DEDAN KIMATHI UNIVERSITY OF TECHNOLOGY

TWO WHEELED ROBOT STABILIZATION USING LMI CONTROL

Anthony Njiri Kung'u

E222-01-2704/2020

A Research proposal is submitted in partial fulfillment of the degree of Masters of Science in Advanced Manufacturing and Automation Engineering at the Dedan Kimathi University of Technology

AUGUST, 2022

Declaration

This research proposal is my original work and has not been presented in any university/ institution for a degree or consideration of any certification.

Signature……………………………………….. Date:…………………….

Anthony Njiri Kung'u

E222-01-2704/2020

Supervisors' Declaration Caption:

This research proposal has been submitted for examination with our approval as University Supervisors.

Signature……………………………………….. Date:……………………….

Dr. Paul Waweru, PhD

School of Engineering

Dedan Kimathi University of Technology

Signature………………………………………… Date:……………………….

Dr Titus Mulembo, PhD

School of Engineering

Dedan Kimathi University of Technology

Dedication

This research is dedicated to my parents. My father, the late John Kung'u and my mother Mary Kung'u, they did not only raise and nurture me, but also taxed themselves dearly over the years for my education and intellectual development. My brother Peter, and sisters Monicah and Rachael, for their unwavering support and my source of inspiration.

I also dedicate this research proposal to my friends who have supported me throughout the process. I will always appreciate their support.

Acknowledgement

I wish to express gratitude to Jesus Christ, our Lord and Savior, for giving the wisdom, strength and support in exploring things to make this study possible.

My deepest gratitude goes to my supervisors Dr. Paul Waweru and Dr. Titus Mulembo who have guided me very well through the development of this research proposal.

Lastly, I would like to thank the management of Dedan Kimathi University of Technology for awarding me the scholarship to pursue a Masters degree in Advanced Manufacturing and Automation Engineering. The program has helped me gain more knowledge and skills in the field of manufacturing and automation.

Table of Contents

List of figures

List of abbreviations

LMI – Linear Matrix Inequality

PID – Proportional Integral Derivative

TWR – Two Wheeled Robot

CAD – Computer Aided Design

Abstract

A future form of movement for common robots may come from research on two-wheeled balancing robots. It differs from more conventional forms of robotics because of the special stability control that is necessary to keep the robot upright. It is extremely flexible and nimble but also unstable because it just has two wheels. The safety features of the two-wheeled robot configuration have become increasingly significant as the number of commercial goods based on it grows. The study of two-wheeled robots has grown in recent years.

A stabilizing control system that maintains the robot's equilibrium at all times must be developed in order to operate a two-wheeled robot safely. The TWR must also be capable of handling various weight and balancing configurations since it is designed to carry a variety of payloads.

In this project, a control scheme for stabilizing a two-wheeled robot near to the equilibrium point is described. Additionally, stabilized motion control is integrated into the system to allow the two-wheeled robot to move and rotate without becoming unsteady. A non-minimum phase load is also implemented on the TWR to challenge its stability while standing and during motion. The proper sensing hardware has been selected to be implemented on the system in order to calculate the tilt angle of the robot. The foundation for controlling the two-wheel robot has been proposed as a linear matrix controller solution for stabilization. A set of parameters will be used to compare this controller to a PID controller. To demonstrate its validity, simulations and experiments will be conducted to achieve stability of the two wheeled robot under a non-minimum phase load.

CHAPTER ONE: INTRODUCTION

1.1 Background to the study

The performance of a two-wheeled self-balancing robot is greatly influenced by the signal processing and control strategy used because it is a multi-variable and uncertain nonlinear system. Control algorithm research has been more prevalent in recent years (Minh et al., 2010).

Robots that can balance themselves are a common example of a nonlinear, unstable system. The most traditional example is a two-wheeled self-balancing robot, and its most well-known commercial variant is the Segway. The response wheel unicycle and, more recently, the unicycle stabilized by gyroscope precession are other instances of self-balancing robots (Lima, et al., 2019).

