ENHANCING STROKE GENERATION AND EXPRESSIVITY IN ROBOTIC DRUMMERS - A GENERATIVE PHYSICS MODEL APPROACH

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ENHANCING STROKE GENERATION AND EXPRESSIVITY IN ROBOTIC DRUMMERS - A GENERATIVE PHYSICS MODEL APPROACH

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To my beloved family,

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SUMMARY

Achieving human like musical expressivity in musical robots has been a long standing goal for roboticists and musicians who work in the field of robotic musicianship. In the case of robotic drumming, a major subfield of robotic musicianship, research towards achieving this goal has mainly been in the area of developing smarter musical algorithms, human-machine interactions, robots that can "listen" to the music played by humans and respond in a contextually appropriate way, algorithms for modeling of different genres of music and methods to capture the gestural component in improvised and collaborative music making. These developments relate to the "what" in robotic drumming i.e., what are the notes, volume levels and time differences between the note onsets and how they are put together. Much less research has gone into "how" each of these notes are played. Rhythms in drumming can be thought of a specification of how certain *building blocks* of drumming (the rudiments) are strung together to create musical phrases. Therefore, it becomes important for a robotic drummer to know the alphabet of the drumming language, the building blocks before attempting to string them together to make "interesting" music.

This thesis focuses on creating a generative model for stroke generation in robotic drummers based on the physics of the interaction between human hand and a drumstick. This physics based model helps in expanding the stroke palette and provides a solid foundation of building blocks for a robotic drummer. Although the physics model developed in this thesis, is a general model for generating any kind of drum stroke, the specific focus here is on generating multiple bounce strokes. This model is also implemented in the *Robotic Drumming Prosthesis* and a software framework for music composition using the stroke library has also been developed.

In this thesis, initial approaches based on exploiting the instability of a PID control system to generate multiple bounces and the limitations of this approach are also discussed in depth. Finally, in order to assess the success of the model and the implementation in the robotic platform a subjective evaluation was conducted. The evaluation results showed that, the observed data was statistically equivalent to the subjects resorting to a blind guess in order to distinguish between a human playing a multiple bounce stroke and a robot playing a similar kind of stroke.

CHAPTER I

INTRODUCTION

The field of robotics is rapidly evolving as robots are making their way out of specialized workspaces in factories where they usually perform repetitive tasks with minimal human intervention, into the daily lives of human beings, where the interactions with humans are more challenging and call for much more sophisticated approach to robot control. Development in the fields of artificial intelligence, machine learning and control theory have contributed much to the development of the field of cyber-human systems, where smooth human robot interaction, the safety of humans and shared control between the human and the robot become the main areas of focus [30, 8]. Social robotics is also a growing area of research, in which a great deal of work is done in improving human robot interaction and making it more intuitive and seamless [5, 6]. Unlike in industrial settings, robots that operate in everyday environment will have to deal with a number of challenges such as unpredictable surroudings and developing robust sensing mechanisms for their own spatial awareness. Robotics is also revolutionizing the field of assistive and rehabilitation technologies as researchers are working on developing smarter prosthetics and augmentation devices [14]. Robots have also found their place in the entertainment industry, specifically music [11]. Musical robots have become popular and have caught the attention of the public eye through various projects such as jazz guitarist Pat Metheny's *Orchestrion Project* [10], all robotic heavy metal band *Z-Machines* from Japan [36] and *CompressorHead* from Germany [16] or the jazz playing, improvising marimba player *Shimon*[15] and Sergei Jorda's one-man multimedia band *Afasia* [17]. Researchers in Japan at the Waseda University have also been successful in making humanoid robots that can play the violin and the flute [18, 29].

One of the main subfields in robotic musicianship is that of robotic percussion. The mechanics of playing a percussion instrument is relatively simple as compared to a wind instrument, which is probably one of the main reasons why many of the robotic musicians are robotic percussionists. Researchers in this domain, have focussed on different aspects of robotic drumming ranging from the perceptual, rhythmic, improvisational and mechanical aspect of sound production, all aimed at creating better and sophisticated rhythms, complex human robot interactions and more expressive music [40].

The goal of this master's thesis research is to enhance the stroke generation capabilities and musical expressivity in robotic drummers. Expressivity can manifest itself in many forms in drumming and music. Variations in timbre, stroke types and activity rates (number of note events per unit time) all contribute in a significant way to the meaning and expression of a musical statement or phrase. Sophisticated musical expression is the art of effectively communication through the medium of music which often requires a solid foundation in the mechanics of music making, knowledge of musical styles, understanding the right musical context and applying the skills learned over years of musical training. For human drummers, as they learn the language of the instrument and the idiosyncrasies of musical styles, the rhythmic content of the music becomes only one aspect of music making. The rhythmic content constitutes the "what" of drumming styles. The question of "how" to play each note is also critical.

The focus of this research is to improve the mechanical aspect of robotic drumming thereby addressing the question of "how" a stroke is executed and also to some extent the "what" by building a library of different kinds of multiple bounce strokes. The approach adopted in this work is to develop a generative model that captures the physics of a drum stroke (primarily focusing on multiple bounce strokes) as performed by a human drummer and implement the model in a robotic drummer through a proper controller design. This is equivalent to teaching a robotic drummer the building blocks of the drumming language, similar to how human drummers who are beginners are required to learn the drum rudiments.

Wherein lies the expressivity of drumming, becomes a crucial question that needs to be addressed if we are to embark upon improving the expressivity of robotic drummers and bring them to par with human drummers (and even beyond in some aspects). When asked about choosing the right kind of cymbal, Elvin Jones, one of the greatest jazz drummers of our times, in an interview with Chip Stern said, "...I never did believe in going through that whole charade of listening to the vibrations and the ding-ding-ding; that seemed to me to be so superfluous, *because it's the stroke that makes the tone...* ", essentially implying that one of the most important factors in sound production is "how" the drummer chooses to produce the sound [33]. Based on my personal experience as a drummer for 20 years, I think that the uniqueness and musical identity of a drummer, which directly depends on the quality of sound produced, can possibly be determined objectively by the following parameters.

- Stroke type employed and its diversity. Stroke types can further be characterized by
    - Onset energy (the loudness of the stroke)
    - After-bounce profile controlled by changing the grip force (The behavior of the stick after the initial stroke, typically as a result of the interaction between the drumstick, the drumming surface and the human hand).
- Temporal variations in the rhythms at a micro-time scale (usually of the order of milliseconds). [28]
- Concatenation of rhythms (rhythmic phraseology) and relevance to musical context.
- The tools (sticks, brushes, the type of drums etc) being used for sound production and the exact point of contact between the tools use and the drum which determines the nature of physical interactions.

Some drumming rudiments focus on controlling the exact number of bounces after the primary stroke (for example, single strokes, double strokes, triple strokes) whereas some others control the statistical aspects of the stroke such as density of the bounces, focussing on creating different kinds of buzzing effect (closed roll) [27]. Non-standard bounce behavior (multiple bounce strokes in which the frequency of bounces change over time) is used for finer musical expressions and ornamentations in soloing and jazz accompaniment contexts. One of the main goals of robotic musicianship research is enabling musical robots to play music that has comparable levels of emotional, intellectual and expressive content as music produced by human beings.

The robotic platform used in this thesis is the **Robotic Drumming Prosthesis (RDP)** developed by the Robotic Musicianship Group at Georgia Tech Center for Music Technology. The design of RDP will be discussed in depth in subsequent chapters. Moreover, in the case of the RDP, the primary motivation to design such a device was to simulate the role of fingers in the drumming and give the user of the prosthetic, control over the bounce of the stick after the stroke. In RDP, a simple control design, in which the bouncing mechanism was modeled as a damped spring mass system oscillating in free space was able to achieve the bounce behavior of a basic double stroke rudiment. However, this model does not generalize well and is not capable of modeling other kinds of drum strokes, especially, multiple bounce strokes. The inherent damping in the robotic device due to the belts and motors is fairly high that the stick is not able to bounce naturally under the effect of gravity and collision with the drumhead.

The work described in this thesis is aimed at circumventing the issue of a lack of natural bounce and expanding the stroke palette that is available to the robotic drummer. The approach adopted is to understand the physics of human fingers-drumstick-drumhead interaction and try to replicate the same behavior with the minimum number of degrees of freedom in a robotic drumming system. This endeavor then, becomes an engineering challenge that could draw ideas from various fields of robotics and mechanical engineering such as system modeling, control theory and system identification. This also calls for more detailed physics modeling and control design of the robotic device. Although making a robot or a computer play music which is indistinguishable from a human musician is tall order, as a composer and a musician, I think that achieving comparable level of expressivity and dynamic range is a worthwhile pursuit in the field of robotic musicianship. This could encourage and inspire music technologists to investigate deeply into how human beings create music from a mechanical and cognitive standpoint.

This thesis is also aimed at pushing the boundaries of what human musicians are able to achieve by harnessing the speed and computational capabilities of a computer and using them to augment and maybe even collaborate with humans to create previously unheard music. For example, a typical buzz roll stroke by a human drummer has an exponentially decaying amplitude envelope (due to the effect of gravity). It will be possible to computationally model a system where the gravity is changing over time and thereby create human impossible interesting decay envelopes for the strokes,. Once a generative model for drum stroke generation has been established, accomplishing the above mentioned behavior is a matter of experimenting with the parameters of the model and possibly letting them go beyond the normal operating range. This kind of an approach has been adopted, for example, by the developers of a real time singing voice synthesizer, *Cantor Digitalis*, in which a source filter model is used to produce an expressive singing voice [22]. When the parameters are set to values that are beyond the range of a human being, the voice synthesizer no longer produces sounds that resemble a human being and can be used in a more experimental, avant-garde musical settings.

Following this introduction, Chapter 2 presents a comprehensive literature survey of the field of robotic musicianship, actuator design and modeling. In Chapter 3, the initial approaches to achieving multiple bounce strokes in the RDP is discussed in detail. Chapter 4 describe the physical modeling approach which is the cornerstone of this work. Chapter 5 discusses the implementation of the physics model in the RDP and the compositional software framework developed for writing pieces using the simulated stroke library. Chapter 6 presents the result of subjective evaluation of the modeling and the control design. Chapter 7 presents some of the future research directions.

1.1 Contributions

The main contribution of this thesis is the development of a physics based model for drum stroke generation for robotic drummers that has helped in expanding their available stroke palette/building blocks. This marks an important step towards achieving human inspired musical expressivity in robotic drummers. This work has also been successful in developing a very simple physics model which describes how human drummers execute a single drum stroke or a multiple bounce drum stroke. The system that is presented is agnostic to the exact specifications of the robotic drummer that will attempt to emulate human like drum strokes, and therefore can be used in any robotic drummer that uses actuators with complete control over the motor position angle. This is possible due to the complete decoupling of the drum stroke generating mechanism and the controller in the robotic drummer. This thesis has also shed light on the generative mechanisms that play an important role in creating diversity in the drum strokes produced by a human drummer. A formal evaluation of the system was also conducted as a part of this thesis. Human subjects were required to participate in a listening test in which they tried to distinguish between a multiple bounce stroke played by a robotic drummer and a human drummer. The observed data was compared to a scenario where the subjects will resort to blind guessing in order to distinguish between two performances of a multiple bounce stroke by a human drummer and the results indicate that the research direction was a fruitful one. The implementation of an alternate approach to achieve multiple bounce strokes based on time varying PID controller gains and its limitations are also discussed in detail in this thesis.

CHAPTER II

RELATED WORK

Numerous researchers have studied the musical, mechanical and perceptual aspects of robotic musicianship and drumming. Different research groups have their own research focus and specific robotic drumming platforms for which the research is directed. In this chapter, significant previous research in modeling of human drumming, actuator design and improving musical algorithms for robotic musicians are presented.

2.1 Human Drumming Modeling

Several studies have looked closely at the mechanics of human drumming from an engineering and bio-physical standpoint. This understanding is an important first step before attempting to simulate such behavior in robotic drumming devices. Researchers have been interested in how human drummers produce drum rolls that have a much higher frequency than the normal range of human motor control. Hajian et al. have studied the relationship between grasp force and the stick bounce and have implemented a mass-spring model which explains the dynamics of a drum roll in a simple, single joint robot which uses pneumatic actuators [13]. Hajian in his thesis, also considered three separate models for describing the physical interaction between the human hand and a drumstick [12].The model which was finally chosen for predicting stroke behavior was the one which worked the best for the specific kind of stroke that was considered in Hajian's thesis, a double stroke roll. Multiple bounce strokes that are considered in my thesis necessitate a different physics model. A simpler parametric model is presented later in this thesis which successfully captures the physics of a human generated drum stroke.

Another study undertaken by Andreas Wagner analyzed the interaction between the human hand, drum stick and the membrane in some detail, but no attempt was made to replicate the behavior in any kind of robotic percussionist [35]. In the thesis, Wagner comes to the conclusion that the dominant factors that shape the interaction process between a drumstick and the drumhead are the deflection and the tension of the drumhead and the vibration of the drumstick. According to Wagner, the role of the human drummer is to determine the initial onset energy (which will determine the dynamic level) and the placement of the stroke (which will determine the modes excited in the drum). The influence of changing grip is not considered in Wagner's work and is left for future research.

Any attempt to model the physics of a drum stroke should also take into account the fact that the physical system in question is inherently a hybrid dynamical system. The equations of motion of the drumstick in free space is different from the equations of motion at the point of contact. The physics of a drumstick bounce is similar to that of the physics of a bouncing ball [24], when the thumb is not in contact with stick and the stick is allowed to fall freely about the fulcrum provided by the first joint of the index finger. When the thumb is in contact with the stick, the free fall behavior is modified giving rise to different kinds of bounce profiles. A common way to model the bounce of the stick (or the ball) is to keep track of the vertical position of the drumstick, invert the sign and reduce the magnitude of the velocity vector when the drumstick hits the drumhead. Energy loss due to the inelastic collision is captured in the reduction of the magnitude of the velocity vector. This approach disregards the exact forces at work during the interaction between the stick and the drumhead and only tries to model the end effect of the interaction.

Another approach is to model the bounce as a restoring force that acts upon the drumstick upon contact, usually as a compressed spring whose spring constant is extremely high compared to the springiness of the human hand. Edgar Berdahl in his work on developing a physically intuitive haptic drumstick adopts the latter approach and considers a lumped mass spring damper model to model the effect of fingers [3]. The drum stroke analyzed by Berdahl in his work is an open double stroke roll and the choice of model suits this particular stroke type. The motivation for Berdahl's work is to build a physically intuitive haptic drumstick. It therefore, becomes necessary to model all the forces that are acting upon the system. Furthermore, the angular displacement of the stick is taken to be very small which allows for linearization of the dynamical equations. In the present work, the angles are not small and therefore such approximations are not applied. Since a closed form analytical solution is not sought after in this thesis, it does not address the non-linearities in the dynamical equation and numerical methods are used for solving the equations of motion

2.2 Actuator design and implementation in robotic drummers

Several approaches have been adopted by researchers in the design of the actuator mechanisms for robotic musicians. Robotic percussionists can be classified into three categories - *membranophones, idiophones and extensions* [19]. One of the most common actuator mechanisms adopted in membranophones is a motor/solenoid system that strikes the membrane with a stick. The system is usually mounted on the rim of the drum. In a solenoid system the force of the drum strike is proportional to the voltage that is applied to the solenoid. This system is very simple and can be integrated seamlessly with the MIDI paradigm in which a note event is represented by a midi note number and the dynamic level is represented by the note velocity. Kapur et.al also provides a comprehensive overview of solenoid based robotic drumming systems [21]. Some of the advantages of a solenoid based actuator system are the low cost, simple control mechanism and easy classroom integration. Kapur et. al also conduct a formal study of the dynamic and speed range of various kinds of solenoids and discusses the pros and cons of each of the solenoid. A piezo sensor based feedback system is used in some of the robotic drummers to guarantee that the intended dynamic level is achieved through a closed loop control. Typically in a MIDI triggered solenoid system, every drum strike corresponds to a single MIDI message. Therefore, in a MIDI based robotic drumming paradigm, a multiple bounce stroke can only be accomplished by sending separate MIDI message for every individual hit in the stroke, although this is not how human drummers execute a multiple bounce stroke. Humans execute a multiple bounce stroke, by manipulating more higher level parameters such as the initial velocity and position of the stick and the grip force. Therefore, to better simulate a stroke by a human drummer and to provide a more intuitive and natural control of robotic drummers, a solenoid based system is not the best choice for the actuator mechanism.

Researchers have also been interested in designing anthropomorphic musical robots to produce physically embodied expressive musical performances. The advances in robotic technology, artificial intelligence and actuator technology motivates this approach where, the goal is to emulate as closely as possible, the dynamics and physical dexterity of humans playing musical instruments. This will also help musicians and researchers understand motor control in humans from a mechanical engineering perspective and the importance of gestures in expressive musical performances. Besides research in robotic drumming, researchers at Waseda University built an anthropomorphic flute playing robotic musician in which the entire air supply mechanism and embouchure were modeled after the human lungs and lips [31, 32]. Researchers at the Robotic Institute of Carnegie Mellon University designed a MIDI controlled robotic bagpipe player which used a custom air compressor module for the air supply and electromechanical actuators ("fingers") to control the chanter [9]. In another study, Zhang, Malhotra and Matsuoka were motivated to study the neuromuscular control that is needed for having better articulation, phrasing and rubato to make more expressive piano music and developed an *Anatomically Correct Testbed Robotic Hand* to mimic the way expert humans play the piano [43]. The evaluations showed that, once the piano playing robotic hand was trained to emulate expressive performances by human experts, the robotic hand was able to play as musically as a human.

Jim Murphy discusses the considerations and challenges that goes into the design of a wide variety of robotic instruments in his Ph.d thesis [23]. According to him, the design and choice of actuators is also motivated by the musical, timbral and dynamics possibilities offered by the acoustic instrument. In a robotic drummer, introducing newer degrees of freedom for the actuator mechanism will allow the drum beater to access different areas of the drumhead thereby increasing the timbral options. In *The Nudge*, a robotic drummer designed by Jim Murphy, the spatial position of the drum beater is controlled using a geared DC servo motor which has high spatial precision. This approach for exciting different parts of the drum and expanding the timbral range is drastically different from the *Karmetik NotomotoN* in which 18 separate solenoid beater assemblies are used [20]. The main drumming mechanism in *The Nudge* is still a solenoid based mechanism in which the drum beater's at-rest height is adjusted using another servo motor assembly in an online manner, thereby achieving the wide range of dynamics and timbral control.

