be found in Tsai [68] and [69].

In this parallel mechanism, there are 3 limbs. For this section, the fix frame is placed at frame $\{1\}$'s location. In the first limb, the screws are:

$$\begin{aligned}
 \xi_1 &= [0 \ 0 \ 0 \ 0 \ 0 \ 1]^T \\
 \xi_2 &= [0 \ 1 \ 0 \ L \ 0 \ r]^T \text{ with } r_2 = [r \ 0 \ -L]^T \\
 \xi_3 &= [1 \ 0 \ 0 \ 0 \ 0 \ 0]^T \text{ with } r_3 = [r \ 0 \ 0]^T
 \end{aligned}$$

$$\xi_4 = [0 \ 1 \ 0 \ 0 \ 0 \ r]^T \text{ with } r_4 = [r \ 0 \ 0]^T$$

$$\xi_5 = [0 \ 0 \ 1 \ 0 \ -r \ 0]^T \text{ with } r_5 = [r \ 0 \ 0]^T$$

It can be found that the rank of the screws is 4, and hence there should be two wrench. The wrench (reciprocal screws that are reciprocal to all) are:

$${}^1W_1 = [0 \ 1 \ 0 \ 0 \ 0 \ r]^T$$

$${}^1W_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1]^T$$

Doing likewise for the other 2 limbs, the wrenches are:

$${}^2W_1 = [-\sqrt{3}/2 \ -1/2 \ 0 \ 0 \ 0 \ 0 \ r]^T$$

$${}^2W_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1]^T$$

$${}^3W_1 = [\sqrt{3}/2 \ -1/2 \ 0 \ 0 \ 0 \ 0 \ r]^T$$

$${}^3W_2 = [0 \ 0 \ 0 \ 0 \ 0 \ 1]^T$$

The net wrench is thus:

$$W = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & r \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\sqrt{3}/2 & -1/2 & 0 & 0 & 0 & r \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \sqrt{3}/2 & -1/2 & 0 & 0 & 0 & r \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.2)$$

Hence, the degree of freedom is $(6-3) = 3$. In addition, it can be seen that the degree of freedom in this particular state are z , θ_x and θ_y .

5.4.2 Inverse Kinematics

This section describes the inverse kinematics that is used to calculate the actuation input. Avedillo *et al.* [70] tried using neural network to solve the kinematics of this manipulator. The author had also tried using a couple of networks. Although the method is easy, the performance was limited. Thus, in order to obtain better accuracy, the inverse kinematics was solved. The style on how the inverse kinematics is obtained is similar to what Lee *et al.* [71–73] proposed, with some modification as the mechanism and point of interest is slightly different. A schematic diagram

of the mechanism is shown in Fig. 5.12. The moving platform, $\{1\}$, is connected to the base, $\{0\}$, by means of an extensible link, in series with a pin joint followed by a ball joint. The actuators are equally spaced at 120° and a radius of r from the center of the base. Hence, the coordinates of the pin joints with respect to $\{0\}$ are:

$${}^0P_1 = \begin{bmatrix} r \\ 0 \\ l_1 \end{bmatrix}, {}^0P_2 = \begin{bmatrix} -\frac{1}{2}r \\ \frac{\sqrt{3}}{2}r \\ l_2 \end{bmatrix}, {}^0P_3 = \begin{bmatrix} -\frac{1}{2}r \\ -\frac{\sqrt{3}}{2}r \\ l_3 \end{bmatrix} \quad (5.3)$$

Similarly, the ball joints are equally spaced at a radius r from the center of the moving platform and the coordinates of the ball joints with respect to $\{1\}$ are:

$${}^1U_1 = \begin{bmatrix} r \\ 0 \\ 0 \end{bmatrix}, {}^1U_2 = \begin{bmatrix} -\frac{1}{2}r \\ \frac{\sqrt{3}}{2}r \\ 0 \end{bmatrix}, {}^1U_3 = \begin{bmatrix} -\frac{1}{2}r \\ -\frac{\sqrt{3}}{2}r \\ 0 \end{bmatrix} \quad (5.4)$$

The position and orientation of $\{1\}$ with respect to $\{0\}$ can be related by a homogeneous transformation. The transformation matrix to map $\{1\}$ to $\{0\}$ is given by:

$$T_{01} = \begin{bmatrix} n_x & o_x & a_x & x_c \\ n_y & o_y & a_y & y_c \\ n_z & o_z & a_z & z_c \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5.5)$$

where $[n_x n_y n_z]^T$, $[o_x o_y o_z]^T$ and $[a_x a_y a_z]^T$ are the directional cosines vectors. At initialization, frame $\{1\}$ has the same orientation as frame $\{0\}$ and the origin of $\{1\}$ with respect to $\{0\}$ is given by $[0 \ 0 \ z_{c0}]^T$. The length of the link between the i^{th} pin joint and i^{th} ball joint is

$$L = |{}^0U_1 - {}^0P_1|, L = |{}^0U_2 - {}^0P_2|, L = |{}^0U_3 - {}^0P_3| \quad (5.6)$$

where L is the length of the link connecting the pin joint and ball joint. Thus,

$$L^2 = (n_x r + x_c - r)^2 + (n_y r + y_c)^2 + (n_z r + z_c - l_1)^2 \quad (5.7)$$

$$L^2 = \frac{1}{4} \left(-n_x r + \sqrt{3} o_x r + 2x_c + r \right)^2 + \frac{1}{4} \left(-n_y r + \sqrt{3} o_y r + 2y_c - \sqrt{3} r \right)^2 + \frac{1}{4} \left(-n_z r + \sqrt{3} o_z r + 2z_c - 2l_2 \right)^2 \quad (5.8)$$

$$L^2 = \frac{1}{4} \left(-n_x r - \sqrt{3} o_x r + 2x_c + r \right)^2 + \frac{1}{4} \left(-n_y r - \sqrt{3} o_y r + 2y_c + \sqrt{3} r \right)^2 + \frac{1}{4} \left(-n_z r - \sqrt{3} o_z r + 2z_c - 2l_3 \right)^2 \quad (5.9)$$

The design of the flexure joints, which ideally imposes the physical constraints equivalent to pin joints, limit the ball joints to move in the respective planes:

$$y = 0, \quad y = -\sqrt{3}x \quad \text{and} \quad y = \sqrt{3}x \quad (5.10)$$

This means that the position of the ball joints, U_i , are constrained into these three planes respectively. The constraint equations are thus:

$$n_y r + y_c = 0 \quad (5.11)$$

$$-n_y r + \sqrt{3} o_y r + 2y_c = -\sqrt{3} \left[-n_x r + \sqrt{3} o_x r + 2x_c \right] \quad (5.12)$$

$$-n_y r - \sqrt{3} o_y r + 2y_c = \sqrt{3} \left[-n_x r - \sqrt{3} o_x r + 2x_c \right] \quad (5.13)$$