The idea of an inverted pendulum serves as the foundation for the two-wheeled robot. One of the most well-known nonlinear dynamical systems is the inverted-pendulum system on a cart, which attracts a lot of attention from academics working in the fields of robotics and control systems. The inverted-pendulum stabilization techniques are directly responsible for many trends in robotic technology and control.

Inverted-pendulum, however, is a crucial reference point in robotics because, among other things, it is an underdamped and underactuated system with many commonalities to the underactuated robotic systems that are typically controlled by less independent actuators than the degrees of freedom (Papadopoulos & Alexandridis, 2016).

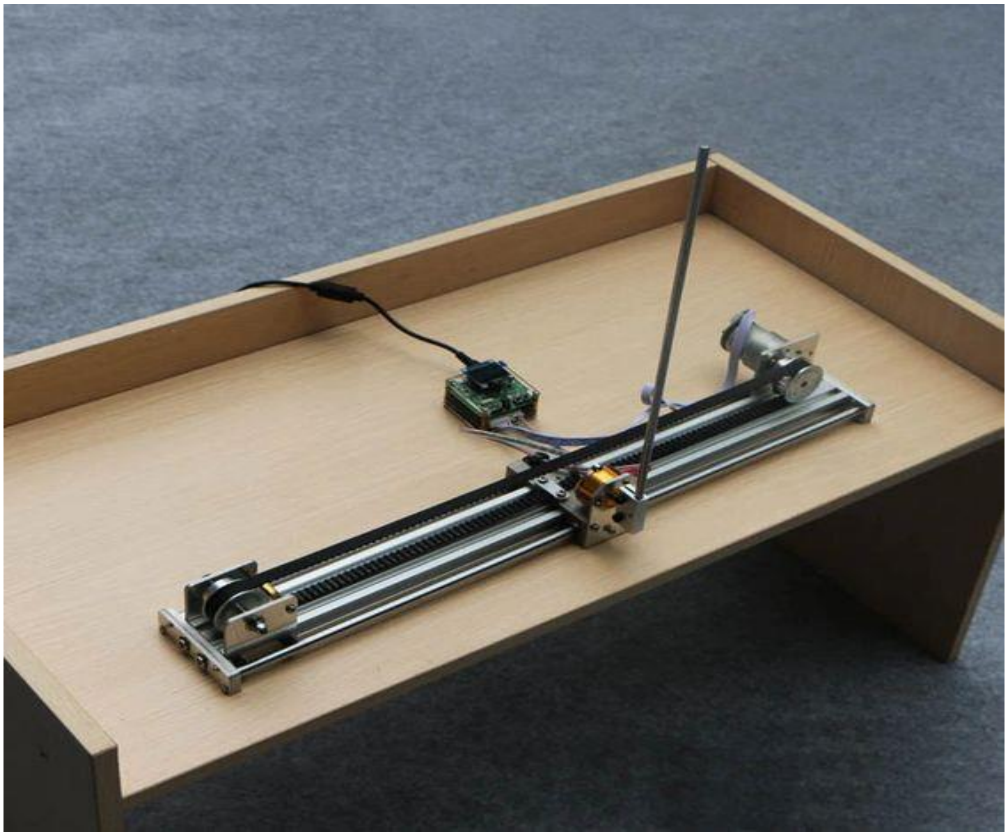

Figure 1: Inverted pendulum (Papadopoulos & Alexandridis, 2016)

Additionally, two-wheeled self-balancing robot has several benefits for an autonomous mobile, including small size, a straightforward structure, and freedom of action, making it appropriate for some occupations requiring a confined workspace or dangerous activity. In general, two-wheeled self-balancing robot is a tool in both the civilian and military sectors and an excellent platform for testing different control algorithms (Sun & Gan, 2010).

The mathematical model of the controlled system is developed based on the mechanical properties of the two-wheeled self-balancing robot. Analyzing the robot's kinematic and dynamic properties yields the theoretical foundation needed to construct the control system (Gong et al., 2015).

The purpose of a control system is to manage, command, direct, or otherwise control the behavior of other devices or systems. Only two groups of control systems have become increasingly popular among scholars over time. Linear and non-linear control are the two subtypes of these sorts of control.