Weinberg and Driscoll were also driven by the idea of expanding the timbral possibilities of a robotic drummer in their design of *Haile*, a two armed robotic percussionist designed to play a native American drum [38]. *Haile* adopts a quasi-anthropomorphic design and utilizes two percussive arms that can move to different locations on the drum [37, 39]. A linear slide along with a pulley system and a potentiometer to provide feedback is used to control the vertical position of both arms. The right arm employs a standard solenoid driven device with a return spring as the primary striking mechanism. Weinberg's research also focuses on the perceptual, cognitive and algorithmic aspect of robotic musicianship and machine listening. Enhancing musical expressivity is achieved by improving the musical content, that is, produce rhythmic responses by using perceptually salient machine listening, improvisation algorithms [41] and style modeling [25]. Weinberg et al. also studies the importance of gestures and visual cues in improvised music and implement the same in robotic musicians [41, 42].

Researchers of the Humanoid Robotics Group at MIT developed *Cog* which could perform a wide variety of rhythmic as well as discrete tasks. Williamson et.al designed a compliant robot arm which has 6 degrees of freedom and uses simple non-linear oscillators to control the arm [7]. The arms use series elastic actuators which incorporate physical springs at each joint. A compliant design for the structure of the arm is important for robustness in unpredictable and noisy environments. The main difference between traditional robot control and Williamson's approach is the way in which robot dynamics play a crucial role in the execution of the task. In a traditional controller, a reference trajectory is usually provided externally, whereas in the case of the non-linear oscillator, it generates this signal internally using its own dynamics. Williamson acknowledges that the traditional approach is more general and the non-linear oscillators are limited to those trajectories that are generated by the oscillators. In *Cog*, the non-linear oscillators are used to produce periodic rhythms as a result of the periodic drumming motions (up and down motions) executed by the robot hand. An auditory feedback loop is used to entrain the oscillators and to make the system more robust. Non-linear oscillators are apt for producing a steady beat, but drumming involves much more than just playing steady periodic beats. Any auditory event can be placed in relation to a metronomic grid and concatenation of such auditory events constitute a specific rhythm phrase. The building blocks of drumming are not necessarily evenly spaced hits, but individual strokes and rudiments, which have their own unique sound characteristics.

The underlying goal in choosing the actuating mechanisms in all these different robotic percussion systems is the need to expand and explore the timbral, dynamical and gestural possibilities of the instrument. Most robotic percussion instruments are disembodied and consists of a striking mechanism mounted on a drum and therefore, the motor torque requirements are not so high. If the robotic device is a wearable one, for example, in the RDP from GTCMT, the impact forces that the device have to withstand are big and therefore a more powerful motor, such as a brushless DC motor, is used.

Improvements in musical expressivity can also be achieved by focusing on the perceptual, cognitive and algorithmic aspects of musical improvisation and composition. While Weinberg et.al have integrated ideas from machine musicianship, music information retrieval and artificial intelligence to develop sophisticated musical algorithms and interactions, they have acknowledged the need for improvements in areas of timbral and loudness control. The actuator mechanism in their robots is very basic and is not capable of simulating/emulating the complex interactions between a human hand and the drumstick. The subtlety, finesse and variations in a human drum stroke are produced by these complex mechanics that are at work. While the musical algorithms and interactivity constitute the “what” in music, the drum strike mechanism and loudness control is about the “how” in music. Weinberg also points out that robotic musicianship research that focuses on developing sophisticated control mechanisms tends to neglect the perceptual and rhythmic aspect of the research and calls for a fine balance between all the elements [39]. Embedding the ability to produce different kinds of drum strokes can be thought of as learning the alphabet. What the musician chooses to do with it in terms of organizing the elements is a question of interactive and perceptual aspects such as listening, analysis and improvisation.

CHAPTER III

ROBOTIC DRUMMING AND THE ROBOTIC DRUMMING PROSTHESIS

Robotic drummers can be broadly classified into two categories based on the context and mode in which they are operated. They are namely,

- Independent Robotic Drummers (IRD) - These are typically static actuators (solenoid based, linear motors etc) that are mounted onto or positioned next to the drum itself. Solenoids are the most commonly actuators used for such kind of robotic drummers because of the ease of operation and low cost involved. Eg: *The Nudge, The Karmetik Machine Orchestra* [23, 20]
- Body Augmented Robotic Drummers (BARD) - These are wearable devices (prosthesis, supernumerary limbs) with different kinds of actuating mechanisms depending on the requirements of the specific use case, for example, brushless DC motor system controlled by a standard PID or PD control system. BARD systems are relatively recent and typically custom made specifically to fit the needs of the specific human user for which they are designed. Eg: *The Robotic Drumming Prosthesis (RDP)* from Georgia Tech Center for Music Technology.

In this thesis, the RDP, although originally designed as a prosthetic for an amputated drummer, is being used as an IRD and is the testbed to implement the generative model that captures the physics of human hand and drumstick interaction. The robotic arm is clamped onto a stand that holds it in place above a drum. Using the RDP as an independent robotic drummer also helps to reduce the need for complex sensing mechanisms that are usually needed for the successful operation of the arm as a wearable device and the focus can solely be on the stroke generation aspect. Due to the fixed mounting system, the geometrical relationship between the robotic drummer and the drum is fixed and does not change over time.

One of the main reasons to choose the RDP as the test bed is the complete positional (motor angle) control that can be achieved by the actuator system that is present in the robotic arm, a brushless DC motor (*Turnigy Gimbal 3508 HD*). By designing an appropriate feedback control mechanism, (PID control with appropriate gains to ensure minimal error in trajectory tracking) the motor can be made to move along any prescribed trajectory with high precision.

3.1 The Robotic Drumming Prosthesis

The Robotic Drumming Prosthesis was built by Meka Robotics for Atlanta based amputee drummer Jason Barnes. [1]

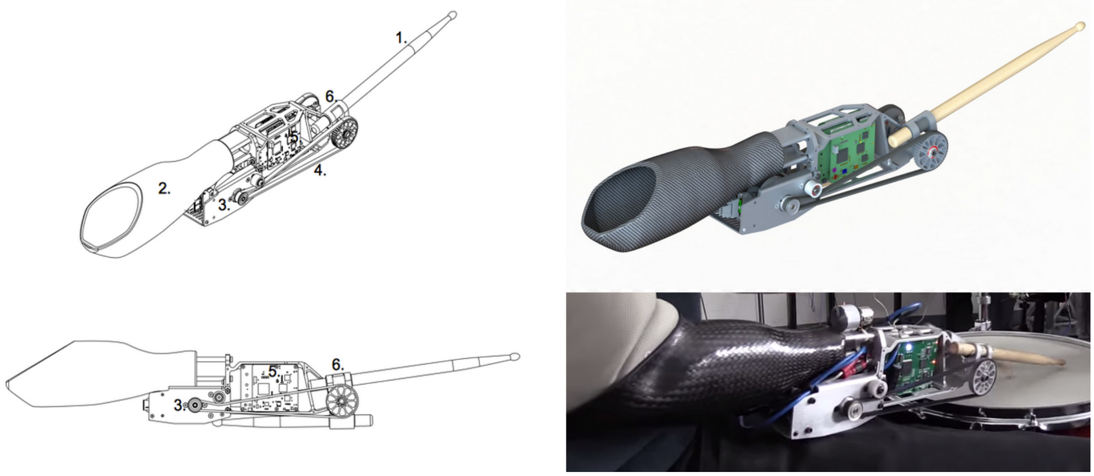

Figure 1: The Robotic Drumming Prosthesis - 1. Drum stick 2. Socket 3. Casing for motors 4. Belt connecting motor to drum stick mount 5. Processor 6. Drum stick mount

The following subsections briefly describe the structural, control and mechanical aspects of the device.

3.1.1 Mechanical Design and Actuators

As the device was originally designed as a BARD, the initial energy to the system is provided by the up and down elbow motion of the user. It is imperative that the device be robust

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[1] https://www.youtube.com/watch?v=ntrlHw6f4E4

enough to handle the frequent large impact forces inherent to drumming. An original non-anthropomorphic design, in which a single degree of freedom is used to simulate the role of fingers in altering drumstick grip, was adopted for the device. A large multi-stage gearbox, typical of robotic actuators, is both too complex and massive for the purposes of the RDP. Therefore, brushless gimbal motors were chosen for the device as they exhibit a low kV rating and are more capable of providing higher torques at low speeds, compared to standard brushless motors used in robotics, which run at high speeds and require significant gear reduction for usable output torque and speeds. The gimbal motors also provide rapid acceleration, an added bonus for the augmented human ability of extremely fast drumming.

A single stage timing belt drive was chosen for the robotic device as it can withstand the repeated shock loading common during drumming. Additionally, a belt drive adds a compliant element between the output and the motors. It was important to have low to zero backlash to facilitate smooth drumming and precise control.

3.1.2 Structure and Electronics

The primary structure is a unibody frame machined from a single billet of aluminum. Diagonal supports are cut into the frame which helps in removing as much material as possible without sacrificing structural rigidity. A structure cut out of a single piece of aluminum also has the advantage of having less weight than one which requires several parts and is held together by heavy steel fasteners. Furthermore, no extra hardware is required to hold the frame together. The frame has an i-beam profile that is closed on each end for stiffness. The control electronics are integrated into the main structure with cavities and mounting features in the middle of the frame. Cutouts along the top and bottom give access to connectors for sensors, power, and control bus.

The main microprocessor boards used in the device are proprietary boards from *Meka Robotics* and are mounted directly to the main structure. Advanced high precision motor control is facilitated by using high resolution optical encoders mounted to the rear of the motors. The boards are equipped with analog inputs for taking input from various sensors (EMG, potentiometers etc) and also comes with an on-board 9-axis accelerometer. The communication between the host computer and the board is over a high speed *EtherCat* based control bus. The development platform (MATLAB/Simulink) is extremely flexible and can be used to rapidly employ different types of control schemes.

3.2 Initial approach towards achieving multiple bounce strokes

The initial motivation for building the RDP was to give the drummer control over the bounce behavior in a basic double stroke roll. For human drummers, this control is usually achieved by subtle variations in grip force. The variable impedance based control system in the robotic device is able to simulate the variable finger pressure in a double stroke. This section describes the initial approach adopted to achieve variable multiple bounces in a stroke.

The initial approach taken towards achieving multiple bounce strokes in the RDP was to create a PD control system with variable controller gains. A PID control is a feedback system in which a reference trajectory is provided and the controller gains are tuned in such a way that, if the actual trajectory deviates from the reference then the control signal will automatically adjust itself so that the error is minimized.

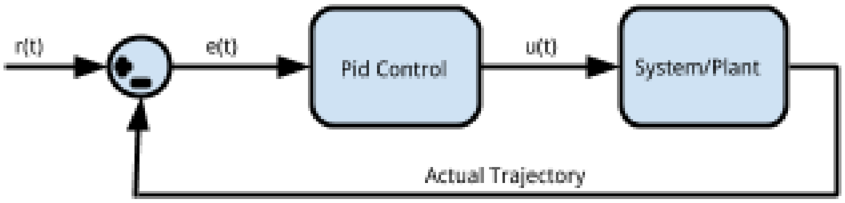


Figure 2: A PID Control Scheme

In **Figure 2**, $r(t)$ is the reference trajectory provided to the controller, $u(t)$ is the control signal and $e(t)$ is the error between the reference and the actual trajectory. When the stick is in steady state position (the angular position in which the stick is at rest relative to the arm, usually specified by the user), the controller is not active and the control signal is either zero or close to zero. Upon impact with the drum, the stick is displaced from the steady position. The job of the controller is to make sure that the motor's angular position is as close as possible to the reference trajectory set by the user. If the reference trajectory is specified as the steady state position, when the stick is displaced due to the impact on the drum, the control system will be activated and will provide the necessary torques to bring the stick back to steady state position. The response time, the overshoot amount and the steady state error in the response, depend upon the exact values of the PID controller gains. An impact with the drum can be thought of as an external impulse provided to the system. PD control system is essentially a second order system, and the k_p and k_d gains can be interpreted as the spring constant and the damping coefficient of a damped harmonic oscillator respectively. The mathematical form of the response looks as follows.

$$u(t) = k_p e(t) + k_d \frac{d}{dt} e(t) \tag{1}$$

We can compare **Equation 1** to the mathematical equation that governs the dynamics of a damped harmonic oscillator in free space which is as follows

$$m\ddot{y} + d\dot{y} + ky = 0, \tag{2}$$

where m is the mass, d is the damping coefficient, k is the spring constant and y is the displacement from the equilibrium position. The fundamental frequency of the system is given by $\omega_0 = \sqrt{k/m}$.

Since both these dynamical equations are second order systems and have the same mathematical form, the response of the PD controller to an external disturbance can be studied by studying the equivalent system of a damped harmonic oscillator in free space. This helps in having a better physical intuition for the controller response. In order to better understand the different conditions in which a damped harmonic oscillator operates, a state space representation of the mathematical equation is useful. This allows us to leverage

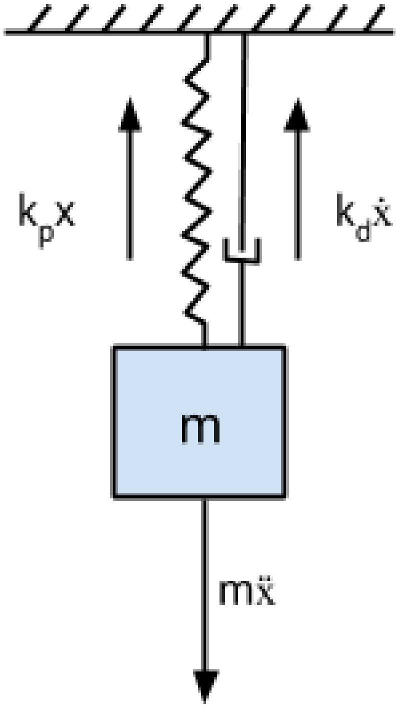


Figure 3: A damped simple harmonic oscillator

concepts from linear algebra and analyze for the stability of the system by evaluating the eigenvalues of the system matrix.

A state space model is simply a structured representation of the differential equations that characterizes a dynamical system and can be useful for performing various tasks such as linearization, stability analysis and time response calculations.

For the damped simple harmonic oscillator shown in **Figure 3**, we can define the following two state space variables x_1 and x_2 such that

$$x_1 = y \tag{3}$$

$$x_2 = \dot{x}_1 = \ddot{y} = -ky - d\dot{y} \tag{4}$$

Writing the above equations in matrix form, we have

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{5}$$

$$\dot{X} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -d \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{6}$$

The system matrix for this dynamical system is

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -d \end{bmatrix} \tag{7}$$

The eigenvalues of the system matrix can be evaluated by finding the roots of the characteristic equation. The characteristic equation is as follows.

$$A - \lambda I = 0 \tag{8}$$

where λ is the eigenvalue and I is the identity matrix.

Solving for the eigenvalues we have

$$\lambda = -\frac{d}{2} \pm i\sqrt{\frac{k}{m} - \frac{d^2}{4}} \tag{9}$$

If $d = 0$, the system becomes a simple harmonic oscillator and exhibits pure oscillations. It is best to look at the phase space plot in which the x-axis represents the damping and the y-axis corresponds to the spring constant. A particular value of spring constant and damping coefficient corresponds to a single point in this phase space. If $d = 0$, the point will always be on the y-axis. For a fixed mass, higher the spring constant k is, the higher will be the oscillation frequency.

For $d > 0$ the eigenvalues become complex quantities. This implies that there will be an exponentially decaying amplitude envelope superimposed on the oscillating position profile of the harmonic oscillator.

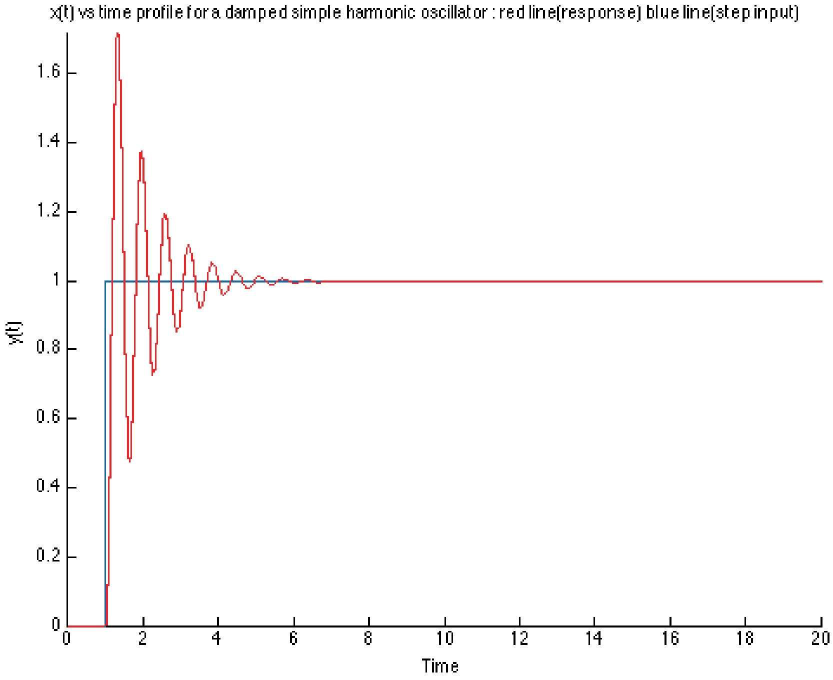


Figure 4: The response of a damped harmonic oscillator to a step input - high damping

Depending on the magnitude of the damping coefficient, the decay rate can be fairly high or low as shown in **Figure 4** and **Figure 5**

For $d < 0$, the system becomes unstable and will give rise to an exponentially increasing amplitude envelope. In real world systems, a negative damping coefficient is not physically possible, as the damping usually arises due to the viscous drag from the medium in which the oscillations occur and is always positive.

When the damping coefficient equals the resonant frequency, there are no more oscillations in the system and the system is critically damped. Critical damping provides the quickest approach to the target value for a damped oscillator.