By adding (5.12) with (5.13) and also subtracting (5.12) from (5.13), the constraint equations respectively becomes:

$$n_y = o_x \quad (5.14)$$

$$x_c = \frac{1}{2} r (n_x - o_y) \quad (5.15)$$

By expressing the directional cosines in terms of the famous Z-Y-Z Euler angles

(α, β, γ) , T_{01} can be expressed as:

$$\begin{bmatrix} C_\alpha C_\gamma C_\beta - S_\alpha S_\gamma & -C_\alpha S_\gamma C_\beta - S_\alpha C_\gamma & C_\alpha S_\beta & x_c \\ S_\alpha C_\gamma C_\beta + C_\alpha S_\gamma & -S_\alpha S_\gamma C_\beta + C_\alpha C_\gamma & S_\alpha S_\beta & y_c \\ -C_\gamma S_\beta & S_\gamma S_\beta & C_\beta & z_c \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus,

$$\alpha = \tan^{-1} \frac{a_y}{a_x} \quad (5.16)$$

$$\beta = \tan^{-1} \frac{\sqrt{n_z^2 + o_z^2}}{a_z} \quad (5.17)$$

$$\gamma = \tan^{-1} \frac{o_z}{-n_z} \quad (5.18)$$

In addition, equation (5.14) becomes:

$$\begin{aligned} S_\alpha C_\gamma (C_\beta + 1) &= -C_\alpha S_\gamma (1 + C_\beta) \\ \Rightarrow \tan \alpha &= -\tan \gamma \\ \Rightarrow \alpha + \gamma &= n\pi \\ \Rightarrow \alpha &= -\gamma \because n = 0 \end{aligned} \quad (5.19)$$

Although there are two possible sets of solution, only n equal to zero is physically possible in this mechanism. Thus, n equal zero was chosen. And also,

$$\begin{aligned} n_x - o_y &= C_\alpha C_\gamma C_\beta - S_\alpha S_\gamma + S_\alpha S_\gamma C_\beta - C_\alpha C_\gamma \\ &= C_\alpha^2 C_\beta + S_\alpha^2 - S_\alpha^2 C_\beta - C_\alpha^2 \\ &= C_{2\alpha} C_\beta - C_{2\alpha} \end{aligned} \quad (5.20)$$

Hence, from (5.15),

$$x_c = -\frac{1}{2}r(1 - C_\beta)C_{2\alpha} \quad (5.21)$$

and from (5.11),

$$\begin{aligned} y_c &= -n_y r \\ &= -r [S_\alpha C_\gamma S_\beta + C_\alpha S_\gamma] \\ &= -\frac{1}{2}r [2S_\alpha C_\alpha C_\beta - 2C_\alpha S_\beta] \\ &= \frac{1}{2}r(1 - C_\beta)S_{2\alpha} \end{aligned} \quad (5.22)$$

Till here, there are 6 variables, namely: x_c , y_c , z_c , α , β , and γ . x_c , y_c and γ are the dependent variables while α , β and z_c are the independent variables. However, the end effector of the micromanipulator is the tip of the needle. Hence, the inputs to the inverse kinematics should be $[d_x \ d_y \ d_z]^T$, which is the desired displacement of the needle's tip from the initial position. Since

$$\begin{bmatrix} d_x \\ d_y \\ d_z \\ 1 \end{bmatrix} = T_{01} \begin{bmatrix} 0 \\ 0 \\ l_{tip} \\ 1 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ z_{c0} + l_{tip} \\ 1 \end{bmatrix} \quad (5.23)$$

d_x , d_y and d_z can be written as:

$$d_x = x_c + l_{tip}a_x \quad (5.24)$$

$$d_y = y_c + l_{tip}a_y \quad (5.25)$$

$$d_z = z_c - z_{c0} + l_{tip}(a_z - 1) \quad (5.26)$$

By replacing x_c , a_x , y_c and a_y with α and β , d_x and d_y can be expressed as:

$$d_x = -\frac{1}{2}r(1 - C_\beta)C_{2\alpha} + C_\alpha S_\beta l_{tip} \quad (5.27)$$

$$\begin{aligned} d_y &= \frac{1}{2}r(1 - C_\beta)S_{2\alpha} + S_\alpha S_\beta l_{tip} \\ &\approx S_\alpha S_\beta l_{tip} \because \beta \text{ is small} \end{aligned} \quad (5.28)$$

As the range of motion of the manipulator is not big, β is small and $(1 - C_\beta)$ can be approximated to be zero. Hence,

$$\alpha = \tan^{-1} \left(\frac{d_y}{d_x} \right) \quad (5.29)$$

$$\beta = \sin^{-1} \left(\frac{d_x}{C_\alpha l_{tip}} \right) \quad (5.30)$$

where $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$, $-\frac{\pi}{2} \leq \beta \leq \frac{\pi}{2}$.

x_c , y_c , γ can be expressed in terms of α , β and z_c using (5.21), (5.22), and (5.19) respectively and T_{01} is in terms of α , β and γ . In addition, α , β and z_c can be calculated using (5.29), (5.30) and (5.26) respectively. Hence, l_1 , l_2 and l_3 can be found by solving equations (5.7), (5.8) and (5.9) respectively.

5.4.3 Workspace

Using a piezoelectric actuator P885.90 from Physik Instrumente stacked with a P885.50 as the input actuation, the workspace of the manipulator is shown in Fig. 5.18. In calculating the workspace, the input stroke is limited to $45\text{ }\mu\text{m}$ and not stretched to the maximum. This is because operating at the maximum might reduce the lifespan of the actuators.

Figure 5.18: Workspace of the manipulator.

5.4.4 Finite Element Analysis

Finite element analysis was performed on the mechanism to analyze the stress. A number of different input was simulated and Fig. 5.19 shows one possible situation, which is when all the actuators are actuating at their limit.

5.5 Experimental Results

In this section, a brief description of the experiment setup is first given, followed by the results. The piezoelectric actuator used for each input is a P885.90 from Physik Instrumente stacked with a P885.50. This gives a total stroke length of about $47\text{ }\mu\text{m}$, though the author limited it to be $45\text{ }\mu\text{m}$.

Figure 5.19: Finite element analysis of the mechanism when all three actuators are actuating.

5.5.1 Experiment Setup

In this chapter, all the displacement readings of the end effector is measured by the system developed by Win *et al.* [56] using position sensitive devices with a RMS error of $2.1 \mu\text{m}$. The experiment setup is as shown in Fig. 5.20.

For measurement purpose, the needle is replace by a rod with a ball attached to the end. The ball is placed such that it is the same as the position of the needle's tip. The ball is required to be used to reflect the IR waves to the position sensitive devices. The controller for the actuators is the controller described in chapter 3.

5.5.2 Results

A number of experiments were conducted to demonstrate the performance of the manipulator. The first experiment is to move the end effector in a circular path with a radius of $85 \mu\text{m}$ at a frequency of 10Hz. Fig. 5.21 shows the 3-D plot of the result while Fig. 5.22 shows the result in the y-axis component. These two figures show that the measured manipulator's end effector (which is the needle tip) is able to track the desired path. Next, the end effector is driven to move in a

Figure 5.20: Experiment Setup.

couple of straight lines of a length of $170\mu\text{m}$ at a frequency of 10Hz along $y=x$, y -axis and x -axis. The result of the trajectory is shown in Fig. 5.23, 5.24 and 5.25 respectively. Table 5.1 summaries the numerical results for all. In this table, the absolute root mean square error can be found along with the root mean square error in the x , y and z axis component.

Figure 5.21: 3-D plot of the end effector when driven to draw a circle.

Figure 5.22: 1-D plot of Fig. 5.21 in the y-axis component.