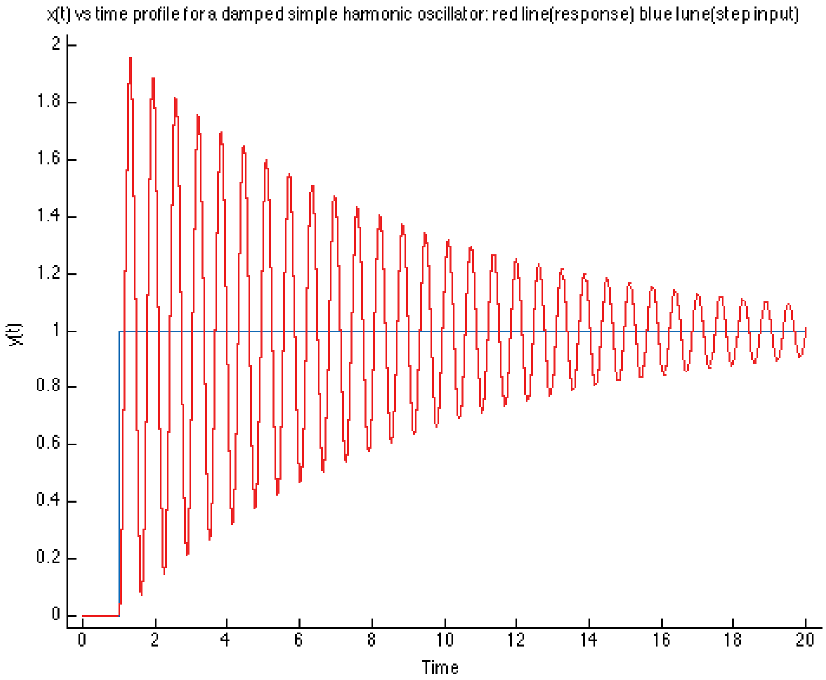


Figure 5: The response of a damped harmonic oscillator to a step input - low damping

It can be seen that if the controller output (in the case of RDP this is the current provided to the motor) follows the same profile as that shown in the **Figure 4** or **Figure 5**, then any quantity that is linearly related to the controller output will also have the same profile. In the RDP the motor current is linearly related to the torque which in turn is linearly related to the angular position of the motor and therefore the stick also follows a angular trajectory that is similar to that of a damped harmonic oscillator.

The use of a PD controller to create multiple bounces is better illustrated when the RDP is used as an IRD device. A particular drum strike message consists of a request of change in motor angle from the steady state position to the strike position. A stroke is generally considered to be complete, when the motor angle goes back to the steady state position after the drum strike. The amount of time the stick remains in the strike position depends on the kind of stroke that is desired. For a single hit, the contact time is usually of the order of milliseconds, whereas in the case of a multiple bounce stroke the amount of time the stick will be in the strike position is usually of the order of seconds.

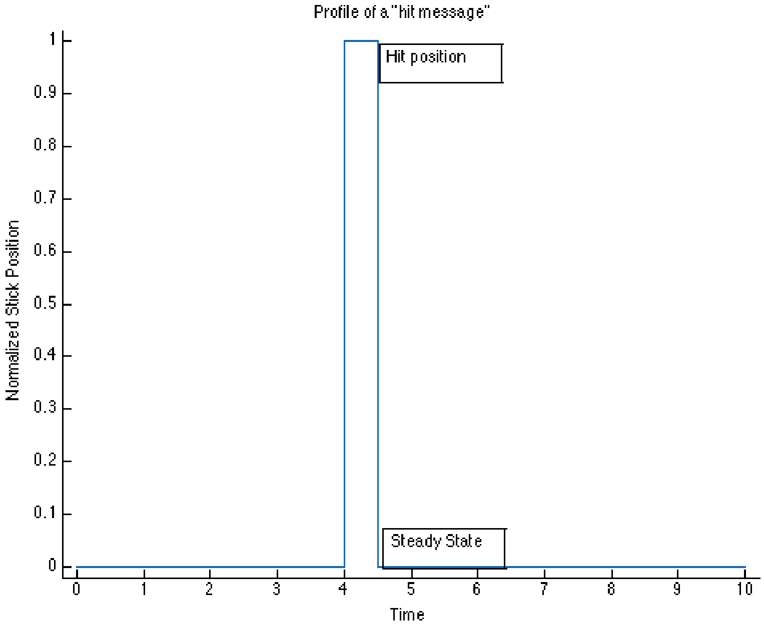


Figure 6: Profile of a “hit message” - Short duration

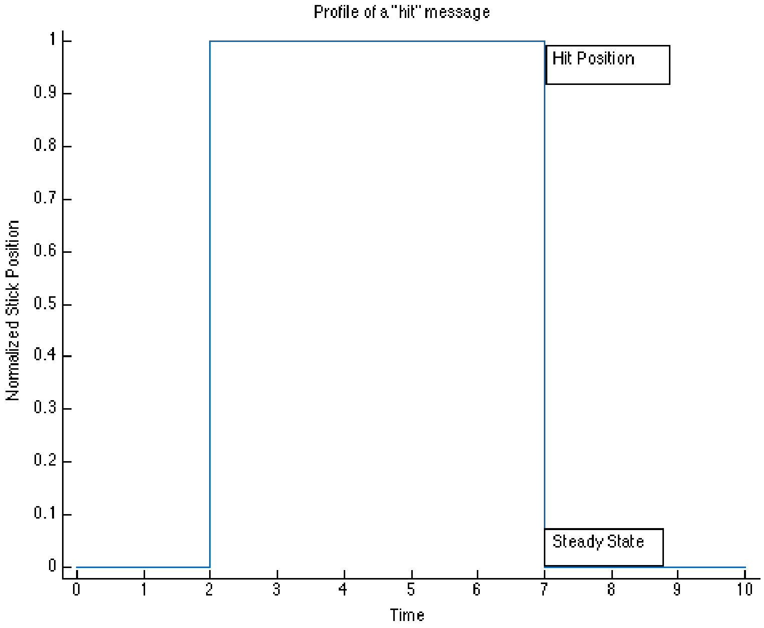


Figure 7: Profile of a “hit message” - Long duration

For certain settings of the spring constant and damping coefficient the controller output results in an overshoot of the target position exhibiting underdamped behavior. If one ignores the collisions with the drumhead, then, by exploiting the instability of the controller output (the overshoot), a multiple bounce stroke can be achieved. Every time the drum stick angle overshoots the requested drum strike end position, it will correspond to a single strike of the drum. The frequency and the rate at which the profile of the multiple bounce stroke decays depends on the relative values of the spring constant and the damping. This corresponds to a particular point in the phase space plot.

By traversing through various trajectories in the phase space, one can dynamically change the frequency and the decay profile, to generate different kinds of multiple stroke behavior. Moving along a trajectory in the phase space corresponds to a damped harmonic oscillator whose spring constants and damping coefficients are also functions of time. The stroke behavior can be drastically different if the same phase space trajectory is traversed at a different rate.

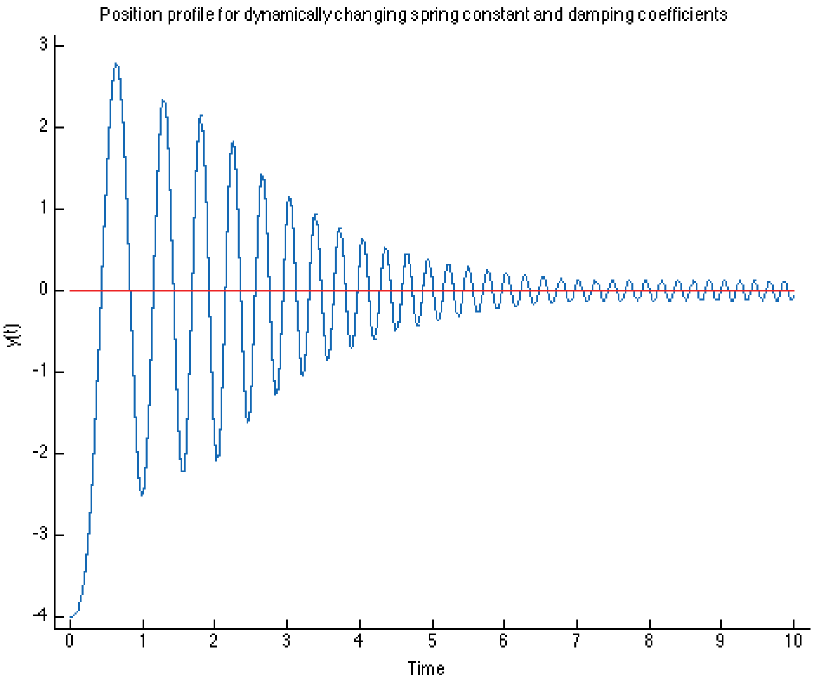


Figure 8: Position profile for dynamically changing damped harmonic oscillator

It can be seen from the above figure that the frequency of oscillation increases over time and the decay envelope is not a smooth exponential. This is due to the time varying spring constant and damping coefficients. The position profile for the damped harmonic oscillator shown in **Figure 8** had the following spring constant and damping coefficient time profiles.

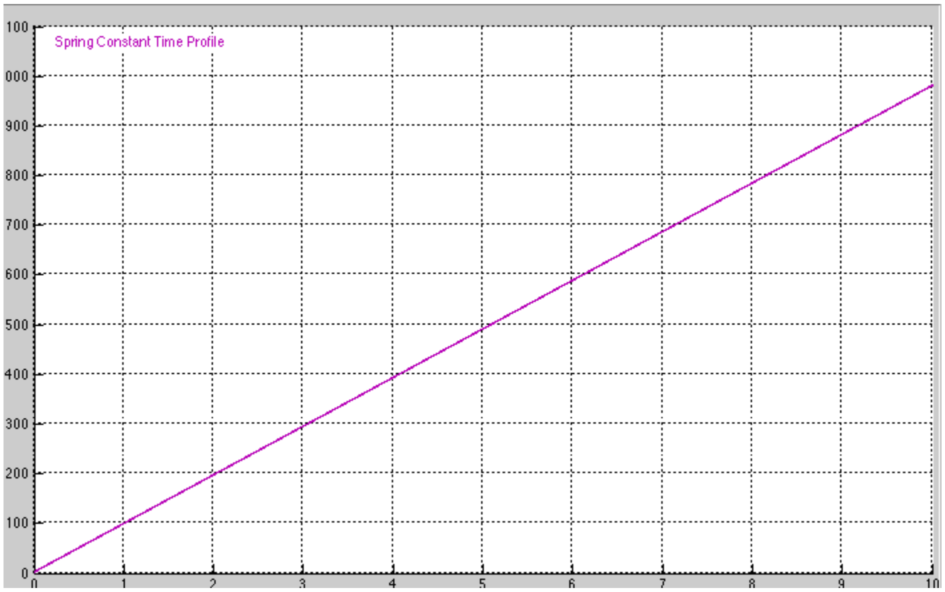


Figure 9: Spring constant vs. time profile

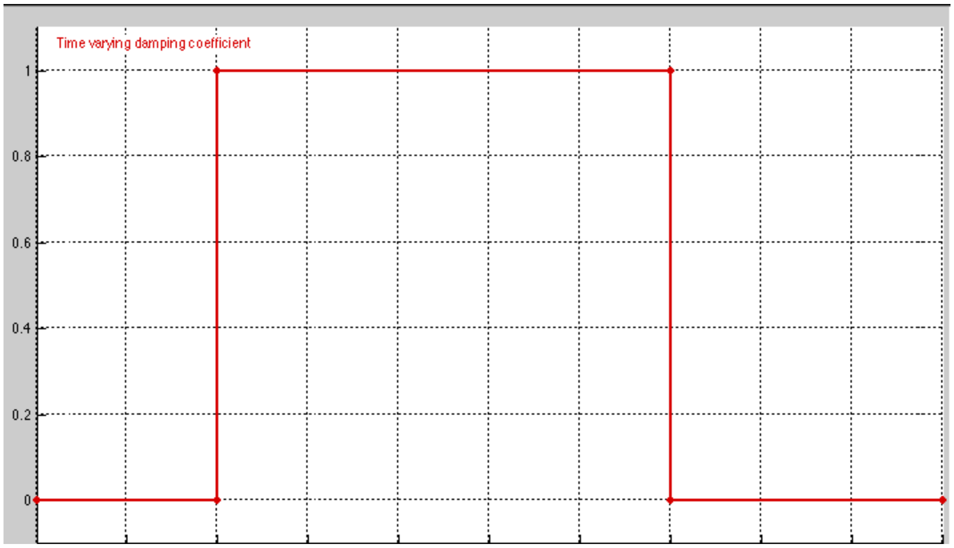


Figure 10: Damping coefficient vs. time profile

Although this approach can produce a wide variety of multiple bounce stroke profiles, the inherent issue with this approach is that, once collisions with the drumhead are considered in the dynamical equations, the system becomes a hybrid system and the damping profile changes drastically. This is because of loss of kinetic energy due to collisions. Therefore, even if the damping coefficient is zero, the stroke can decay and die out fairly quickly depending on the coefficient of restitution between the drum stick and the drumhead.

This can be illustrated by considering the dynamics of a damped harmonic oscillator in which there are constraints in the displacement of the mass.

In the following figure, the equilibrium position of the system is at zero and the initial displacement is -4 units. The displacement constraint is such that $-\infty < y(t) < 0.1$ and the coefficient of restitution is -0.4 between the constraint surface and the mass.

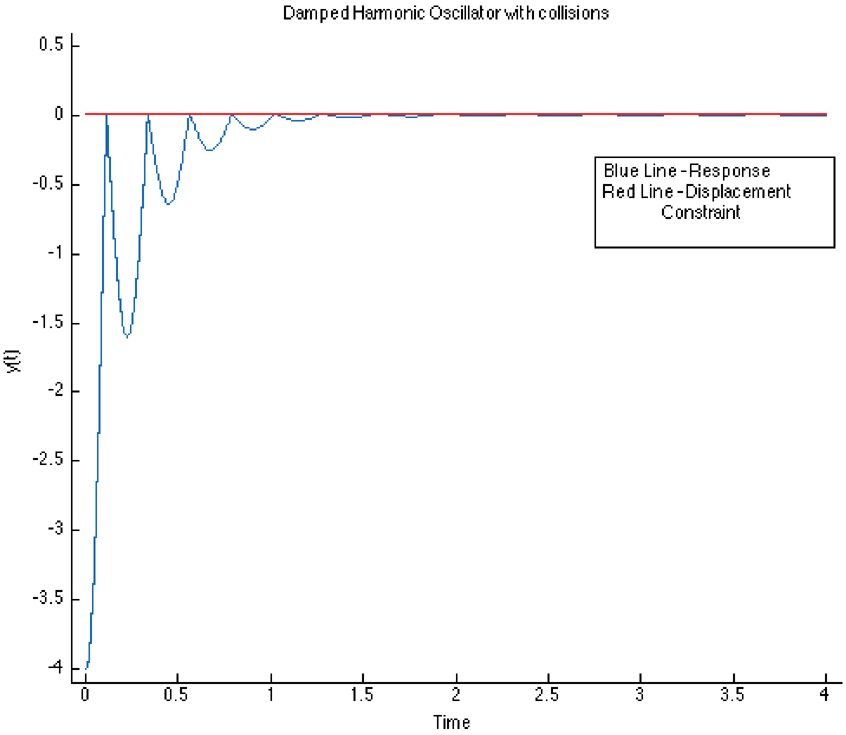


Figure 11: $y(t)$ vs. *time* - Damped harmonic oscillator with displacement constraints

From this, it is clear that a strike message which lets the stick stay down for longer need not necessarily produce a long multiple bounce stroke as the multiple bounces can die out fairly quickly depending on various factors such as the damping due the belt and the loss of energy from the collisions. This means that in order to continue the stroke, more energy needs to be pumped into the system. This can be done by producing a series of strike messages with different inter-onset times, so that the stroke is sustained, thereby resulting in an actual multiple bounce stroke. The number of strokes, the amplitude of each of the strokes and the inter-onset times all have an effect on the bounce profile. Since the number of variables in this approach is huge, the number of possible outcomes is extremely high and quite unpredictable. Reverse engineering the time varying profiles for the parameters of the above mentioned system to produce a desired multiple bounce trajectory (with desired time varying oscillation frequency and time varying decay profile) is almost impossible because of the size of the search space. Regardless, this phenomena inspired the design of an interactive interface, which the user can use to specify the time varying spring constant (k_p for the controller) and damping coefficient(k_d for the controller) profiles. Energy lost due to the collisions is compensated by issuing extra hit messages at varying amplitudes and inter onset times. The interface lets the user customize all the parameters and is discussed in detail in the next section.

3.2.1 The interactive MaxMSP interface for real time manipulation of PD controller gains

The design of this interface was motivated by the idea that a multiple bounce trajectory with a time varying frequency and decay profile can be generated by exciting the system and changing the controller gains (which are equivalent to the spring constant and damping coefficient) over time. The interface was developed in Max/MSP and communicates via a custom built UDP messaging protocol with the host computer that controls the robotic arm. The interface issues “strike messages” at different amplitudes at different times and the response of the stick to a particular strike message is dependent on the spring constant and damping coefficient at that point in time.

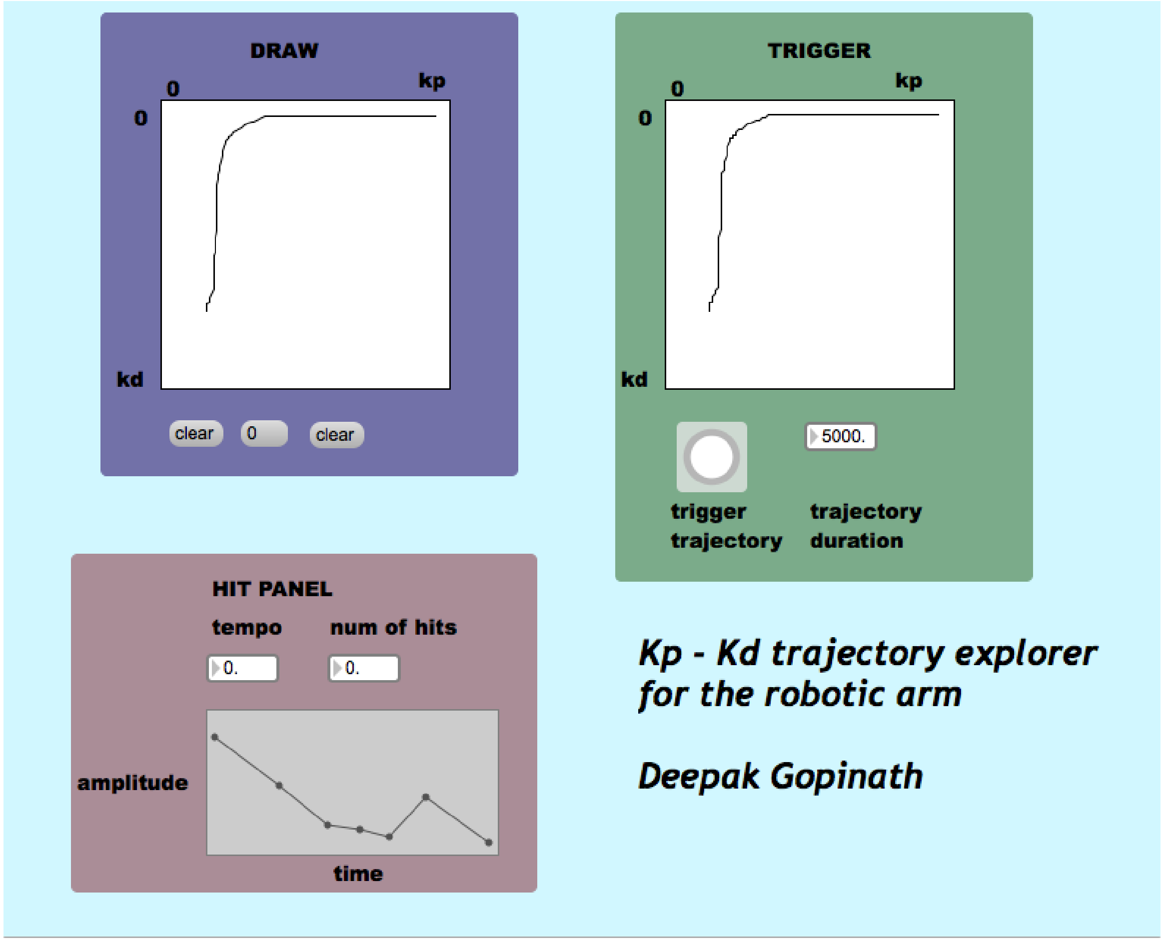


Figure 12: MaxMSP interface for real time manipulation of controller gains

The main interface consists of three panels, namely

- *Drawing Panel* - in which the user can draw a k_p-k_d profile.
- *Trigger Panel* - in which the user can trigger the trajectory that was drawn in the Drawing Panel at different rates (total time taken to traverse the profile) and,
- *Hit Panel* - in which the user can specify the number of strike messages (along with the amplitudes and inter-onset times) to be issued during the time taken to traverse the trajectory.

3.2.1.1 *Drawing Panel*

The *drawing panel* in the interface represents increasing values of k_p (proportional controller gain) along the positive x-direction and the increasing values of k_d (derivative controller gain) along the negative y-direction. The origin of the drawing panel is in the top left corner. Although, using the mouse, any trajectory can be drawn on the panel, not all trajectories will produce a satisfying multiple bounce behavior. This is because, the principle behind creating a multiple bounce stroke in this system is to exploit the unstable response of the controller to any deviations from the steady state reference position. Once the actual angular position reaches the reference position provided, the controller becomes inactive and any further change in the controller gains do not have any effect on the position of the motor. This can be explained well by considering a trajectory as shown in **Figure 13**

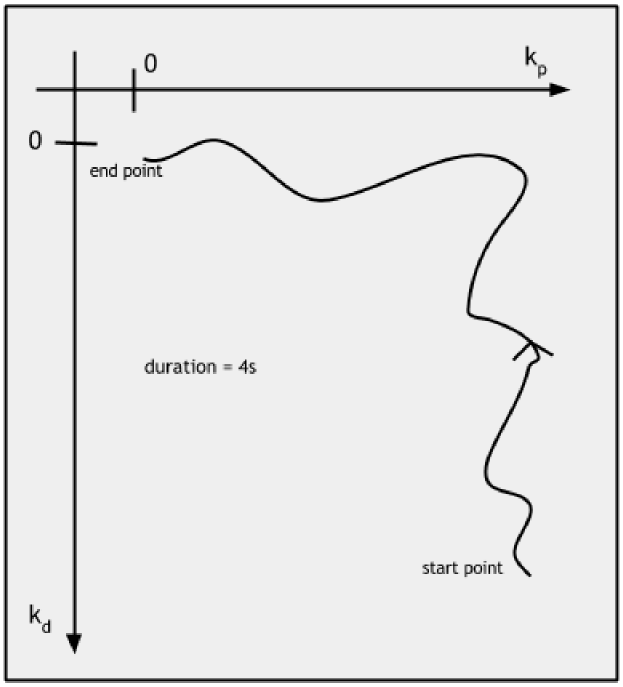


Figure 13: k_p, k_d trajectory - Example 1

In this scenario, since the trajectory starts off with a fairly high damping value (k_d) and a high spring constant (k_p), the stick will reach the reference quite early on in the trajectory and the controller becomes inactive. This is because, a high k_p results in faster controller response whereas a high k_d results in very little overshoot, thereby reaching the requested motor angle in a shorter time. Although, the time taken for the trajectory traversal is close to 4s in this example, variations in the k_p, k_d values towards the end of the trajectory do not have any effect on the motion (unless more energy is pumped into the system via more "hit messages". This will be discussed later).

In contrast to the previous scenario a more useful k_p-k_d trajectory can be found in **Figure 14**

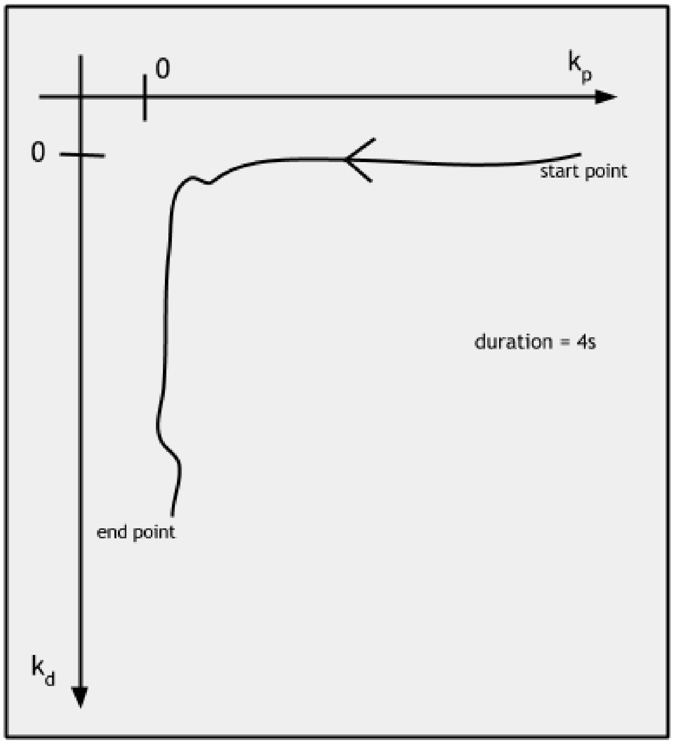


Figure 14: k_p, k_d trajectory - Example 2

In this case, the trajectory starts off with a high value of k_p and a low value of k_d which results in unstable behavior (oscillations about the reference point) at a high frequency and minimal damping. As time progresses the frequency of oscillations decreases due to decreasing values of k_p. Towards the end of the trajectory, k_d increases and introduces damping into the system and therefore the slow oscillations decay out fairly quickly. This kind of a profile, typically will result in a multiple bounce stroke which can last for a few seconds. The length of the stroke can be prolonged further by injecting more energy into the system in order to compensate for the energy lost to collisions. The angular position profile as a result of such a k_p-k_d profile is shown in **Figure 15**

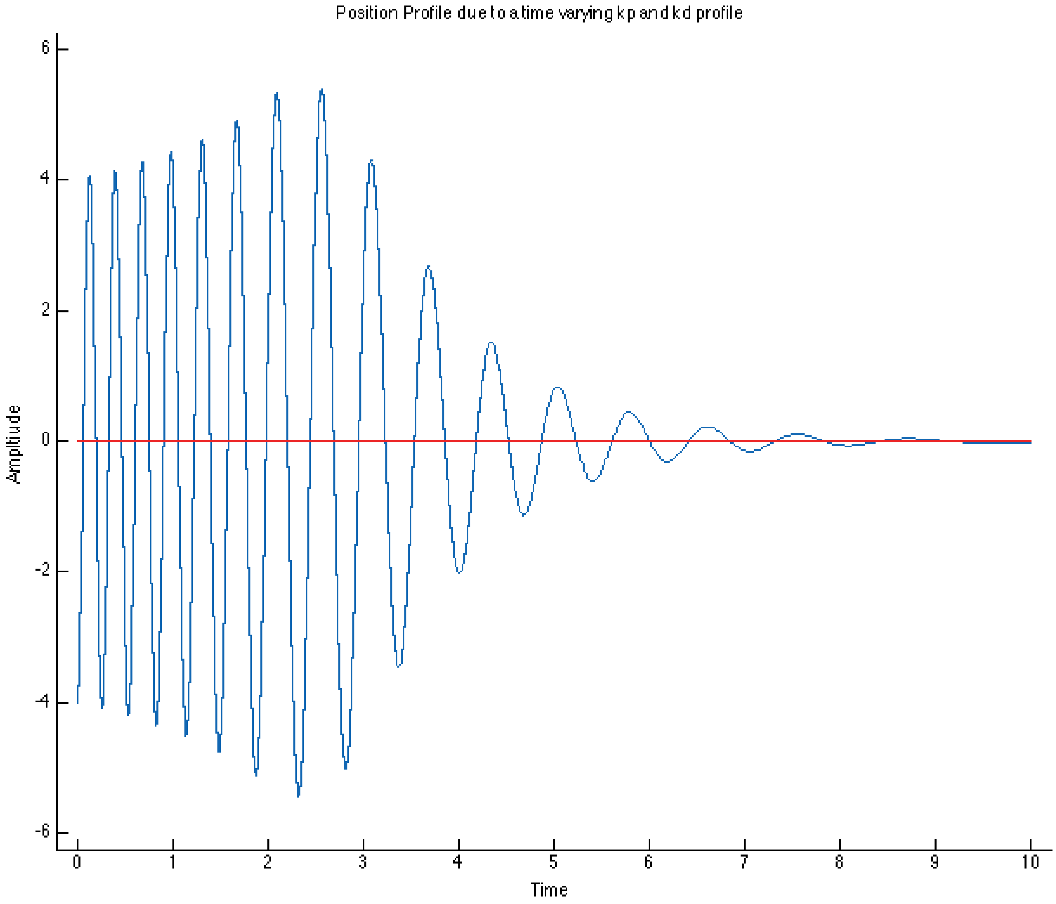


Figure 15: Position profile due to the time varying profile shown in **Figure 16**

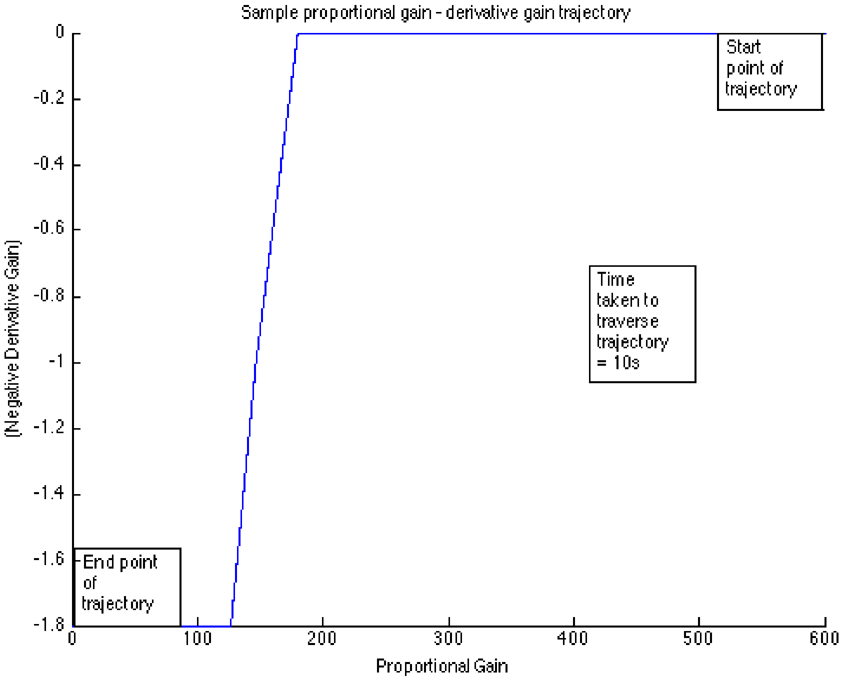


Figure 16: A time varying k_p-k_d trajectory

3.2.1.2 Trigger Panel

The *trigger panel* redraws the k_p-k_d trajectory drawn by the user in the *drawing panel* at a rate specified by the user. The number box under the trigger panel is used for the specifying the total time (in milliseconds) to be taken to redraw the trajectory. This panel also takes care of communicating the controller gain values to the host computer which controls the robotic arm in real time as the redrawing happens. The “trigger trajectory” button is used for triggering the profile.

3.2.1.3 Hit Panel

The *hit panel* is used to specify the parameters of the sequence of “hit messages” that excites the system so that the multiple bounce stroke does not die out prematurely. The parameters include, the total duration for the drum hit sequence, the inter onset times (the time gaps between each one of the “hit message”) and the amplitude of each of the hit messages. The inter onset times and amplitude can be captured quite easily by using a x-y graph in which the x-axis corresponds to normalized time coordinate and the y-axis corresponds to the strength of each of the hits. These parameters can be easily manipulated in the interface by clicking on each of the breakpoints and moving them around. The number box tagged "tempo" in the *trigger panel* is used for specifying the total duration for the drum hit sequence.

3.3 Limitations

The exploratory nature of this approach and the large number of possibilities make a formal evaluation of the system almost impossible. A slight change in any one of the parameters (the profile drawn in the drawing panel, the time taken to traverse the trajectory, the number of "hit messages", the time taken to traverse the "hit sequence") can result in drastically different results. But once a user starts to play with the system and acquire a sense of the most appropriate and useful range of parameters, then various stroke profiles can be easily explored.

Although this system offers a wide variety of stroke possibilities, the inherent limitation of relying on the instability of the controller's response makes the system less reliable and predictable. Furthermore, it is almost impossible to use this approach when the RDP is to be used in the IRD mode. This is because, in the IRD mode, if the stick needs to hit the drumhead with minimal damping due to the collisions, the reference angle should be kept slightly above the drumhead so that when the actual stick position overshoots the reference, it makes contact with the drumhead at the local maxima of the position curve. Since the oscillations are always centered around the reference point, once the decay envelope is activated the local maxima does not reach the drumhead and therefore the stick will not hit the drumhead, thereby defeating the whole purpose, which is to produce sound. A possible solution to this is to compensate for the offset by adding an inverted exponential decay envelope to the actual position profile. Once again this proves to be difficult especially in the case of time varying controller gains as the envelope itself is modulated in time. The above mentioned limitations inspired a different approach towards achieving multiple bounce strokes in the robotic drummers.

The following chapter provides a mechanical description of how a human drummer performs a drum stroke (single or multiple bounce), a simplistic model for describing a drum stroke, the system identification performed on the human hand-drumstick system and the detailed physics that determine the actual trajectory tracked by the tip of the drumstick.

CHAPTER IV

GENERATIVE PHYSICAL MODEL FOR DRUM STROKE GENERATION - AN ALTERNATE APPROACH TO ENHANCING EXPRESSIVITY

4.1 Degrees of freedom in human drumming

Human drumming is a complex bio-mechanical task in which various degrees of freedom available in limbs are utilized for effective musical expression and communication. Although for a drum set player, the feet are also engaged in playing drums, for the purposes of this thesis and the scope of this work, they will not be considered and the focus will exclusively be on understanding the mechanical and physical principles of drumming using the hand.

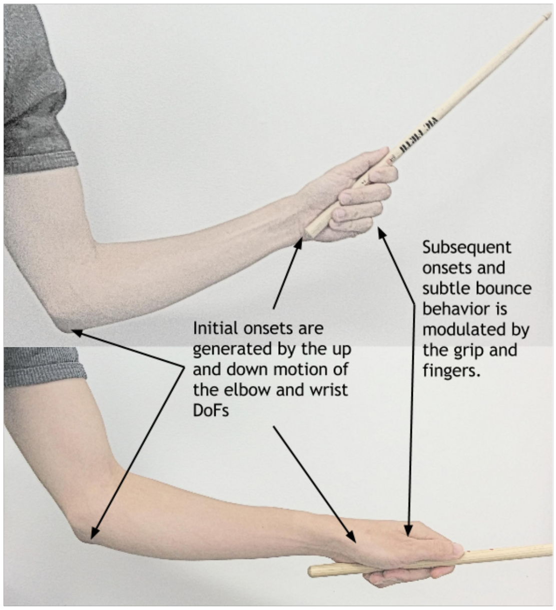


Figure 17: Degrees of freedom in drumming - elbow, wrist and fingers

In the case of human drumming the degrees of freedom available at the elbow, wrist and fingers, all play an important role in shaping the motion of the drumstick before and after a drum stroke. The motions from the elbow, wrist and fingers interact to produce the necessary volume level, control and finesse to each drum stroke. On one end of the spectrum, bigger muscle groups are activated by moving the elbow and are useful for producing high volume drum hits. Finer motor control that is needed for subtle manipulation of drumstick is not available at this hierarchical level. Furthermore, bigger muscles are not able to produce faster strokes and fatigue becomes a problem as well. The degree of freedom available at the wrist is the most commonly used in drumming, as it allows for a wide range of possibilities. There is a good tradeoff between control, speed, dexterity and fatigue. Fingers are used to generate faster strokes and also for softer volume levels. Changing the grip strength and the thumb position also enables the drummer to manipulate the after bounce profile of a drum stroke thereby creating a diverse array of multiple bounce strokes.

If human drumming is considered to be the benchmark and epitome of musical expression in drumming, then in order to achieve a level of musical expressivity close to that of humans in robotic drummers, it becomes necessary to understand the physics of human-drumstick interaction and make the robotic drummer perform similar kind of drumstick motion. This is under the assumption that all of the sound produced is a result of the motion of the drumstick in a particular way and its interaction with the drumhead. The same kind of drumstick motion can be achieved by various techniques (which is why there is no one correct technique to play drums), but regardless of the actual techniques used (squeezing thumb and forefinger to control the bounce or using the middle and ring fingers to limit the range of bounces), the overall effect of all of these factors on the drumstick is that of moving it in free space and making contact with the drumhead in a particular fashion.

This idea motivated the development of a physics based generative model summarizing the mechanisms underlying a multiple bounce drum stroke produced by a human drummer. The output of such a physical model (a angular position of the drum stick versus time) will be used as the reference motor angle trajectory for the PID controller whose job is to make the robotic arm track the reference trajectory as close as possible. Then the controller gains are tuned in such a way that the actual motor angle remains as close to the reference trajectory as possible throughout the entire stroke profile, ensuring that the robotic arm's stick motion almost mimics the one by a human.

4.2 Simplified model of drumming mechanics

Hajian has presented multiple bio-mechanical models that offer a detailed and microscopic analysis of the physics between the human hand and drumsticks in his thesis [12]. Various models such as the rolling contact spring model and the fixed contact spring model are discussed. These contact models are developed in an attempt to model the complicated hand kinematics that are presented during the performance of a double stroke roll.