Figure 5.23: 2-D plot of the end effector when driven to move along $y=x$.

Figure 5.24: 2-D plot of the end effector when driven to move along y-axis.

Figure 5.25: 2-D plot of the end effector when driven to move along x-axis.

Table 5.1: Experimental Results

Type of Motion	x rmse	y rmse	z rmse	rmse
circle	4.5061	4.9720	1.6137	6.9014
straight line along x-axis	4.3429	2.8307	1.6383	5.4367
straight line along y-axis	1.8563	4.0526	1.0122	4.5710
straight line along y=x	4.2612	4.3842	0.9994	6.1950

This table summarizes the experimental results. All the readings are in μm . All the motions are driven at 10Hz with an amplitude of $85\mu\text{m}$ ($170\mu\text{m}$ peak-peak). The data are collect over 2.5 sec. x rmse, y rmse and z rmse are the root mean square errors along x, y and z axis. The rmse root mean square of the absolute errors.

5.6 Discussion

The performance of the micromanipulator can be seen from table 5.1. It can be seen that the absolute root mean square errors for all the trajectories are less than $7\mu\text{m}$. These trajectories were driven at 10Hz with a amplitude of $85\mu\text{m}$. In other words, the amplitude in the acceleration domain is 335.6mm/s^2 .

One major disadvantage of using rapid prototyping is its poorer resolution as compared to more precise machining. Modeling of the mechanism is important for close-loop control. However, as the dimension is not that accurate, the model of the mechanism that is obtained through theoretical calculations does not fit the actual mechanism well. In addition, the mechanism is built layer by layer. The properties of the material is not isotropic and same throughout. This makes modeling of the mechanism even more challenging.

The property of the material also changes over time. It seems that the flexure joints tends to cure a few days after putting the actuators in a pre-stressed position. Curing of the material means reduction in the spring stiffness. This will affect the performance of the mechanism. Luckily, the targeted segment is microsurgery and in surgery, they have to use a new piece for each new surgery for non-infection purpose.

The hysteresis-like effect shown in design 1 is due to the higher bending moments when driven at higher frequencies. This effect can be resolved if better material like metals is used. Fabricating the prototype through machining metals will definitely improve the mechanical flexure properties. However, it is not possible to machine the mechanism as a single piece. The number of parts needed will increase. The prototype will involve more than 20 components. Due to the fasteners needed, the size of the instrument will increase. In addition, the accuracy of the mechanism will be affected because of the accumulated assembly errors. Hence, it is a trade off between cost, accumulated assembly error versus mechanical properties and poorer fabrication resolution. In addition, RP machines are good at building parts that are symmetrical. The errors are the also symmetrical, which is in some way good for a symmetrical design like design 2. A couple of groups had used machining / EDM (eg: [74]) to make the mechanism, but to the author's knowledge, none of these groups are able to make a mechanism that met all the following advantages of the proposed manipulator: 1) sufficiently small to be suitable for a slender handheld instrument, 2) good performance when driven at relatively high frequency of 10Hz, and 3) low cost.

Another precaution is to ensure that actuations must not be large enough to operate the flexure joints in the material's plastic region. The consequence is the permanent deformation of the flexure joint and the mechanism will not behave like before.

As seen in Fig. 5.18, the workspace is shorter in Z than in X and Y. The main requirement in this instrument is handheld. Hence, an obvious solution is to place all the actuators in the direction of the z-axis. Such parallel mechanism arrangement will result in a larger X and Y motion because of the needle. It would be good to have a more spherical workspace, but the requirement of handheld seems to make it challenging. In addition, it is noted that the range of motion in the x- and y- axis meets the design specifications. However, the range of motion in z-axis is insufficient. The solution that the author had in mind was to have a forth actuator placed in series with the parallel mechanism to provide this z-direction

motion. However, this was not implemented due to limitation of resources as a forth amplifier for the piezoelectric actuator will be needed.

Chapter 6

Estimating Displacement of Periodic Motion with Inertial Sensors

In order to compensate the undesired motion, the disturbance motion must be known. In this handheld instrument, accelerometers are used to sense the tremor motion. It is desirable to have a handheld instrument that will not be influenced by the environment like lighting and metallic materials. Inertial sensors is one of the solutions. Unfortunately, inertial sensors are rarely used alone when information in the lower order Laplace domain is desired. This is due to its inherent integration drift and this is a common restriction in the sensing research area. The older version of Micron performed sensor fusion of the accelerometers with magnetometer to solve the drift issue. However, it is desirable to have a sensing system that is independent of the environment condition. The performance of the magnetometer is affected when there is big block of metal or when a magnetic field exists in the vicinity. Hence, this chapter describes a technique which makes use of a couple of existing filtering algorithms, primarily developed from Riviere *et al.* [75], and modified the algorithms to provide a good displacement estimation of periodic motion from integrated MEMS accelerometer measurement without the aid of an externally referenced sensor.

6.1 Background

Broadly speaking, there are two main types of motion sensing devices, namely externally and internally referenced sensors. Externally referenced sensor requires

interactions with external active sources or receivers. Externally referenced sensing includes infra-red, radio frequency and electromagnetic wave. Some examples are Polaris from Northern Digital Inc. and motion capture systems from Vicon. Unfortunately, the space required for these sensors are not small and it is a desire to implement the disturbance compensation system as a stand alone system.

Another type of sensors is internally referenced sensors. Internally referenced sensors sense the inertial quantities of a moving body, such as acceleration, angular velocity and angular acceleration. Examples include gyroscopes and accelerometers.

Integrated MEMS accelerometer chips are used because of their compact size, high resolution and no reliance on external sensors. However, accuracy of inertial sensors is hampered by the inherent integration drift when measurements in the inferred domains, like displacement, are desirable. The fast growing measurement drift arises from the numerical integration of bias error, which is almost impossible to calibrate out [76]. To make things worse, the bias error has been shown to be sensitive to temperature drift [77]. This drift due to numerical integration is depicted in Fig. 6.1.

Hence, inertial sensors are seldom used alone in measurement of displacement. In most cases, at least one or more externally referenced nondrifting sensors [e.g., cameras, global positioning system (GPS), etc.] are employed to fuse with inertial-based measurements. In this chapter, a method to perform drift-free displacement estimation of periodic motion with inertial sensors is proposed. An adaptive algorithm models the Fourier components of a periodic signal (acceleration or velocity) and thereafter displacement is obtained via analytical integration of the motion model. A motion tracking experiment is performed with a MEMS accelerometer to verify the proposed method.

Figure 6.1: Integration drift of velocity and displacement given sinusoidal motion.

6.2 Extraction and Estimating Disturbance Motion

The information sensed by the accelerometer consists of both intended and unintended motions. In order to perform compensation, the unintended motion has to be extracted out from this information. Knowing the frequency band of the intended motion, a bandpass filter can be used to extract the unintended motion. However, a bandpass filter introduces a phase difference. Thus, this section discusses methods that can be used to extract and model the required information, and then used to estimate the disturbance displacement.

6.2.1 Weighted-Frequency Fourier Linear Combiner (WFLC)

Given a periodic motion with a prior known frequency, the motion (tremor in this case) may be modeled in real-time by a Fourier linear combiner (FLC) [78], which uses a least mean square algorithm to adaptively adjust a series of Fourier components. If the frequency of the motion is unknown, Weighted-frequency Fourier Linear Combiner (WFLC) [75], may be used. WFLC, an extension from FLC, is an adaptive signal processing algorithm that forms a truncated Fourier series model of a periodic signal of unknown frequency and amplitude. There are two major parts in WFLC, namely estimation of the frequency and estimation of the filtered signal. An overview is illustrated in a block diagram shown in Fig. 6.2

Figure 6.2: Block diagram of method using WFLC.

Analytical integration is then proposed by the author to estimate the disturbance displacement. The algorithm is as follows.

Frequency Estimation

The first portion of WFLC is the frequency estimation of the disturbance. Since the frequency of the intended motion is estimated from WFLC, the signal from the accelerometer is first passed through a notch filter to filter out the intended motion. The input $\vec{x}_k$ vector to WFLC is:

$$x_{k_r} = \begin{cases} \sin\left(r \sum_{t=0}^k w_{0t}\right), r = 1 \dots M \\ \cos\left((r - M) \sum_{t=0}^k w_{0t}\right), r = M + 1 \dots 2M \end{cases} \quad (6.1)$$

where M is the number of harmonics used. The input is the sensing domain of the inertial sensor and can be acceleration or angular velocity. The frequency can be

estimated by updating every sample via:

$$\epsilon_k = s'_k - \vec{w}_k^T \cdot \vec{x}_k \quad (6.2)$$

$$w_{0_{k+1}} = w_0 + 2\mu_0\epsilon_k \sum_{i=1}^M (w_i x_{M+1} - w_{M+i} x_i) \quad (6.3)$$

$$\vec{w}_{k+1} = \vec{w}_k + 2\mu_1 \vec{x}_k \epsilon_k \quad (6.4)$$

where $\vec{w}_k^T$ is the coefficients of the input, s'_k is the signal input after the notch filter, and μ_0 and μ_1 are the adaptive gain parameters. w_0 will adapt to the frequency. An accelerometer was excited at a frequency of 10Hz with peak-peak motion of 100 μm . Fig. 6.3 shows the estimated disturbance frequency using WFLC.

Figure 6.3: Convergence of the estimated disturbance frequency using WFLC.

As shown in Fig. 6.3, it can be seen that WFLC is able to adapt to the frequency of 10Hz. The convergence in this case is quite slow as a small μ_0 is chosen. This is because the author prefers a more stable and robust system.

Disturbance Estimation

The first portion of the algorithm is to track the frequency. A second set of FLC is used to estimate the acceleration. Using the same input $\vec{x}_k$, the weights of the

second FLC is updated via:

$$\hat{\epsilon}_k = s_k - \vec{w}_k^T \cdot \vec{x}_k \quad (6.5)$$

$$\vec{w}_{k+1} = \vec{w}_k + 2\mu \vec{x}_k \hat{\epsilon}_k \quad (6.6)$$

where $\vec{w}_k^T$ is the coefficients of the second FLC, s_k is the noisy signal input. Thus, an estimation of the acceleration/velocity can be calculated as:

$$a_k = \vec{w}_k^T \cdot \vec{x}_k \quad (6.7)$$

As mentioned in the previous section and illustrated in 6.1, a drift is usually resulted from numerical integration. Supposing the input signal is periodic with one dominant frequency, the frequency and amplitude weights can be assumed to be constant after a finite adapting time period. Thus, instead of integrating the acceleration/angular velocity sensed numerically, (6.7) is integrated analytically. A good estimate of displacement from acceleration reading can be obtained through double integration as:

$$w_{d_{kr}} = \begin{cases} -\hat{w}_{kr} / \left(\frac{rw_{0_k}}{T}\right)^2, & r = 1 \dots M \\ -\hat{w}_{kr} / \left(\frac{(r-M)w_{0_k}}{T}\right)^2, & r = M + 1 \dots 2M \end{cases} \quad (6.8)$$

$$y_k = \vec{w}_{d_k}^T \vec{x}_k \quad (6.9)$$

where y_k is the estimated displacement, $\vec{w}_{d_k}$ are the weights of the FLC to estimate the displacement, and T is the sampling period. If the sensing domain of the inertial sensor is velocity, like gyroscope, estimation of displacement can be obtained as:

$$w_{d_{kr}} = \begin{cases} -\hat{w}_{kr} / \left(\frac{rw_{0_k}}{T}\right), & r = 1 \dots M \\ \hat{w}_{kr} / \left(\frac{(r-M)w_{0_k}}{T}\right), & r = M + 1 \dots 2M \end{cases} \quad (6.10)$$

$$y_k = \vec{w}_{d_k}^T \vec{x}_k \quad (6.11)$$

6.2.2 Band-Limited Multiple Fourier Linear Combiner (BMFLC)

One limitation of WFLC is its inability to track more than one dominant frequency (modulated signals). To overcome that, Veluvolu *et al.* proposed a new algorithm

BMFLC [79]. This approach relies on choosing a predetermined band of frequencies with spacing of frequencies chosen according to users requirement. The input to BMFLC is:

$$x_{k_r} = \begin{cases} \sin(2\pi f_r kT), & r = 1 \dots N \\ \cos(2\pi f_{r-N} kT), & r = N + 1 \dots 2N \end{cases} \quad (6.12)$$

where f_r are the frequencies within a given band of interest and N represents the number of frequencies used. The frequencies can be integer as well as rational. The weights of BMFLC can be updated via:

$$\epsilon_k = s_k - \vec{w}_k^T \cdot \vec{w}_k \quad (6.13)$$

$$\vec{w}_{k+1} = \vec{w}_k + 2\mu_1 \vec{x}_k \epsilon_k \quad (6.14)$$

An estimate of the acceleration/velocity can be given by:

$$a_k = \vec{w}_k^T \cdot \vec{x}_k \quad (6.15)$$

Thus, similar to (6.8) to (6.8), an estimate of the displacement from acceleration is:

$$w_{d_{k_r}} = \begin{cases} -\hat{w}_{k_r} / (2\pi f_r)^2, & r = 1 \dots N \\ -\hat{w}_{k_r} / (2\pi f_{r-N})^2, & r = N + 1 \dots 2N \end{cases} \quad (6.16)$$

$$y_k = \vec{w}_{d_k}^T \vec{x}_k \quad (6.17)$$

While the estimation of displacement from velocity is:

$$w_{d_{k_r}} = \begin{cases} -\hat{w}_{k_r} / (2\pi f_r), & r = 1 \dots N \\ \hat{w}_{k_r} / (2\pi f_{r-N}), & r = N + 1 \dots 2N \end{cases} \quad (6.18)$$

$$y_k = \vec{w}_{d_k}^T \vec{x}_k \quad (6.19)$$

Experimental Results of BMFLC

Accelerometer board (DE-ACCM2G) from Dimension Engineering, containing an ADXL322 accelerometer, is used in the experiment to illustrate the algorithm. Fig. 6.4 shows the experiment setup. The accelerometer board is placed on a nanopositioning system P-561.3CD from Physik Instrumente, which has a resolution of

Figure 6.4: Experiment Setup.

subnanometers for periodic motions. The nanopositioning system provides a $100\ \mu\text{m}$ peak-peak sinusoidal motion. The voltage reading from the accelerometer is acquired using a DAQ card.