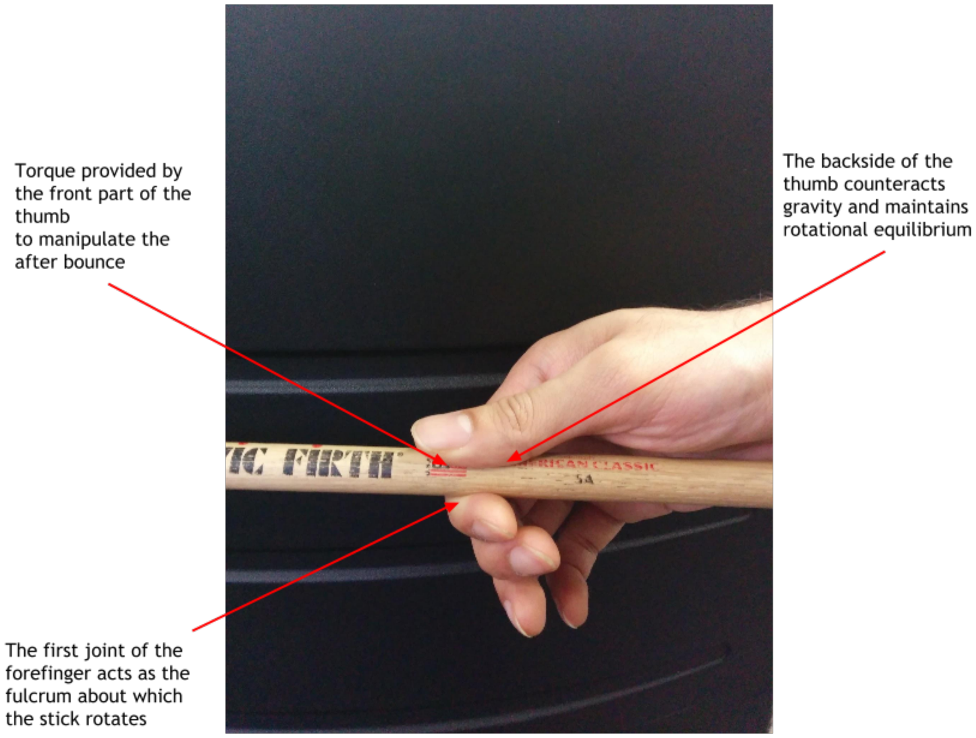


Figure 18: Hand holding a drumstick

Similar to the work by Hajian, a simple model of drumming is considered in this thesis as well. The degrees of freedom available at the elbow and the wrist are disregarded and the drumstick is considered as a pivoted rod rotating about a fixed pivot point.

When the stick is in rotational equilibrium about the fulcrum, the torque due to gravity is balanced by a counter torque provided by the backside of the thumb as shown in **Figure 18**.

In order to produce a buzz stroke (a multiple bounce stroke), typically the drummer would release the stick by opening up the thumb letting the stick drop, and the torque due to gravity will make the stick accelerate towards the drum head. Upon hitting the head, the thumb (and/or the fingers) is usually used to provide a time varying torque (or restrict the motion of the sticks) to control the after bounce profile.

The hypothesis is that, although there are many different kinds of forces at work between the fingers and drumstick at a microscopic level, the effect of all of these forces on the drumstick is that of manipulating the torque due to gravity by adding additional torques by pushing down on the stick using the thumb. This is illustrated in **Figure 19**.

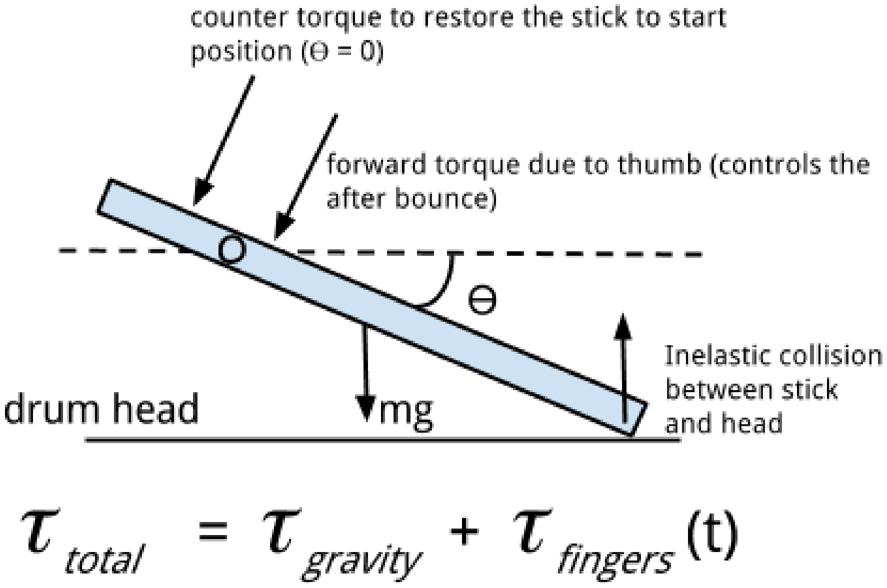


Figure 19: Torques acting on a drumstick

The torques provided by the thumb are usually time varying. The extreme case, in which the thumb is not in contact with the stick, the only torque acting on the system is due to gravity and the bounce behavior of the stick is very similar to that of a freely bouncing ball. The coefficient of restitution between the drum stick and the drum head is another critical factor that determines the stroke profile. A more taut drumhead such as the one for a snare drum, will have a fairly high coefficient of restitution whereas for a floor tom, which is a relatively low pitched drum this parameter will be low. This parameter is something that can be determined experimentally, although in this work, the values are chosen in a more intuitive way.

This simple time varying torque model provides a physics framework which can be used for generating different kinds of multiple bounce strokes. Any kind of time varying profile can be chosen for the simulations and the possible stroke types are limitless. A few categories of strokes can still be identified such as,

- No External torque - One in which the torque due to the thumb is zero and the bounce behavior is similar to a bouncing ball.
- Constant external torque - One in which the behavior is still like a bouncing ball but as if in an environment with stronger gravitational force.
- Low to High variation in torque - One in which the initial onsets are widely spaced with a sudden increase in the frequency of onsets. Clearly, this is a very broad class of strokes in which the rate of change of torque, the exact magnitudes and the timings all matter.
- High to Low variation in torque - One in which the initial onsets are closer together followed by a sudden decrease in the frequency of onsets.
- Un-natural variations in torque - One in which the profiles are really hard to produce by human drummers, but is possible in a physics simulation thereby giving rise to strokes that are not human like.
- Regular Pulse - One in which the torque profile is a train of pulse triggered in such a way the stroke is sustained.

4.3 Dynamics of the system

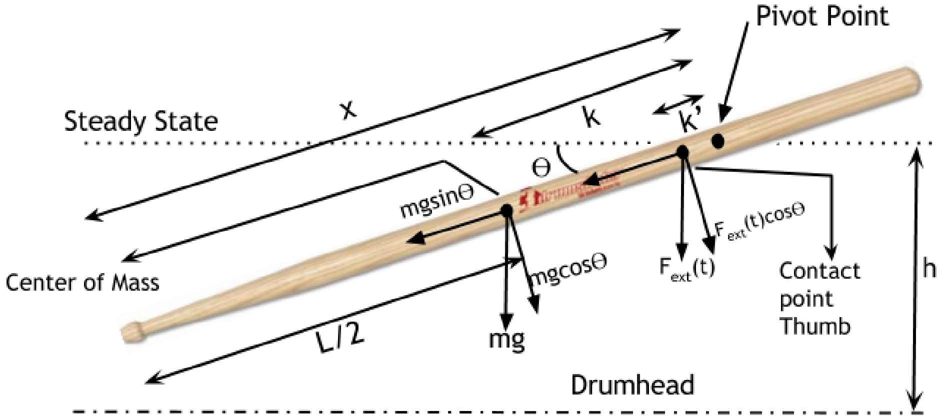


Figure 20: Detailed torque diagram

4.3.1 Moment of Inertia

Let L be the length of the drumstick and x be the distance of the fulcrum from the tip of the drumstick. The stick is treated as a one dimensional rod with uniform density. If m is the mass of the stick, then density $\rho = \frac{m}{L}$. θ is the angular displacement of the stick and is zero when the stick is parallel to the drumhead. As the stick moves downwards towards the drum, the values of θ decreases (downward direction is taken as negative). The moment of inertia I is given by

$$I = \int_{-x}^{L-x} r^2 dm \tag{10}$$

where r is the distance of the infinitesimal point mass from the fulcrum and dm is the mass.

$$dm = \rho dr = \frac{m}{L} dr$$

Upon integration, **Equation 10** yields

$$I = \frac{m}{3L}(x^3 - (x-L)^3) = \frac{m}{3}(3x^2 - 3xL + L^2) \tag{11}$$

4.3.2 Equations of Motion

The drum stick is treated as a freely rotating rod about a pivot point which is at a distance of x from the tip of the stick. Gravity acts at the center of mass which is approximately located at the midpoint of the stick and is at a distance of k from the fulcrum. The thumb is in contact with the stick at a distance of k' from the fulcrum. The total torque acting upon the consists of two components -

- Torque due to gravity
- External torque due to the thumb pressing down on the stick.

The total torque acting on the drumstick can be written as

$$\tau_{total} = \tau_{gravity} + \tau_{ext}(t)$$

where the external torque is a function of time and can have different kinds of profile.

$$\tau_{gravity} = -mgcos\theta * k$$

and

$$\tau_{ext}(t) = -F_{ext}(t)cos\theta * k'$$

Let $F_{ext}(t) = ma_{ext}(t)$, where $a_{ext}(t)$ is the linear acceleration provided by the thumb. From Newton's laws we have

$$\tau_{total} = I\ddot{\theta}$$

where I, is the moment of inertia and $\ddot{\theta}$ is the angular acceleration. Then,

$$I\ddot{\theta} = \tau_{gravity} + \tau_{ext}(t) \tag{12}$$

$$I\ddot{\theta} = -mgcos\theta \times k - F_{ext}(t)cos\theta \times k' \tag{13}$$

$$I\ddot{\theta} = -mgcos\theta \times k - ma_{ext}(t)cos\theta \times k' \tag{14}$$

Substituting 11 in 14 and rearranging the terms we get

$$\ddot{\theta} = -\frac{3cos\theta(gk + a_{ext}(t)k')}{3x^2 - 3xL + L^2} \tag{15}$$

Since the geometrical relationship between the pivot point, the stick and the drumhead are fixed, the vertical distance of the pivot point from the drum head (h) is constant. From h and x, the maximum angular displacement possible for the stick from steady state position can be calculated as

$$\theta_{max} = -sin^{-1}(\frac{h}{x}) \tag{16}$$

In order to incorporate collisions of the stick with the drum, two approaches can be adopted. In the first approach, the forces acting upon the stick at the moment of contact can be approximated and for a short duration the dynamical equation can be modified. In a more simplistic approach, the effect of all the contact forces can be summarized and can be treated as an inelastic collision.

So when, $\theta = \theta_{max}$ (condition for collision), the velocity undergoes an instantaneous change in direction and magnitude. Therefore,

$$\dot{\theta}_{after} = -c\,\dot{\theta}_{before} \tag{17}$$

where c is the coefficient of restitution between the drum stick and the drum head. For taut drum heads this value can be fairly high, whereas for low pitched drums, the value can be low. For the purposes of simulation this can be treated as a tunable parameter.

For the purposes of simulation, a *Zildjian Maple Mini-ball* [1] stick was chosen. For this stick, the following table shows the approximate values of all the variables involved.

Table 1: Parameters values for Zildjian Maple Miniball stick

Parameter	**Value**
L	0.39m
x	0.27m
k	0.075m
k'	0.01m
h	0.07m
θ_{max}	-0.2623 rad
vol	6.23×10^{-5}
ρ	600 kg/m^3
m	$0.0373kg$

Substituting these values for the parameters in Equation 15 with acceleration due to gravity $g = 9.8\ m/s^2$ we have

$$\ddot{\theta} = -\frac{cos\theta \times (0.735 + 0.001 \times a_{ext}(t))}{0.0714} \tag{18}$$

This is a second order differential equation for which an analytical solution is extremely hard due to θ's cosine dependency and also the time varying external linear acceleration. Therefore, numerical solutions are preferred. The external linear acceleration $a_{ext}(t)$ is in the range $0 - 250m\ /s^2$. For a stick with $m = 0.0373kg$ this corresponds to a force of approximately in the range $0 - 10N$ which is the characteristic force range that can be produced by finger tips during the interaction with a drumstick during a stroke. This has been empirically studied and documented by Hajian in his thesis [12].

---

[1] http://zildjian.com/Products/Drumsticks-and-Mallets/Maple-Series/Maple-Mini-Ball

4.3.3 Restoring torque

In the previous section, the only external torque due to the thumb is in the same direction as that of torque due to gravity. Because of the inelastic collisions with the drum head and the physical constraint that θ cannot be less than θ_{max}, when the bounces die away eventually, the stick will remain at $\theta = \theta_{max}$. Typically, a stroke is considered to complete when the stick position is restored back to the steady state position and in order to accomplish this, a restoring torque has also been incorporated into the model to bring the stick back up to the steady state position.

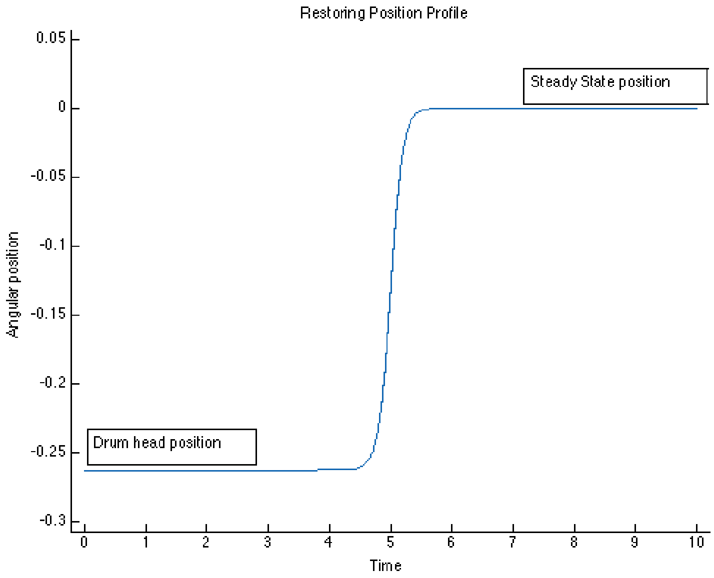


Figure 21: Stick restoring position profile

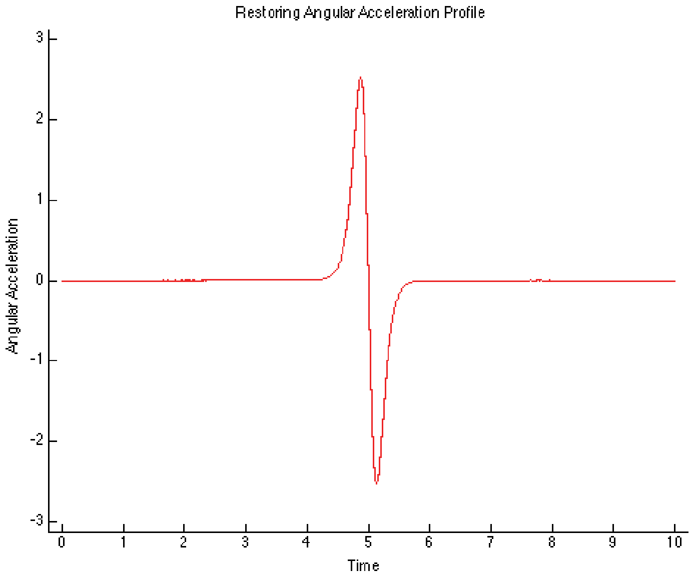


Figure 22: Stick restoring angular acceleration profile

This torque is the one provided by the back side of the thumb behind the fulcrum on the butt end of the stick. Besides the actual magnitude of this restoring torque, the timings of the torques are also important in determining the stick motion. A sigmoid function is used as the reference for the restoring trajectory. Once the position profile is determined, then the net angular acceleration (and torque) profile can be calculated by double integrating the position profile. This can been seen in **Figure 21** and **Figure 22**. The restoring torque should be sufficient enough to counteract the effect of gravity and provide a net torque in the positive direction.

From the purposes of simulation, this can be achieved by “turning off” gravity after the stroke has come to an end and then apply the net restoring torque to bring the stick back up to the steady state position from the striking position.

4.3.4 Simulink model

Matlab/Simulink was used for simulating this model. **Figure 23** is a snapshot of the Simulink model.

The *Simulink* model uses a second order integrator for obtaining numerical solutions to the differential equation described in **Equation 18**. The sample rate is set at 1000Hz. A output scaling module is also integrated into the model as the robotic arm's motor encoder operates in a different range. As a result angular position in radians needs to be converted into the appropriate ranges if this model can be used on the robotic arm.

The parameter that can be chosen freely is the linear acceleration provided by the thumb to alter the bounce behavior of the stick. A predefined set of acceleration profiles are used for simulation purposes. The restoration profile module works by checking whether the stroke has been completed and then turns off gravity and applies the restoring torque, thereby bringing the stick back up to the steady state position. The initial angular position and velocity can also be freely specified. The coefficient of restitution is kept at -0.86. This value can also be freely chosen. Regardless of the exact values of the parameters chosen, the goal here is to obtain a angular position vs. time profile that can be given as a reference trajectory to the PID controller which in turn will make the robotic arm's stick move along that trajectory as closely as possible. A useful analogy is the source filter model in speech synthesis in which there are a great number of free parameters. Choosing the parameters in the appropriate ranges will result in human like speech sounds. Once the parameters are taken beyond the normal human range, the same algorithm/physical model can be used to produce non-human like sounds.