Figure 6.5: Estimated displacement (solid) result from the accelerometers reading of a $100\ \mu\text{m}$ peakpeak sinusoidal motion (dotted).

The voltage reading is then converted to acceleration domain. Fig. 6.1 shows the result of numerical integration. The estimated displacement using BMFLC is shown in Fig. 6.5 and the error between the estimated and actual displacement is

Figure 6.6: The error between actual displacement and estimated displacement.

shown in Fig. 6.6. The estimated displacement tends to the actual displacement and the root mean square error (RMSE) between the two during steady-state from 2 to 4 s is $3.498 \mu\text{m}$. Comparing the results of BMFLC with numerical integration (third graph of Fig. 6.1), it is evident that the problem of drifting is eliminated.

6.3 Discussion

The proposed algorithms provide good displacement estimation from integrated accelerometer measurement without the aid of an externally referenced sensor. WFLC and BMFLC are proposed to be used to estimate displacement of a periodic motion from an accelerometer. The main motivation to use them is because the periodic signals in the acceleration domain can be modeled by a series of sine and cosine components. In addition, the original idea of WFLC and BMFLC is for zero phase band-pass filtering. Thus, when using the method to estimate displacement, intended motion and unwanted noises from the accelerometers are also removed. However, the algorithm is limited to periodic motion. Given a nonperiodic motion, the weights of the WFLC and BMFLC will keep changing to adapt itself to the current reading. In this case, direct analytical integration will not perform that

well.

The algorithms are capable of handling any frequency; provided the frequency is within the bandwidth of the inertial sensors and suitable initial values are selected. However, it is also worthwhile for the readers to note that the amplitude of acceleration increases with frequency. A higher frequency will increase the signal-to-noise ratio, but it also means larger adaptive parameters μ_0 and μ_1 or appropriate initial weights are needed to ensure convergence to the global minimum.

Although the focus of this chapter is to use inertial sensors to infer information in the lower domains, these methods are also applicable for obtaining information in the higher domain from sensors like displacement sensors. In infer information in the higher domain, differentiation is needed and noise is amplified during differentiation. By performing the proposed method and using differentiation instead of integration, these noise that are amplified due to the numerical differentiation process can be greatly reduced.

In this dissertation, the proposed method was intended to be used to estimate the displacement of the tremor, which is not totally periodic. It is found that there is a dominant frequency in the tremor of each subject, which is normally in the range from 8 to 12Hz. The objective of this method is to cancel that particular dominant frequency, which will hence result in a great degree of improvement in the hand's accuracy.

Chapter 7

Integrated Handheld Instrument

After performing many experiments and ensuring that each individual component is functioning up to exceptions, the handheld instrument's performance with integration of the sensing portion is next shown. As described in the introduction, the function of the intelligent handheld instrument is for active disturbance compensation. The overview was illustrated in Fig. 1.1. This instrument senses its motion and distinguishes between desired and tremor motion through advanced filtering techniques. The tremor is next compensated by an equal but opposite deflection of the surgical tip. Thus, ideally, the surgical tip will move according to the intended motion without the erroneous unintended tremor.

7.1 Integration

The research in the placement and kinematics of the sensors in the handheld instrument were done by the author's teammate and will not be discussed here. The details can be obtained from [80–83]. These are integrated with the piezoelectric-driven handheld manipulator mentioned in chapter 5.

Two prototypes are built in the process of integrating the piezoelectric-driven manipulator with the sensor. The first design is connected directly, and hence larger than desired. To make the handheld instrument smaller and the center of gravity within the holding area, a second prototype is designed and built.

In this section, the first design is first shown, followed by the second design.

7.1.1 Design requirements

The design requirements of the handheld instrument is as follows:

1. The length of the instrument, inclusive of the needle, must be less than 200mm because of the constraint set by the workspace of the surgical microscope.
2. The width of the tool should not be large as the instrument should be comfortable to hold. The outer most diameter is targeted to be less than 25mm.
3. The total weight of the instrument, inclusive of actuators and sensors, is targeted to be less than 100g.

7.1.2 Design 1

The first design of the instrument is designed in a way that the sensing and actuation components are connected directly. A photo of the integrated instrument is shown in Fig. 7.1 with respect to a Singapore fifty cents coin. Fig. 7.2 shows a photo of the mechanism portion while Fig. 7.3 shows how the instrument looks like when it is held by a hand.

Figure 7.1: Photo of first integrated instrument with respect to a fifty cents coin.

7.1.3 Design 2

However, the first design was relatively long and the total length exceeds the constraint, set by the microscope, of 200mm. Hence, a second design was proposed and developed. In the second design, the sensing component is combined into the holder for the actuators. Fig. 7.4 shows a picture of second version integrated Micron while Fig. 7.5 shows a photo of a hand holding the second design with respect to a fifty cents coin.

Figure 7.2: Photo of the Mechanism.

Figure 7.3: Photo of a hand holding the first design of the instrument.

A photo to illustrate the comparison between the two designs is shown in Fig. 7.6.

The dimension of the second design meets the requirement. The total length is 189mm (inclusive of a 55mm long needle) while the diameter of the holder is 22mm. The weight of the new design of the handheld instrument is 75 grams. This is considerably light, taking into account that actuators, sensors and mechanism are included. In addition, the instrument is designed in a way such that the center of gravity (CG) lies within the holding area. This is important as any offset of the

Figure 7.4: Photo of a hand holding the second design.

Figure 7.5: Photo of a hand holding the second design.

Figure 7.6: Comparison between the two design.

CG will create momentum that will encourage higher amplitude of tremor. Trials with surgeons have also concluded that weight does not matter as much as the

distribution of weight, like a large mass at the back end to create a moment and strain the fingers grasping it.

There is another advantage in using flexure-based mechanism for this type of application whereby the motion is sensed using accelerometers. The non-existence of backlash in the joints not only enable more precise positioning capability, it also eliminate a major problem when the mechanism is combined with the sensing portion. Small spacing do exist inside traditional pin joints for it to rotate easily. The accelerometers will actually picked up these impulse signals due to the spacing. To make matter worse, these impulse signals are difficult to filter out as the frequency is the same as the actuation frequency, which is the same as tremor. This is another strong reason why flexure-based joints are encouraged in this application.

7.2 Experiments

This section covers the experiments that were conducted to evaluate the performance of the handheld instrument.

Experiment Setup

The disturbance is provided by a nanopositioning system P-561.3CD from Physik Instrumente (PI). All the displacement readings of the output from the piezoelectric-driven mechanism are obtained through position sensitive devices developed by Win *et al.* [56]. Fig. 7.7 shows the experiment setup.

All the proposed methods mentioned in the previous chapters, except the portion on adaptive controller, were implemented into this prototype. The adaptive controller was not incorporated because of the lacked of resources as 3 sets of actuators with displacement sensor like strain gauge is needed. The adaptive method would be useful in the future when we extend the use of microscope imaging to guide tremor compensation.

Figure 7.7: Experiment Setup of the Bench Test.

Experimental Results

A couple of experiments were performed to evaluate Mircon. Firstly, a 10Hz sinusoidal disturbance in the direction of x-axis was provided and the result is shown in Fig. 7.8. The RMS disturbance dropped from 0.0354mm to 0.0051mm by 85.59%.

Disturbance were also applied to y-axis direction and the result is shown in Fig. 7.9 and the RMS disturbance dropped from 0.0331mm to 0.0043mm by 86.87%.

To simulate a more real life situation, instead of the 10Hz sinusoidal disturbance, real tremor data was input into the nanopositioning device in both x-axis and y-axis directions simultaneously. Fig. 7.10 shows the result.

As seen from Fig. 7.10, the amplitude of the disturbance motion is greatly reduced when the instrument was switched on. The RMS tremulous motion in the x-axis reduces from 0.0174mm to 0.0053 by 69.5% while the y-axis reduces from 0.0164mm to 0.0050mm by 69.4%. The reduction in the absolute tremulous motion is 69.45%.

Figure 7.8: Experimental Result of 10Hz sinusoidal Disturbance along x-axis.

Figure 7.9: Experimental Result of 10Hz sinusoidal Disturbance along y-axis.

7.3 Comparison between current instrument and work by previous researchers

There are a couple of improvements achieved in the new handheld instrument. Some of the advantages of the present instrument over previous work is due to

Figure 7.10: Bench Test Experimental Result.

the contribution on the singularity-free model. The advantages include: 1) Stability, 2) better accuracy, and 3) no pulses generated that will be picked up by the accelerometers.

With the singularity-free model, there is an increase in stability. The problem at the singularity point is solved. The controller will not be required to generate an infinite voltage with the proposed method.

The singularity-free model not only provides a more stable controller, it also increase the accuracy of the model as smaller threshold value of the Prandtl-Ishlinskii (PI) play operator can be used. This has been described in Chapter 3.

In addition, with the singularity-free model, the problem due to the ill-condition has been solved and jerks around the turning point that are shown in Fig. 3.20 are avoided. This is very important for this handheld instrument as such jerks

generated impacts, that will be picked up accelerometers. As these impacts are of the same frequency as the tremor, it is too challenging to be removed via filtering techniques.

A new flexure-based mechanism is also being used in this instrument. The mechanism is built as a single piece and errors due to assembly is minimized. Choi *et al.* [57] had a similar design as the first design shown in Chapter 5, and the purpose of the newer design is to remove the problem of the levers bending as mentioned in Chapter 5.

In addition, a closed-form solution for the inverse kinematics has been presented for this manipulator. Although the computation speed of current computers is very fast, a close-form solution is still preferred for this application because the tremor is compensated in real-time and computation time should be minimized as much as possible. In the previous prototypes, numerical method is used and a couple of numerical iteration is needed to evaluate each inverse.

The performance of the micromanipulator, as seen from table 5.1, demonstrates an improved results from previous design driven at 10Hz. It can be seen that the absolute root mean square errors for all the trajectories are less than $7\mu\text{m}$ and these trajectories were driven at 10Hz with an amplitude of $85\mu\text{m}$. In other words, the amplitude in the acceleration domain is 335.6mm/s^2 .

There is another advantage in using flexure-based mechanism for this type of application whereby the motion is sensed using accelerometers. The non-existence of backlash in the joints not only enable more precise positioning capability, it also eliminates a major problem when the mechanism is combined with the sensing portion. Small mechanical free play exists in all pin joints to allow smooth rotation. The accelerometers in the handheld instrument are sensitive enough to pick up the impacts between the mechanical parts due to this free play. To make matter worse, these impact signals are difficult to filter out as the frequency is the same as the actuation frequency, which is the same as tremor. This is another strong reason why flexure-based joints are chosen in this application.

The proposed method of estimating displacement using inertial sensors has also allowed us to have a new instrument that only uses accelerometers, without the need for externally-referenced sensors to eliminate the problem of integration drift.

In terms of the compensation results, to the author's knowledge, there is no published results by previous researchers whereby the sensing component is self-reliance and the experiment is performed by real humans. The best results that were obtained by previous researchers is by Choi *et al.* [84]. However, in this paper, the sensing is achieved using externally referenced position sensitive devices. As mentioned in Chapter 6 it is desired to have a handheld instrument that will not be influenced by the ambient light and magnetic field in the vicinity of the instrument.

7.4 Discussion

Realtime active disturbance (tremor) compensation has been shown to be a feasible idea. From results, it can be seen that the amplitude of the disturbance are greatly reduced. In addition, it can also be seen that the system will only improve the situation as the erroneous motion never exceed the peak to peak of the disturbance. The results is better than previous designs. However, the author cannot conclude that the improved result is solely due to the contribution written this dissertation. The new instrument incorporates a new sensing system developed by the author's teammate too. Hence, the improved result is due to the contributions from the two.

The present handheld instrument has 3-DOF. Increasing the number of DOF will be more useful, but at the expense of size and weight. Microsurgeons have mentioned not to over design the instrument. This is because they will adapt and take care of the remaining DOF if they are given the 3 DOF of compensation.

Another reason why 3-DOF was decided is because the concerned end effector is the tip of a needle, which is can be considered as a point. In addition, in order to keep the instrument as slim as possible for handheld purpose, the 6 actuators should be placed in the z-direction for a 6-DOF parallel mechanism. In the 3-DOF

instrument, the control input to the inverse kinematics is the desired position of the needle tip while the extra desired control inputs to the inverse kinematics gained in the 6-DOF as compared with the 3-DOF instrument is the orientation of the needle. A rotation about the z-axis does not offer much advantage. And also, the angle of rotation is not amplified by the needle and the range of change in orientation will be very small, meaning little improvements will be made. Hence, after weighing the pros and cons, 3-DOF was the decided mechanism to be used.

Chapter 8

Conclusion and Contributions

This chapter concludes the dissertation. A summary of the dissertation is first provided. Contributions made are then pointed out and potential future work are also listed out.

8.1 Conclusion

This dissertation, which is a continuation of Dr. Riviere and Dr. Ang's work [14], has presented the design and control of a piezoelectric-driven handheld manipulator for the purpose of tremor compensation. Instead of going with the more familiar approach like vibration absorber, a real-time disturbance compensation has been presented.

The main research focus of this dissertation is on the research and development of the piezoelectric-driven handheld manipulator. The two primary objectives, namely: 1) control of the piezoelectric actuators, and 2) design and development of the mechanism, are fulfilled.

8.1.1 Control of Piezoelectric Actuators

Piezoelectric actuators are used to actuate the manipulator because of their rapid response, compact size and large bandwidth. However, the hysteretic behavior of the actuator makes control difficult. Hence, chapter 2-4 of this dissertation presented the methods to handle the hysteretic behavior.

Singularity-Free Prandtl-Ishlinskii Model

The hysteresis model used in this dissertation is Prandtl-Ishlinskii (PI) model.

This is because it is more efficient, and its availability of a simple inverse model makes it ideal for real-time application. However, there is a limitation in the PI model. The inverse expressions are not valid when the slope of the hysteretic curve is not positive definite. To overcome this, a solution is proposed. This problem is solved by mapping the ill-conditioned hysteresis through a transformation onto a singularity-free domain, whereby the inversion can be obtained. The proposed method has been detailed in chapter 3.

Adaptive Controller

Chapter 4 has proposed an adaptive controller. The hysteretic behavior is dependent on the individual actuator and also environmental conditions like temperature. Hence, the hysteretic behavior of the actuator has to be modeled regularly. It is troublesome and costly to model the hysteresis regularly. To overcome this, the feedback loop is closed to obtain an adaptive rate-dependent feedforward controller for piezoelectric actuators.