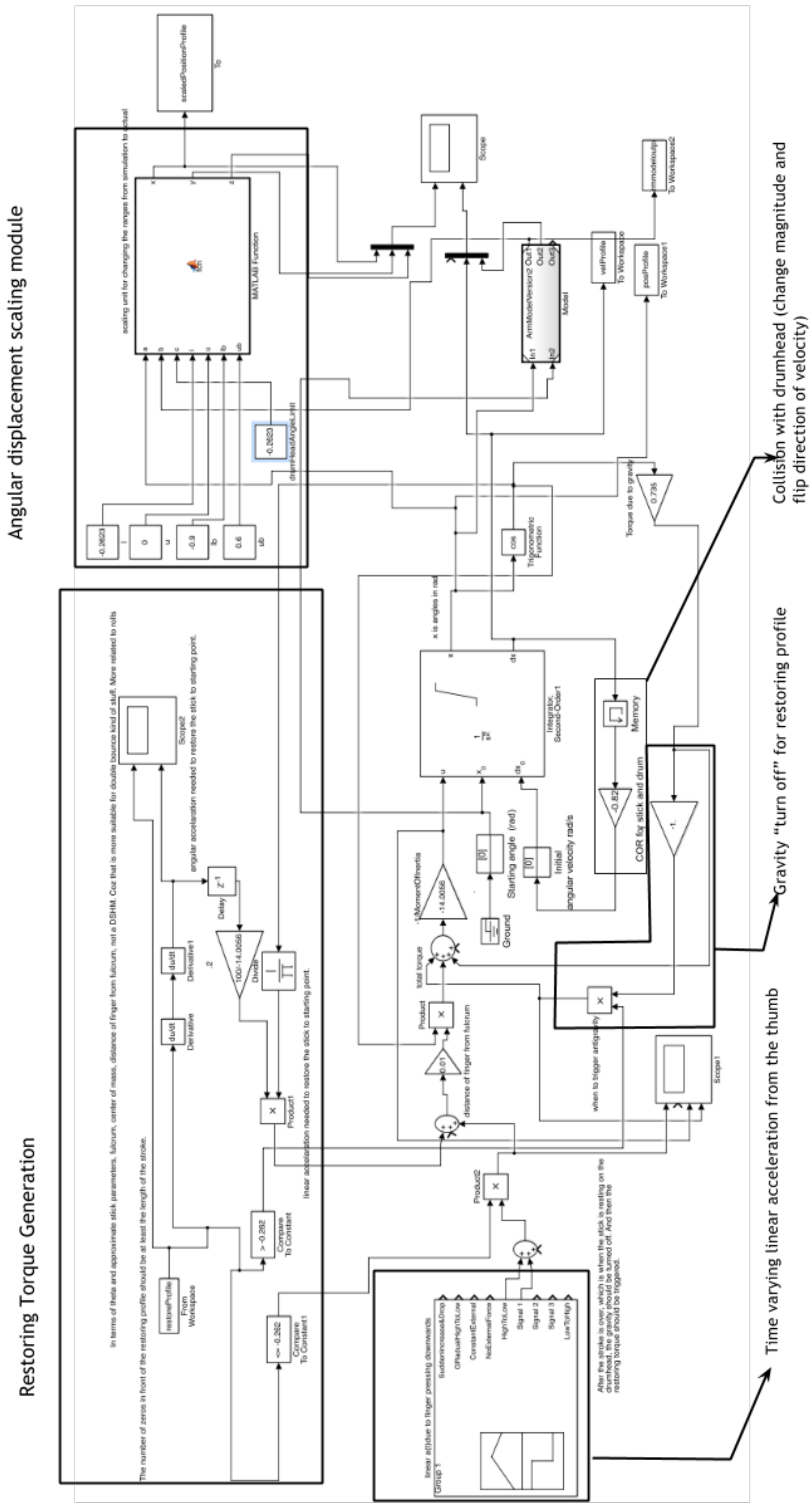


Figure 23: Simulink Model

4.3.5 Results from the simulations

This section presents the results of simulations for different time varying external force profiles from the thumb. 5 main categories are profiles are presented. In each figure, the plot at the top shows the angular position profile over time and the bottom plot shows the external torque from the thumb over time profile. The following conditions are kept constant.

$$\theta_{initial} = 0 \tag{19}$$

$$\theta_{max} = -0.2623\, rad \tag{20}$$

$$\dot{\theta}_{initial} = 0 \tag{21}$$

$$Coefficient\ of\ Restitution = -0.86 \tag{22}$$

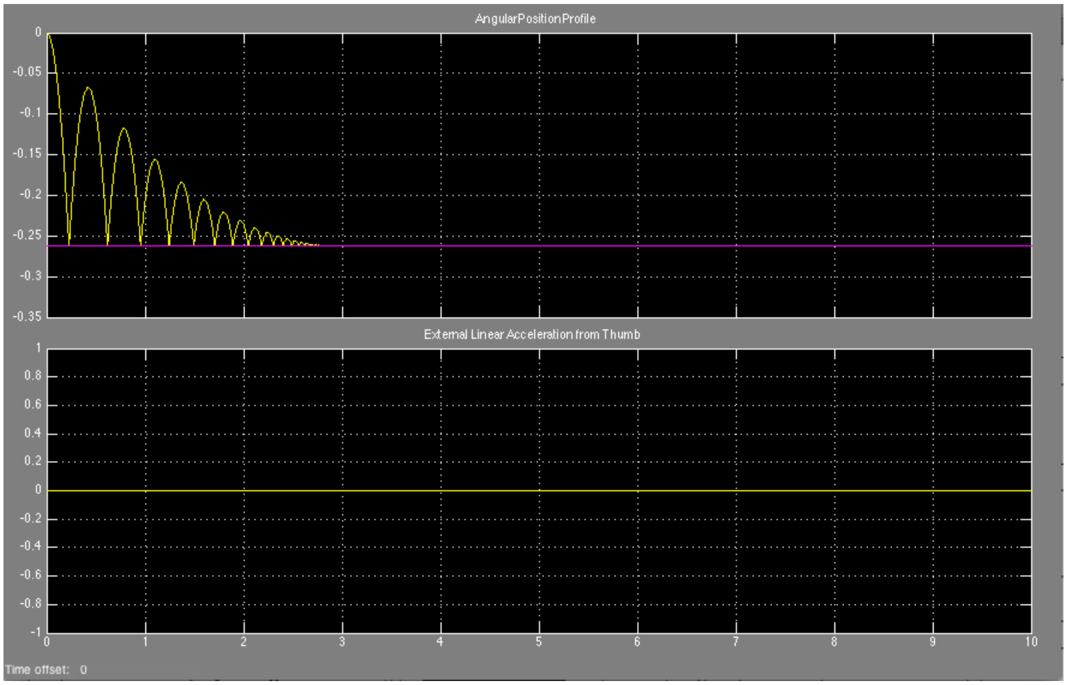


Figure 24: Results of simulation - No external force from thumb - Free bounce

Figure 24 shows the simulation result in the case where the stick is allowed to bounce freely on the drum head. The result is very similar to that of a bouncing ball. In drumming, this can be achieved by balancing the stick at the first joint of the forefinger and then letting it go and having the thumb not to be in contact with the stick at any times. This particular stroke is usually employed in a more improvisational musical context which calls for more rubato playing. By changing the initial angle and the velocity even a free fall stroke can have a large number of variations.

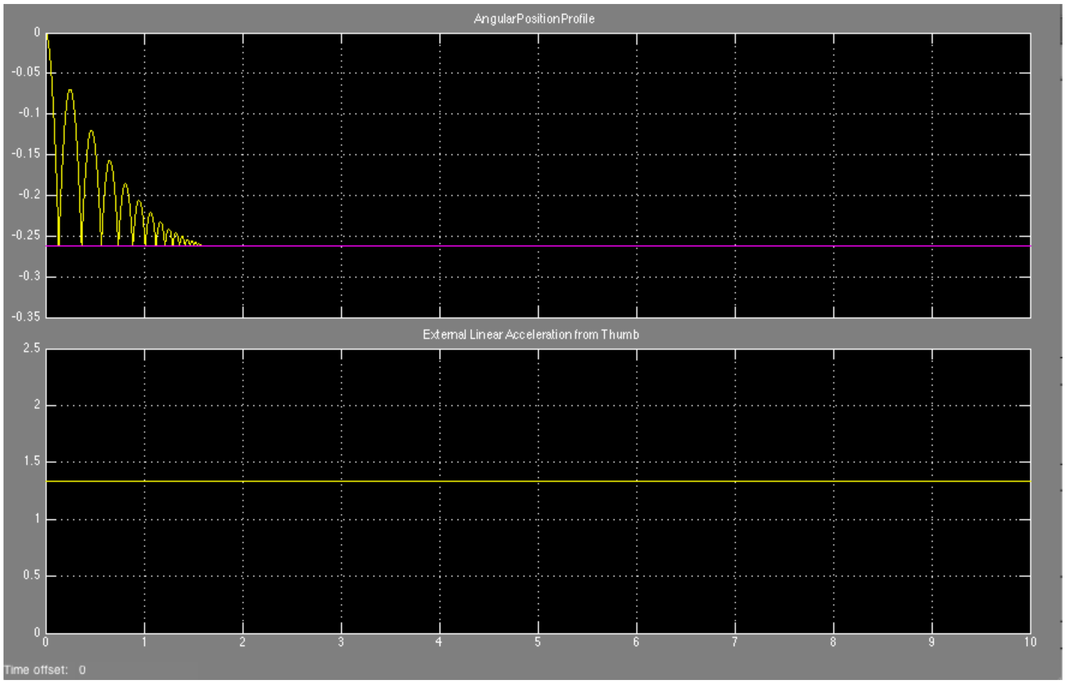


Figure 25: Constant Grip Force

Figure 25 shows the simulation result in the case where the grip force on the stick from the thumb is constant over time and is non-zero. This would roughly correspond to the scenario in which the drummer is trying to modulate the gravitational torque in such a way that the "effective" gravity is more than the $g = 9.8\ m/s^2$. Comparing **Figure 24** and **Figure 25**, it is clear that the total duration of the stroke is drastically reduced in the second case, but the shape of the profile remains the same. This is akin to compression of the position profile in **Figure 24** along the time dimension. This kind of stroke is typically employed by drummers in a jazz accompaniment context, for example, a buzzing effect on the snare drum.

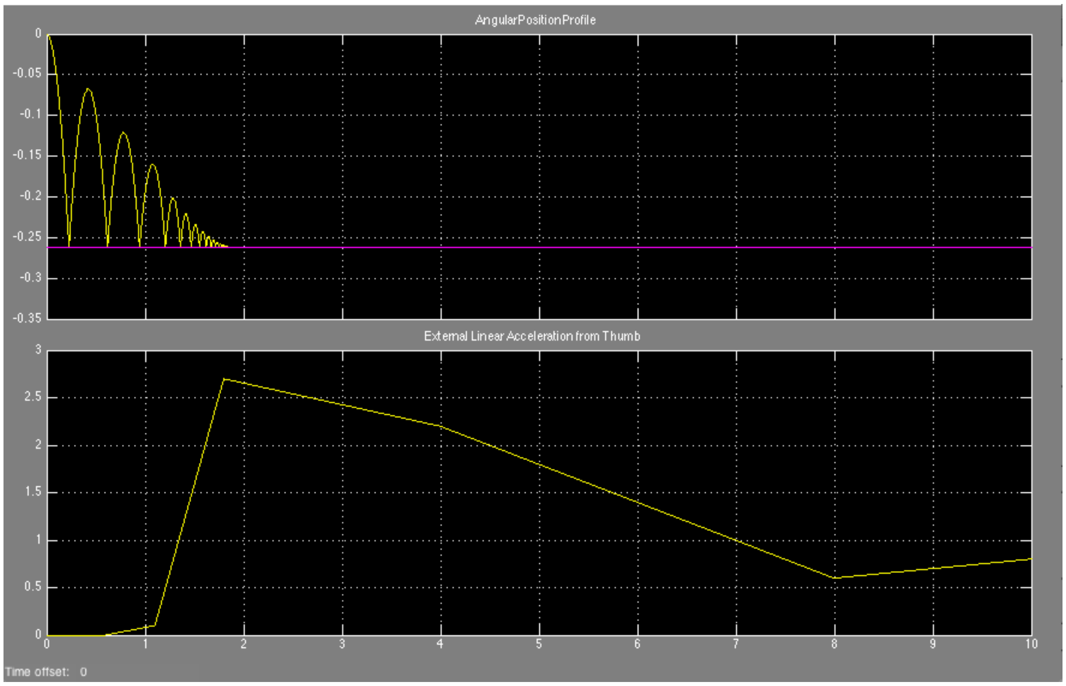


Figure 26: Low grip force to high grip force and back

Figure 26 shows the simulation result in the case where the grip force on the stick starts off as a low value and then increases suddenly and drops back to a smaller value. The effect of increasing the force is to increase the frequency of bounces drastically (between $1.5s$ and $2s$ in the plot). Once the stick comes to rest on the surface of the drum, further changes in the external force do not have any effect on the position of the stick as this would only result in further pressing down the stick into the drum. This kind of stroke can employed in a variety of musical situations ranging from free improvisation, jazz accompaniment and classical snare drum playing.

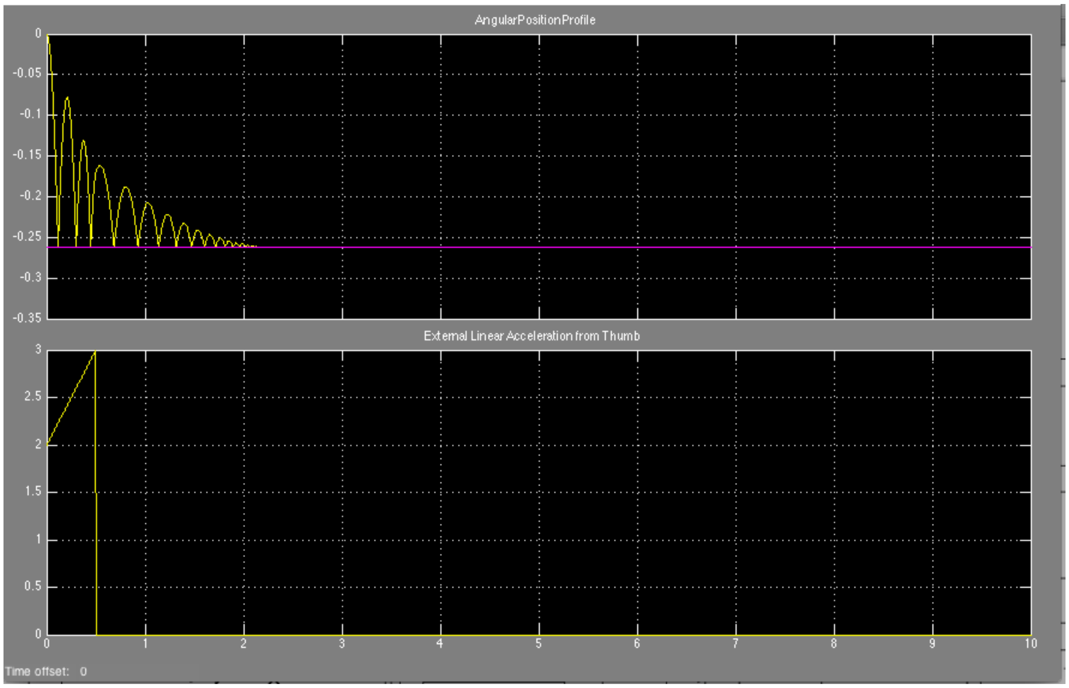


Figure 27: High grip force to low grip force

Figure 27 shows the simulation result in the case where the grip force on the stick starts off at a high value and decreases suddenly to zero. The effect of this profile is that the initial few bounces happen at a very frequency followed by a drop in the rate of bounces, as can be seen in the plot after $0.5s$. Once the external force becomes zero, the only force acting on the stick is gravity and the position profile is same as that of a free fall. This is a slightly unnatural multiple stroke which calls for higher skill level from the drummer, although the effect can be very interesting musically, especially in a rubato/free improvisational context.

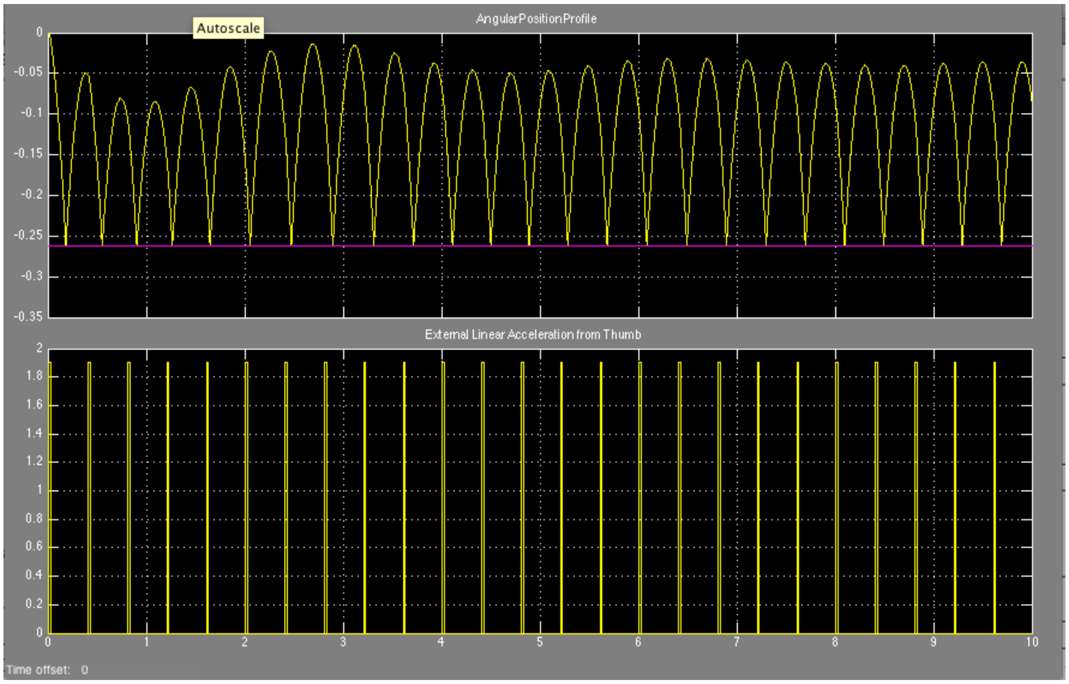


Figure 28: Periodic impulses from the finger sustaining a stroke

The generality of the model is demonstrated in simulation result shown in **Figure 28**. In drumming, fingers are often used to generate fast pulsing actions so that a multiple bounce stroke can be continued and sustained for a longer duration. The constant pulses from the fingers add more energy into the system and compensates for the energy lost due to the inelastic collisions. The phase and amplitude of the pulses becomes very critical and in the case of human drumming, the constant feedback loop (through haptic and aural) helps in providing the pulses at the right time. Typically, this leads to a resonant frequency scenario in which the the long term behavior becomes constant. In **Figure 28**, the impulses from the fingers are approximated by using a square wave with a duty cycle of 5%, period length $= 0.4s$ and amplitude $= 189\ m/s^2$.

More simulations results for various initial conditions and force profiles have been included in the appendix of this thesis. The number of possibilities is huge as any of the parameters can be varied freely to approximate different initial conditions, force profiles and even different drumming surfaces. When these parameters are taken beyond the normal operating range, then non-human like behaviors will begin to emerge and helps in exploring the musical possibilities in robotic drumming.

CHAPTER V

IMPLEMENTATION IN THE ROBOTIC DRUMMING ARM - MUSICAL APPLICATIONS

5.1 Implementation in the RDP

In the present work, the results of the physics simulation described in the previous chapter provide the trajectories for the motor angles for different kinds of strokes. Once these profiles are available, a successful implementation of the these profiles in a robotic arm requires proper controller design. As mentioned in the second chapter, the RDP uses a simple PID controller to do reference trajectory tracking.

For the purposes of this thesis, the simulations are done offline and the output motor angle profiles are stored as text files in the host computer which communicates with the RDP. At runtime, the different profiles stored in the text files are loaded into memory and then accessed as and when needed depending on the composition. The motor angles loaded into the memory are then fed into the PID controller as the reference trajectory.

The success of a PID controller in tracking a given reference trajectory (minimum error between actual trajectory and the reference) depends on how well the controller gains are tuned. Numerous tuning methods are available in control theory literature which optimizes for different kinds of cost functions. *Control Theory Toolbox* in Matlab also comes with various tools which helps in controller gain tuning.

In this thesis, formal methods of tuning the controller gains were not adopted, instead the exact values of the gains were determined manually by trial and error. Since the diversity of simulated strokes is very high, it is obvious that one particular combination of k_p, k_i and k_d values will not guarantee robust reference tracking for all kinds of strokes. This is indeed a compromise and in order to improve the performance of the controller, adaptive PID control techniques need to be adopted [1]. This requires a much deeper understanding of control theory and its applications in actuator control. This is currently beyond the scope of this thesis, but a good direction to take in the future.

Changing each one of the 3 controller gains (k_p, k_i and k_d) has a different (and sometimes even opposing) effect on the reference tracking. A high value of k_p is needed for a relatively quick response, whereas a high value of k_d helps in reducing the overshoot beyond the reference point. Higher values of k_i helps in reducing the steady state error between the actual trajectory and the reference trajectory [26].

5.2 Musical Applications

Various multiple bounce stroke profiles were simulated from the physics model and the results were compiled into a library of stroke profiles to be used in a composition. This kind of compositional framework in which a library of building blocks (drum strokes) is predetermined and stored in memory lends itself perfectly to a note-list based compositional strategy. This is similar to the early computer music written using the *Music-N* languages and *Csound* in which a strict dichotomy between the orchestra (the sounds which will eventually constitute a piece) and the score (the time ordering of the different sounds) is clear and always maintained [4].

A composition written for a single drum utilizing the library of stroke profiles can be thought of as a specification of how the different strokes profiles should be concatenated. Besides the order in which the strokes are strung together to create a piece, the dynamic curve of the strokes over the entire composition is also important for musical expression. The musicality of a piece is also dependent on the form of the piece which determines how cohesive the presented material is. Classical forms such as fugues and sonatas, which heavily rely on the concept of functional harmony have been adopted and customized by composers who write for percussion [2], despite the fact that most of the percussion music is written for non-pitched percussion instruments. The concept of theme and variations in composition is also an extremely effective strategy for percussion writing. In order to create different kinds of variations on a single stroke profile, a few different kinds of transformation functions have also been integrated into the compositional framework and these will be discussed in depth in the subsequent subsection.

5.2.1 Stroke Library and Transformation functions

Currently, the stroke library consists of 17 different stroke profiles. They are (the default duration of each stroke in samples is in parentheses. The sampling rate at which the RDP operates is 1000Hz).

- A stroke profile capturing the motion of the drumstick for a single hit (454).
- A stroke profile which is a sigmoid shaped curve, used for stroke preparation (to connect the end of one stroke and the beginning of the next) (5000)
- Only gravity - 5 in total, for 5 different dynamic levels (pp-f) (5000)
- Low to High - 5 in total, for 5 different dynamic levels (pp-f) (5000)
- High to Low - 5 in total, for 5 different dynamic levels (pp-f) (5000)

This library can easily be expanded by adding the results of more offline simulations and there is no upper limit to the number of strokes the library can have.

The following transformation functions are also integrated into the compositional framework which lets the composer customize the building blocks according to their use in a composition.

- **xStretchFunc(strokeProfile, timeStretchFactor)** - This function takes in a stretch factor specified by the composer and stretches or shrinks the specified stroke profile along the time axis. This is similar to compositional technique of augmentation and diminution, in which the rhythmic values of the notes are altered in a uniform way, either by increasing or decreasing them [34].
- **changeRange(strokeProfile, lowerBound, upperBound)** - This function is useful for controlling the amplitude and therefore the dynamic level of a particular stroke. The output of this function is a scaled and shifted version of the original stroke profile. This is particularly useful for the restoring profile which is used for stroke preparation in which the stick has to move from the end position of one stroke to the start

position of the next in a smooth manner. For all other strokes besides the restoring stroke profile, the lower bound is always the angle at which the stick hits the drum head.

- **reverse(strokeProfile)** - This function is intended to create unnatural stroke profiles from natural stroke profiles. This function is particularly effective if used on multiple bounce strokes. For example, reversal of a naturally decaying multiple bounce stroke, will result in a stroke in which the initial bounces are soft and extremely close to each other and progressively gets more louder and further apart in time and creates an interesting crescendo. This transformation can be thought of as a retrograde of an original motif.

Therefore, in this framework, the complete specification of a single phrase (a single entry in the note list) consists of the following

- The stroke profile to be played,
- The length of the stroke, specified as a time stretch factor,
- The smallest and largest motor angle for the stroke for the changeRange() and
- A flag indicating whether the stroke needs to be reversed or not.

Currently this compositional framework lends itself more suitable to free-form, rubato kind of composition than beat-based compositions.

5.2.2 *Alive* - a solo snare drum piece for a robotic drummer

Utilizing the library of strokes and the above mentioned compositional framework a solo snare drum piece titled *Alive* has been composed for the robotic drummer.

Unlike composing a snare piece to be played by a human drummer, composing for a robotic drummer using this framework poses additional challenges. The composer had to be extremely aware of the drumstick position at all times, as the composition essentially is a specification of the drumstick angle over the entire duration of the composition. Unlike a piece for a human, in this case, the “rests” in the piece also have to be composed and completely specified, without which the stroke preparation will not be precise. This piece was composed also with an intention to showcase all the different stroke profiles available in the library and the use of transformation functions in order to create compelling musical phrases. *Alive* also helps the listener to understand the musical context in which the strokes can be effectively utilized. The audio and video recordings of the piece can be obtained by directly contacting the author.

CHAPTER VI

EVALUATION

The goal of this master's thesis was to develop a human inspired physics based model for drum stroke generation in order to expand the stroke palette for a robotic drummer. The hope is that, this approach will lay the foundation for a robotic drummer to achieve musical expression that is similar to a human drummer. In such a system, the most important criterion for determining the success of the model and the implementation are the results of a perceptual listening test performed by human listeners.

In order to evaluate the work done in this thesis, an evaluation study was designed in which the participants of the study were required to distinguish between and rate the similarities between the audio recordings of a human performing a multiple bounce stroke and a robotic drummer performing a similar kind of multiple bounce strokes.

6.1 Evaluation Study Design

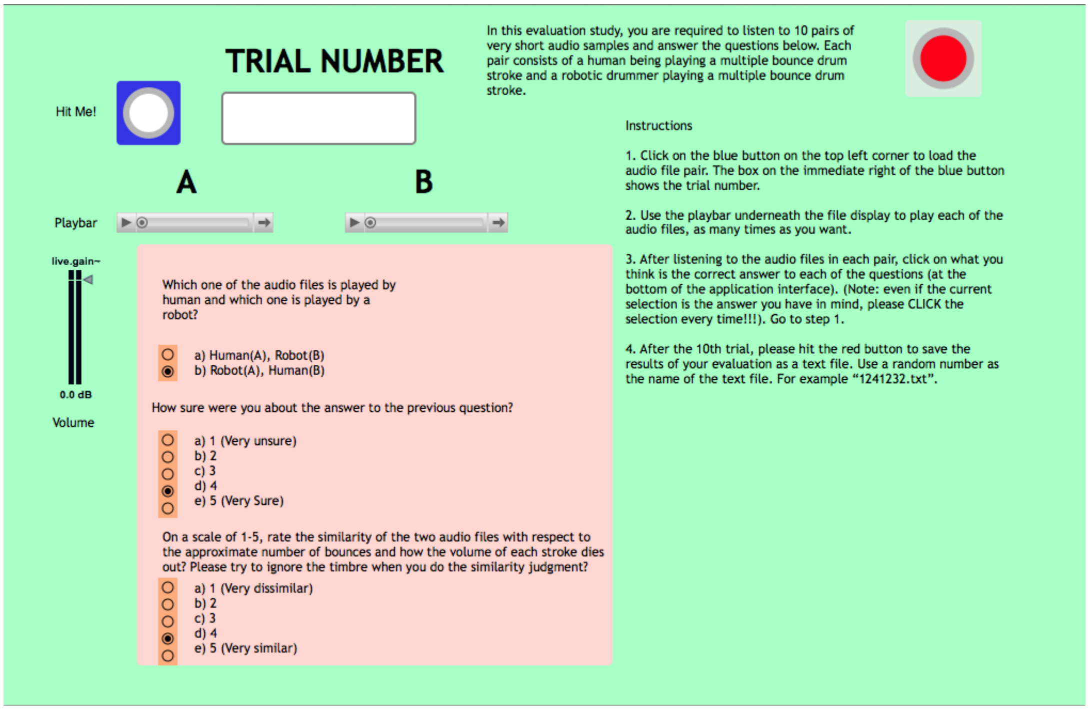
Twenty two subjects (both male and female) were recruited for the study. All subjects have had previous musical experience and have heard a human drummer play drums.

The subjects participated in a short listening test in which he/she listened to 10 pairs of audio files (on headphones) each lasting approximately 2-3s long. Each audio pair consisted of a human drummer playing a multiple bounce stroke on a snare drum (either with the snares on or with the snares off) and a robotic drummer playing a similar type of multiple bounce stroke again on a snare drum, either with the snares on or with the snares off, in a random order. The recordings were made using a *Shure SM57* microphone, on a *Gretsch Catalina Club* snare drum and a standard audio interface. The audio files were recorded at 44100Hz and stored as .wav files. Different areas on the drumhead were used for playing the stroke in order to randomize the timbral quality of the audio recordings. Two different stroke profiles were chosen for the evaluation - Only Gravity, the thumb is not in contact with the stick (6 out of 10) and Low to High, the grip force increases during the duration of the stroke (4 out of 10).

After listening to a pair of audio files, the subjects were required to answer the following three questions.

- Which one of the audio files is played by human and which one is played by a robot?
- On a scale of 1-5, how sure were you about the answer to the previous question?
- On a scale of 1-5, rate the similarity of the two audio files with respect to the approximate number of bounces and how the volume of each stroke dies out? Please try to ignore the timbre when you do the similarity judgment?

Figure 29 shows the application interface for the evaluation study. The application was build using Max/MSP.



In this evaluation study, you are required to listen to 10 pairs of very short audio samples and answer the questions below. Each pair consists of a human being playing a multiple bounce drum stroke and a robotic drummer playing a multiple bounce drum stroke.

Which one of the audio files is played by human and which one is played by a robot?

○ a) Human(A), Robot(B)
● b) Robot(A), Human(B)

How sure were you about the answer to the previous question?

○ a) 1 (Very unsure)
○ b) 2
○ c) 3
● d) 4
○ e) 5 (Very Sure)

On a scale of 1-5, rate the similarity of the two audio files with respect to the approximate number of bounces and how the volume of each stroke dies out? Please try to ignore the timbre when you do the similarity judgment?

○ a) 1 (Very dissimilar)
○ b) 2
○ c) 3
● d) 4
○ e) 5 (Very similar)

Instructions

1. Click on the blue button on the top left corner to load the audio file pair. The box on the immediate right of the blue button shows the trial number.

2. Use the playbar underneath the file display to play each of the audio files, as many times as you want.

3. After listening to the audio files in each pair, click on what you think is the correct answer to each of the questions (at the bottom of the application interface). (Note: even if the current selection is the answer you have in mind, please CLICK the selection every time!!!). Go to step 1.

4. After the 10th trial, please hit the red button to save the results of your evaluation as a text file. Use a random number as the name of the text file. For example "1241232.txt".

Figure 29: Evaluation Survey Interface

6.2 User Study Results

For this data set, arithmetic means and standard deviations were computed for the first and the third question. Statistical significance was tested only for the results of the first question. Scatter plots were generated to test for correlation between the first and second questions and the conclusions are presented in the discussion. This section presents the results from the study.

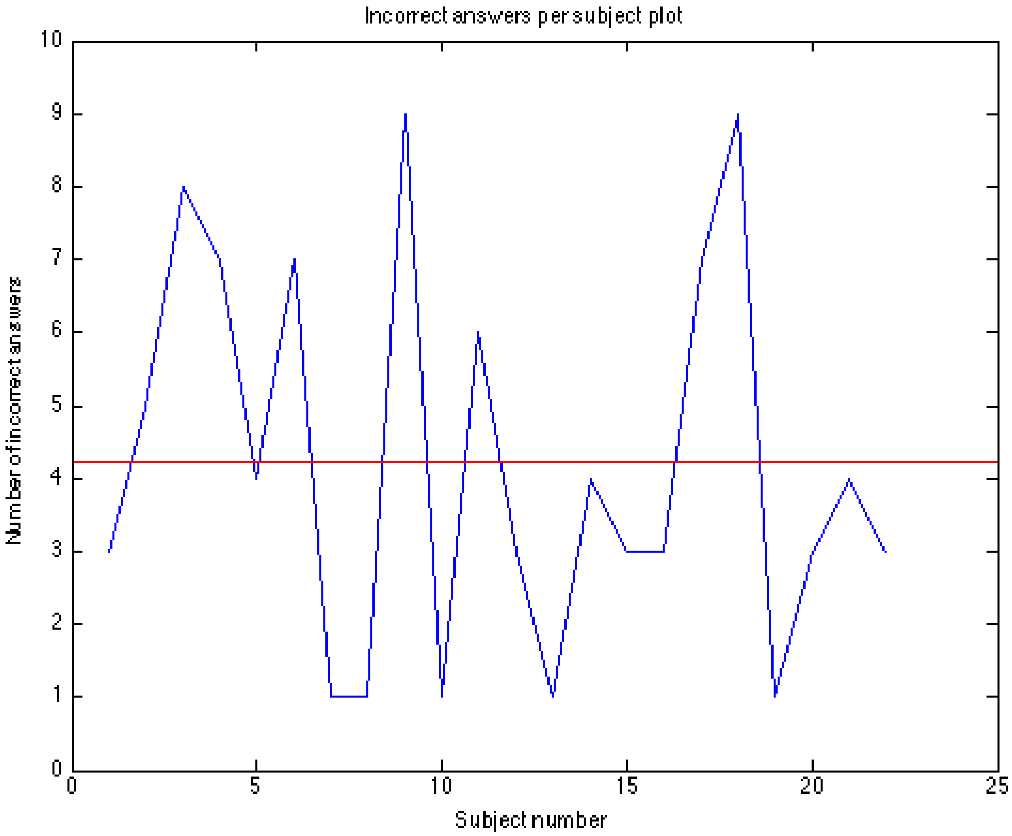


Figure 30: Number of incorrect answers per subject plot

Figure 30 indicates that there is high variability in the number of incorrect answers reported by the subjects. The red line in the plot indicates the mean across all subjects and all audio pairs. The mean is 4.227 and the standard deviation is 2.6535.

If the model was successful in emulating a human drum stroke completely, then the expected value for the number of incorrect answers will be 5 (assuming the total number of audio file pairs is always 10). In order to test the statistical significance of the observed data, Welch's t-test was used to compare the means of two groups. The two groups considered are 1) observed data and 2) a simulation of the experiment in which subjects made a 50-50 choice for each question. For the simulations (number of runs = 50000) the mean number of incorrect answers were approximately 5.0005 and the mean standard deviation was 1.5643

$$t_s = \frac{(\bar{X}_1 - \bar{X}_2)}{s_{\bar{X}_1 - \bar{X}_2}} \tag{23}$$

where $\bar{X}_1$ and $\bar{X}_2$ are the means of the two groups respectively and

$$s_{\bar{X}_1 - \bar{X}_2} = \sqrt{\frac{{s^2}_1}{n_1} + \frac{{s^2}_2}{n_2}} \tag{24}$$

s_1 is the standard deviation of group 1 and s_2 is the standard deviation of group 2 and n_1 and n_2 are the number of samples in each group.

Substituting the means and standard deviations obtained from the data and the simulations in the above equation yielded a t-score of -1.1774. In order to perform statistical testing the degree of freedom is calculated as follows.

$$degrees\ of freedom = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{(s_1^2/n_1)^2/(n_1 - 1) + (s_2^2/n_2)^2/(n_2 - 1)} \tag{25}$$

Using a p-value calculator, for a two tailed hypothesis, the p-value for the above derived t-score and degrees of freedom was computed as 0.2474. With such a high p-value, the null hypothesis cannot be rejected, which implies that the observed data is statistically as good as a 50-50 chance. In the context of the present work, this is ideal, because this implies that when the subject has no clue of which audio file is played by human and which one by the robot, he/she would resort to guessing.

Figure 31 shows the similarity between the robotic arm playing a multiple bounce stroke and a human playing a multiple bounce stroke average over all 10 trials for each subject. The red line indicates the mean across all subjects and is equal to 3.2409 which is equal to 64.81% similarity.