8.1.2 Design and development of Mechanism

The design of the handheld manipulator is also presented. The design and development of the low-cost flexure-based handheld mechanism for micromanipulation has been presented in chapter 5. For the purpose of cost efficiency, the 3 DOF piezoelectric-driven manipulator is fabricated using Objet.

8.1.3 Integrated Handheld Instrument

While the focus is on the piezoelectric-driven mechanism, a method to estimate the displacement of a periodic motion using inertial sensors is also proposed during the course of the Ph.D. candidature years. Integrated MEMS accelerometer chips are used because of its compact size, high resolution and no reliance on external sensors. As accuracy of inertial sensors is hampered by the inherent integration drift when measurements in the inferred lower order domains (like displacement) are desirable, chapter 6 presented how readings from inertial sensors can be used

to infer displacement for periodic motions.

The piezoelectric-drive manipulator is next integrated with the author's teammate's sensing portion. The handheld instrument is developed and is demonstrated. The performance, together with its advantages and improvements over previous work, has been presented in Chapter 7.

8.2 Contributions during Ph.D. Candidature

During the author's Ph.D. candidature years, a number of publications have been published and they are listed in Appendix A. In order to fulfill the objectives, a number of contributions were made along the way.

Singularity-Free Prandtl-Ishlinskii Model

The first contribution is the Singularity-Free Prandtl-Ishlinskii model. As mentioned in the dissertation, there is a limitation in the PI model as the inverse expressions are not valid when the slope of the hysteretic curve is zero or negative. A solution to solve the ill-conditioned issue has been proposed and presented in chapter 3. The proposed solution is to transform the ill-conditioned hysteresis onto another domain that gives a well conditioned hysteresis graph to model. The transformation functions were proposed and proven with simulations and experiments.

The proposed solution, which is the most significant contribution of this dissertation, brings along a number advantages to the instrument. The first advantage is stability. With the singularity-free model, a more stable controller is presented. Situations whereby an indefinite solution (generated due to one divided by zero) is generated are no longer a concern. The limitation of the inverse model has been removed.

In the past before the singularity-free Prandtl-Ishlinskii model is proposed, small intervals between the first few threshold values are avoided. This is to avoid the limitation of the inverse model. With the removal of this limitation by the

singularity-free model, smaller intervals of threshold values can be used. This means an increase in accuracy of the model.

In the intelligent handheld instrument, accelerometers are used as the sensors to predict the tremulous motion and the singularity-free Prandtl-Ishlinskii model provides another advantage. With the proposed solution, impacts caused by the jerks at the turning point due to the ill-conditioned problem will be removed. Accelerometers will no longer pick up this impacts which make the sensing component unstable.

Although the application here is with piezoelectric actuators, the solution is a general method and can be extended to model any hysteretic materials or systems. [J1] of Appendix A is the representative journal (*IEEE/ASME Transactions on Mechatronics*) paper for this contribution.

Adaptive Controller

The hysteretic behavior of the piezoelectric actuator is not only dependent on individual actuator, it is also dependent on environmental conditions like temperature. In order to accurately control the actuator, the hysteretic behavior of the actuator has to be modeled regularly. Time and effort are needed. In addition, the accuracy will improve if some form of adaptive model is implemented.

Hence, to overcome the requirement modeling the actuator regularly, the feedback loop was closed and an adaptive rate-dependent feedforward controller for piezoelectric actuators is proposed. This is achieved by adapting the coefficients of the equation relating the weights of the play operators to velocity. In this dissertation, the adapting mechanism used is recursive least square. Other adapting mechanism like least mean square or Kalman filtering can be used too.

One of the essence of the proposed adaptive controller is its ability to perform tracking control to non-periodic motions. To illustrate this, a couple of different randomly generated waveforms were used. These waveforms are obtain by passing random numbers through a lowpass filter. To simulate a real-time application, each point is treated to be known only at the very each instant.

Experiments are conducted and the adaptive controller is found to produce a smaller tracking error. In addition, since it is adaptive, experiments are no longer needed to be conducted to obtain the actuator's model and precious time is saved.

The adaptive controller can be found in Chapter 4 and [J2] of Appendix A is the representative journal (*Sensors and Actuators A: Physical*) paper.

Design and Development of a Flexure-based Hand-held Mechanism

In order to provide the compensation, a low cost 3-DOF handheld manipulator driven by 3 piezoelectric actuators has also been designed and fabricated. Parallel mechanism is the preferred choice because of its compact size, non-accumulative errors and rigidity. The size of the mechanism is designed to be small and suitable for handheld purpose. A flexure-based mechanism is also the proposed design because of its non-existence of backlash.

Traditional joints like pin joints have space in between the linkages. These spacing results in backlash and will affect accuracy. In addition, these spacings will generate impacts whenever the direction is changed. Such impacts are not desirable as the accelerometers will pick them up and the sensing will be unstable. Filtering these impacts through filtering techniques will be challenging as the frequency of these impacts is the same the frequency of the tremor. Hence, a flexure-based mechanism is proposed.

The mechanism is fabricated using a rapid prototyping machine, Objet. This machine offers design complexity that traditional machining are unable. The mechanism is built as a single piece, thus avoiding any assembly errors. In addition, the cost of building this mechanism is quite low. The total cost of building this prototype is only S\$200 Singapore dollars (less than USD\$150).

Experiments were also conducted to evaluate the mechanism and the root mean square errors for all the different trajectories were found to be less than $7\mu\text{m}$. The details are presented in chapter 5 while the representative papers for this contribution is an ICRA 2009 paper [C1], and a journal paper, [J3] of Appendix A, under revision submitted to *IEEE/ASME Transactions on Mechatronics*.

Estimating Periodic Displacement with Inertial Sensors

In order to compensate the undesired motion, the tremulous motion must be first known. One of the aims is to have a handheld instrument that will not be influenced by the environment and inertial sensors are one of the solutions. However, inertial sensors, like accelerometers and gyroscopes, are rarely used to infer information of a lower order domain like displacement. Accuracy of inertial sensors is greatly handicapped by the notorious integration drift when measurements in the inferred domains are desirable. The drift arises due to numerical integration of the sensing errors. In order to obtain the displacement of the disturbance without external sensors, this dissertation proposed an extension of two filtering techniques to provide a good estimate of the desired inferred information.

The solution is achieved by first modeling the signal in the higher domain, like acceleration. Analytical integration is then performed to the model to obtain the required information in the lower domain. Chapter 6 presented the method while [J4] of Appendix A is the representative journal (*IEEE Sensors Journal*) paper for this contribution.

Integrated Tremor Compensating Handheld Instrument

Finally, the manipulator was integrated with the teammate's sensing component. The integrated handheld instrument was designed, built and implemented. The experimental results, together with the advantages and improvements made in the current prototype over previous works, are illustrated in Chapter 7.

8.3 Future Works

The handheld instrument has been proven its ability to compensate hand tremor. However, this is not the end and there are a couple of potential future works.

Trials

From the medical side, in order to commercialize the instrument, more experiments and trials are required. One possible animal trial that can be conducted is on dogs'

eye, which most eye surgeons used during their trainee days. Surgeons can be asked to use the intelligent handheld instrument to inject anticoagulant into the dogs' veins in the eye.

The trials need not be limited to animals' eye. Experiments using the intelligent handheld instrument can also be explored in the area of cells. There has been an increasing popularity in cells manipulation. Scientists are curious to find out how cells can be modified to help humans. With the intelligent handheld instrument, tremor is no longer a limitation to these scientists. The scientists can use the instrument to inject the specific chemical/formula that they want into a specific location without worrying that their tremor might damage the cell.

Compliance Modeling

The current targeted application of the instrument is on eye retina surgery and cells. The reaction force from the eye retina or cells onto the instrument's needle is negligible. However, the load in other applications are not small and cannot be treated as negligible. Hence, in order to widen the range of application, the compliance of the mechanism must be modeled.

Fabrication

One of the concerns that some people have about fabricating the mechanism using rapid prototyping is the material. There are pros and cons about using rapid prototyping for a flexure-based mechanism. Once the design of the mechanism has been finalized, one of the possible solution to eliminate this concern is to fabricate moulds and use casting to make the mechanism. In this way, metal material can be used. The cost of the mould is expensive, but allows mass production and will be worthy of the price in the longer term.

Degrees of Freedom

Another possible area for future work is to increase the number of degrees of freedom. Increasing the number of degrees of freedom will widen the range of applications. Currently, the instrument is designed to compensate 3-DOF. More

degrees of freedoms can be taken into consideration for the next version. However, the trade-off will be a thicker and heavier instrument. An instrument with more DOF will be heavier because more DOF will mean more actuators are needed and currently, the actuators are contributing to the majority of the weight.

Drift Compensation

Drift is a low frequency motion that exists in human too. As seen from the experiments, drift is another problem of humans. Although this is a smaller problem as the frequency is much lower and the surgeon can compensate on his own, it will make the job much easier if drift compensation is provided. The next version can make use of some form of guidance to compensate the drift. This can be achieved using means like vision to track the drift.

Other Applications

The techniques developed in this dissertation have applications beyond tremor compensation. For example, the controller developed for piezoelectric actuator can be implemented on nanopositioning devices for applications like high-speed high-precision manufacturing. Implementation of the methods in other industries can be explored.

Appendix A

During the author's Ph.D. candidature years, a number of publications were published. The core publications are as follows:

Dissertation Related Publications:

Book Chapter

- [B1] **U-X. Tan**, W. T. Latt, C. Y. Shee, C. N. Riviere, and W. T. Ang, "Modeling and Control of Piezoelectric Actuators for Active Physiological Tremor Compensation," *Human Robot Interaction*, I-Tech Education and Publishing, Vienna , Austria, pp. 369-394, 2007.

Refereed Journal

- [J1] **U-X. Tan**, W. T. Latt, C. Y. Shee, C. N. Riviere, and W. T. Ang, "Feedforward Controller of Ill-Conditioned Hysteresis using Singularity Free Prandtl-Ishlinskii Model," *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 5, pp. 598-605, Oct., 2009.
- [J2] **U-X. Tan**, W. T. Latt, F. Widjaja, C. Y. Shee, C. N. Riviere, and W. T. Ang, "Tracking Control of Hysteretic Piezoelectric Actuator using Adaptive Rate-Dependent Controller," *Sensors and Actuators A: Physical*, vol. 150, no. 1, pp. 116-123, 2009.
- [J3] **U-X. Tan**, W. T. Latt, C. Y. Shee, and W. T. Ang, "Design and Development of a Low-cost Flexure-based Hand-held Mechanism for Micromanipulation," *IEEE/ASME Transactions on Mechatronics*, 2010 (revision).
- [J4] **U-X. Tan**, K. C. Veluvolu, W. T. Latt, C. Y. Shee, C. N. Riviere, and W. T. Ang, "Estimating Displacement of Periodic Motion with Inertial Sensors," *IEEE Sensors Journal*, vol. 8, no. 8, pp. 1385-1388, Aug., 2008.

Refereed Conference

- [C1] **U-X. Tan**, W. T. Latt, C. Y. Shee, and W. T. Ang, "Design and Development of a Low-cost Flexure-based Hand-held Mechanism for Micromanipulation," *IEEE Intl. Conf. on Robotics and Automation*, pp. 4350-4355, Kobe, Japan, 2009.
- [C2] **U-X. Tan**, F. Widjaja, W. T. Latt, K. C. Veluvolu, C. Y. Shee, C. N. Riviere, and W. T. Ang, "Adaptive Rate-Dependent Feedforward Controller for Hysteretic Piezoelectric Actuator," *IEEE Intl. Conf. on Robotics and Automation*, pp. 787 - 792, Pasadena, CA, USA, May 2008.
- [C3] **U. X. Tan**, T. L. Win, M. Tanjaya, H. T. Wirawan, C. Y. Shee, and W. T. Ang, "Real-Time Disturbance Compensation with Accelerometers & Piezoelectric Driven Mechanism," *IEEE Intl. Symposium on Computational Intelligence in Robotics and Automation*, Florida, USA, June, 2007.
- [C4] **U. X. Tan**, T. L. Win, C. Y. Shee, and W. T. Ang, "Rate-Dependent Hysteresis Model of Piezoelectric using Singularity Free Prandtl-Ishlinskii Model," *IEEE Intl. Symposium on Computational Intelligence in Robotics and Automation*, Florida, USA, June, 2007.
- [C5] **U. X. Tan**, T. L. Win, and W. T. Ang, "Modeling Piezoelectric Actuator Hysteresis with Singularity Free Prandtl-Ishlinskii Model," *IEEE Intl. Conf. on Robotics and Biomimetics*, pp. 251- 256, Kunming, China, 2006. (Shortlisted Finalist for Best Student Paper)

Others:**Refereed Journal**

- [J5] W. T. Ang, **U-X. Tan**, H. G. Tan, T. Myo, C. K. Ng, K. L. Koh, and B. S. Cheam, "Design & Development of a Novel Balancer with variable difficulty for Training and Evaluation", *Disability & Rehabilitation: Assistive Technology*, 3(6), pp. 325-331, 2008.

Refereed Conference

- [C6] U. X. Tan, H. G. Tan, T. Myo, D. G. Zhang, B. S. Cheam, K. L. Koh, and W. T. Ang, “Design and Development of a Novel Balancer with variable Difficulty for Training and Evaluation,” *Intl. Convention for Rehabilitation Engineering & Assistive Technology*, Singapore, April, 2007.

Appendix B

Mechanical Properties of VeroWhite - FullCure830

Property	ASTM		Units
Tensile Strength	D-638-03	49.8	MPa
Modulus of Elasticity	D-638-04	2495	MPa
Elongation at Break	D-638-05	20	%
Flexural Strength	D-790-03	74.6	MPa
Flexural Modulus	D-790-04	2137	MPa
Izod Notched Impact	D-256-06	24.1	J/m
Shore Hardness	Scale D	83	Scale D
Rockwell Hardness	Scale M	81	Scale M
HDT at 0.45 MPa	D-648-06	42	C°
HDT at 1.82 MPa	D-648-07	40	C°
Tg	DMA, E''	58	C°
Ash Content	NA	0.4	%
Water Absorption	D570-98 24 Hr	1.15	%

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