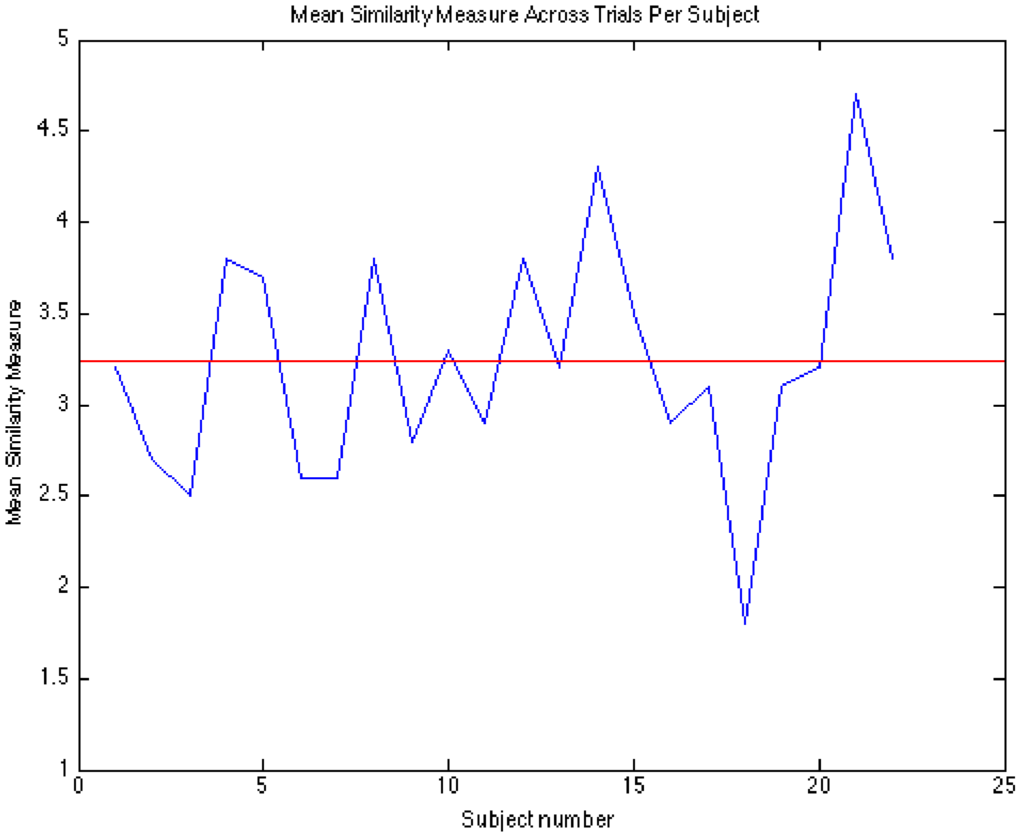


Figure 31: Mean Similarity Measure Across all Trials per Subject

If we consider the mean number of incorrect answers for each group (Only Gravity - Torque Profile and Low to High Torque Profile) separately, the plots looks as in **Figure 32** and **Figure 33**.

The red lines in both the plots indicate the mean number of incorrect answers for the separate cases. The normalized values for the mean number of incorrect answers are 0.4318 (Only Gravity) and 0.4091 (Low to High). This means that subjects made more errors when the stroke profile was only due to gravity. This is intuitive because, in the case of a Low to High profile, the torque profile used in the simulation can never be exactly replicated by the human and therefore will introduce variations. And these variations would be clearly audible to many listeners that they will be able to make a clear distinction between a human and a robot.

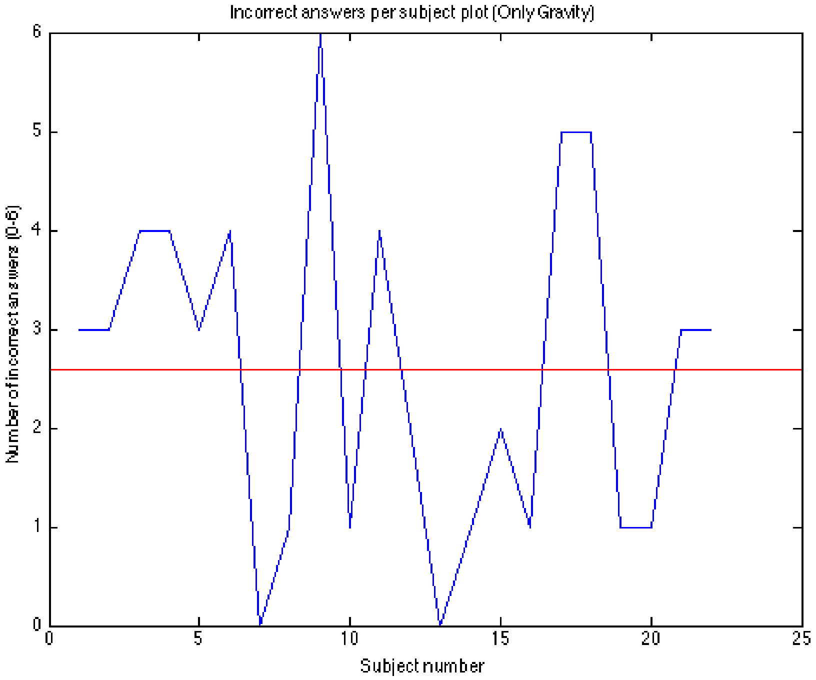


Figure 32: Number of incorrect answers per subject plot (Only Gravity) - 6 samples each

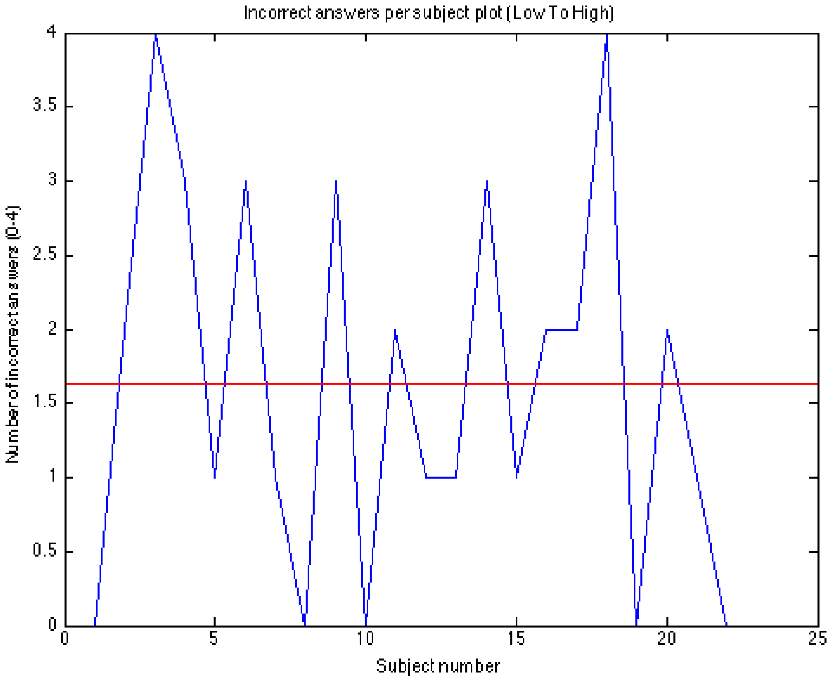


Figure 33: Number of incorrect answers per subject plot (Low To High) - 4 samples each

6.3 Discussion

The statistical analysis of the results indicates that the generative physics model and its implementation in the RDP has had considerable success because statistically the experiment results are equivalent to the subjects trying to randomly guess whether an audio file was played by a human or a robot. The model is able to closely capture the nuances of a human playing a multiple bounce drum stroke fairly successfully that the listener is often getting confused. 64% average similarity measure between the two audio files in a pair also indicates that there has been some success in capturing the approximate number of bounces and volume decay profile. No correlations were found between the number of incorrect answers and how sure were the subjects when they answered the first question. This is probably because, the subjects might have felt very confident about the judging criterion they had employed, despite the fact that it gave incorrect answers. Similarly, no correlations were found between the similarity ratings and the number of incorrect answers. Although, it was explicitly mentioned in the third question to ignore the timbral differences between the audio files, this is extremely hard as the human auditory system is very sensitive to timbral changes. Even though the number of bounces and the volume decay envelope are very similar to that of a human stroke, the timbral differences can be fairly prominent and can influence the similarity judgment in a strong way.

CHAPTER VII

FUTURE WORK

The work done as a part of this thesis is an important first step towards improving the musical expressivity and stroke generation capabilities of a robotic drummer. However numerous improvements can be done to the current system, to make it more robust and adaptable to various scenarios. This chapter describes a few such possible future directions to improve upon the current work.

7.1 Controller Design

In a typical PID controller system, the reference trajectory is not time varying, and therefore once the controller gains are tuned, optimal performance is guaranteed. In the RDP, the reference trajectory (the stroke profile) itself is time varying. In some of the stroke profiles, the changes in the trajectory are at a high rate (for example, the tail end of a multiple bounce stroke, where a large number of bounces occur at a small amplitude in a relatively short time), whereas in other situations the rate can be low (the beginning part of a multiple bounce stroke, where the onsets are widely spaced). In order to have optimal tracking of a reference trajectory which has a high bandwidth, it is clear that a single combination of PID controller gains is not and adaptive PID control methods need to be adopted so that the control gains are automatically adjusted depending on the system requirements.

In the current system, the controller gains are tuned manually beforehand and do not change during the operation of the RDP. All the different strokes are performed with the same controller gain settings and therefore invariably some of the strokes are played much better than the others. A crude way of accomplishing an ad hoc adaptive pid controller is by trial and error in which every single stroke is played individually and the controller gains are tuned in such a way that the performance is optimal for that stroke. The optimal controller gains for each stroke can then be stored in memory along with the stroke profiles themselves and can be used to modulate the gains during run time.

7.2 Introducing Wearability

The uniqueness of the robotic platform used in this thesis is the fact it is a *wearable* drumming device. In a wearable scenario, in which the user has control over the position of the device, the fixed geometry between the actuator (pivot position of stick) and the drumhead is no longer available. The distance between the pivot point and the drumhead is no longer constant and for successful integration of the model described in this work, real time tracking of this distance will be required, so that the right amount of offset can be applied to the stroke profiles. This would mean incorporating accurate distance sensing mechanisms using infra-red or ultrasonic technologies. The data collected from the sensors will also have to be time synced properly with the execution of the profiles.

7.3 Estimating model parameters

For more accurate modeling of multiple bounce strokes, better estimation of model parameters becomes necessary. The stroke profiles currently in the library were simulated using parameters derived from a particular stick and a drumhead model. Different sticks and different drums have different physical parameters and will result in drastically different simulation outputs for the same initial angular velocity, initial angular position and time varying torque profile from the thumb. For example, a snare drum is a higher pitched drum than a floor tom and the drumhead is much more tighter in the former compared to the latter. Therefore, a multiple bounce stroke decays much slower when played on a snare drum compared to a floor tom. This also becomes important in the wearable scenario where the user not only has the control over the position of the robotic device above a single drum, but also can determine which drum to play. By keeping track of the drum on which the user intents to play the drum stroke, the model parameters can be adjusted accordingly for natural results.

7.4 Real time capabilities

In order to incorporate real time stroke simulation capabilities the current Simulink model needs to be converted into a real time target. A typical scenario would be one in which force sensitive resistors (or foot pedals or eMG sensors) are used as input devices to control the time varying torque profile and the model will produce the stroke profile output in real time. When used as a wearable device, this kind of control interface provides the most natural and intuitive way to control the bounce behavior.

7.5 Incorporating concept of bars and beats in the compositional framework

As mentioned before, the current compositional framework renders itself perfectly to a note list based compositional strategy wherein the timings (the start point and end point of a phrase) are completely determined by the composer usually in seconds. This is not the normal way of thinking about musical time. The concept of metrical time (with beats, measures and time signatures) which serves as a grid on which note events happen is the more common notion found in music. This would make the compositional process drastically easier. The note list compositional strategy is well suited for more free form/rubato kind of compositions as opposed to beat based music. Integrating this capability into the compositional framework will be a very useful direction in improving the usability of the model.

APPENDIX A

MORE SIMULATION RESULTS

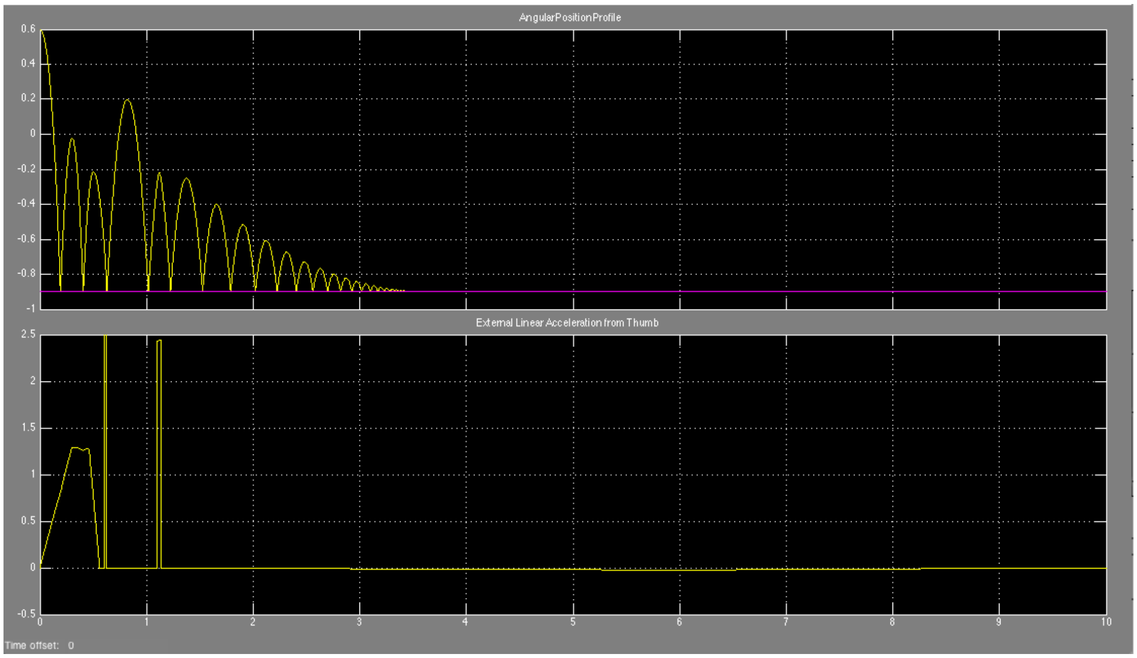


Figure 34: Position vs. time profile. The second graph shows the torque profile. COR = -0.88. $k^{'} = 1.3$ cm

The three simulations results presented in this appendix are a result of unusual torque profiles provided by the thumb. This kind of torque is extremely hard for a human being to provide to the drumstick as it involves a great deal of sudden changes in the gripping force. For the sake of simulation any kind of torque profiles can be chose and herein lies the power of robotic drumming. By choosing unusual torque profiles, unusual stroke profiles can be generated which will make the robotic arm play music that a human being possibly might not be able to.

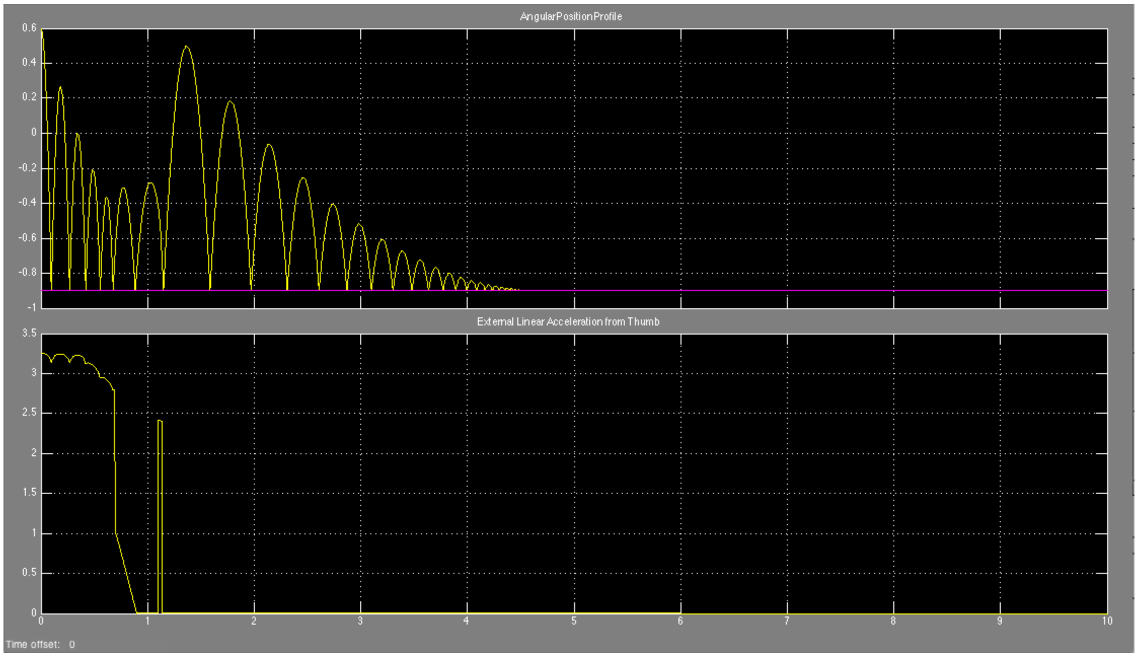


Figure 35: Position vs. time profile. The second graph shows the torque profile

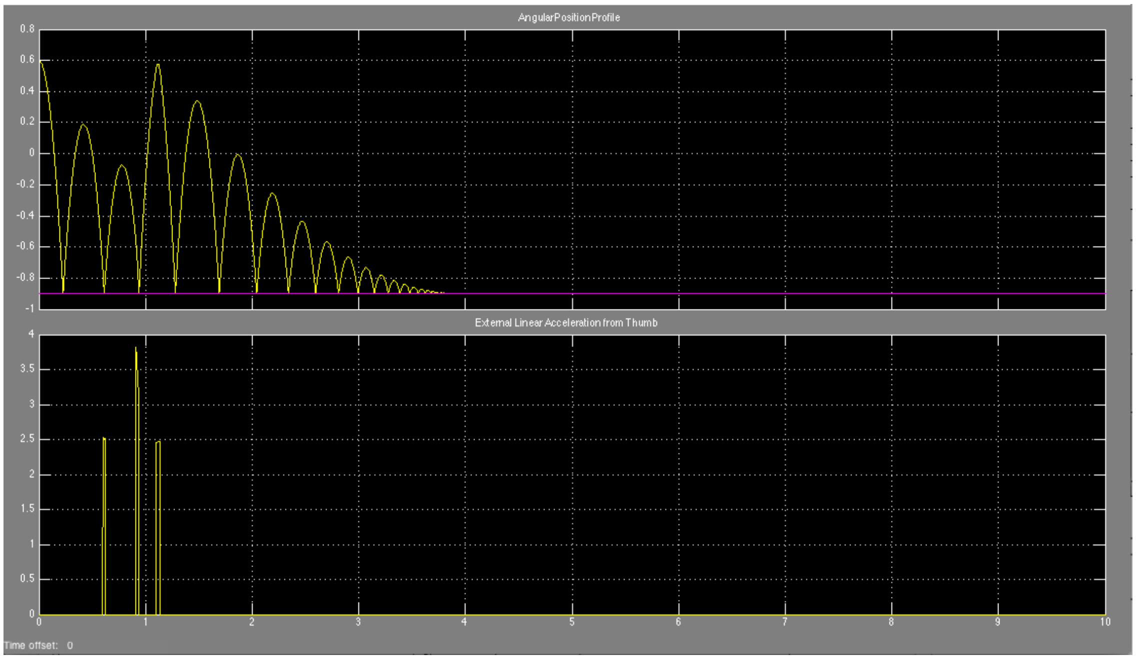


Figure 36: Position vs. time profile. The second graph shows the torque profile

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