To keep the controlled process within a reasonable operating range, linear control systems employ linear negative feedback to mathematically generate a control signal depending on other variables. The system's intact dynamics model is used by non-linear controllers while creating their controller designs. Comparatively to non-linear control systems, linear control systems are often the most widely used (Ghani et al., 2010).

1.2 Problem Statement

The model for a two-wheeled, self-balancing robot includes considerable uncertainties because of its complex, non-linear structure. If the system is controlled using the conventional methods, these uncertainties result in an inaccurate solution. The PID control system has been widely used by the control systems community for the longest however being a more conventional method. In the world of control engineering, the PID has shown to be well-liked. “For more than 60 years after their inception, proportional-integral-derivative controllers have remained the workhorse of industrial process control”, according to the article's author, Vance J. Van Doren (Maniha et al., 2011).

However, the convectional controllers have issues in robot stabilization when tested for accuracy. Congying Qiu and Yibin Huang during their research on PID controller system found out that the controller suffered from crucial flaws in controlling of two-wheeled self-balancing robot, such as long settling time and large overshoot. These are important factors to be considered when stabilizing of a robot is involved. The two-wheel robot needs to quickly settle after an external disturbance to avoid toppling from swaying too much (Qiu, 2015).

Linear Matrix Inequality controller (LMI) is regarded as a unique technique for creating nonlinear control systems. It enables the creation of a Lyapunov stable controller as well as the consideration of a performance metric, like minimizing the H1 and/or H2 norm. The ability to create non-linear controllers against parametric uncertainty is another intriguing feature (Lima et al.,).

Flavio H. B. Lima et al, during their ball balancing robot with omni wheels using LMI found out that the controller provided accurate control and stabilization amid uncertainties. The controller was also proven to be excellent at smoothening vibrations experienced during control of a magnetically levitated rotor by Wang et al. To this purpose, LMI control approach will be used to provide accurate stabilization and control of a TWR which will be subjected to external disturbances to ascertain proper stability. This controller will be tested against the PID to ascertain its validity in the stabilization of our robot. Simulations and experimentation will be carried out to demonstrate the proposed solution.

1.3 General Objective

Develop a Linear Matrix Inequality controller for a two wheeled robot bearing a non-minimum phase load and its validity in two wheeled robot stabilization and control.

1.3.1 Specific Objectives

- Design the two wheeled robot mechanical structure in a CAD software
- Model and design the controllers
- Perform experiments on the two wheeled robot based on performance indexes
- Validate the control method using experimental data

1.4 Research Questions

The main questions we will try to answer in this research are;

- Is it possible to control the disturbance created by the non-minimum phase load accurately when the robot is upright and also in motion?
- Is it possible to acquire data while stabilizing the robot?

1.5 Significance of the study

Two wheeled mobile robots are a focus of extensive research into how to implement them so that they can reflect the extremely flexible adaptability in the dynamic change of complex unknown situations, in addition to adapting to specific conditions and mission needs. This is dependent on having a suitable controller that can accurately provide stabilization for two wheeled robots during maneuvering and upright standing while transporting objects.

1.6 Scope/Delimitation

This research will involve control and stabilization of a two wheeled robot under a non-minimum phase load using a Linear Matrix Inequality control approach. It will involve designing the structure of the two wheeled robot using a CAD software. Additionally, the LMI and PID controllers will be modelled to develop mathematical equivalents. Thereafter, simulations will be conducted under performance parameters to compare the behaviors of the controllers. Following will be experimentation and validation of the LMI controller for the stabilization of the two wheeled robot.

1.7 Assumptions

The following assumptions will be made in the process of this research study:

- It is assumed that the two wheeled robot is not prone to actuator vibrations.
- It is assumed that the hardware (sensors) of the two wheeled robot are working perfectly and that they provide accurate information.
- Additional assumptions may be made in the resolution of collected data.

1.8 Operational Definition of Terms

- **Linear Matrix Inequality (LMI)** – Type of a non-linear controller used to solve control problems by use of matrices.
- **Proportional Integral Derivative (PID) controller** - This is a control loop mechanism employing feedback that is widely used in industrial control systems and a variety of other applications.
- **Two wheeled robot** – This is a mobile robot constructed with just two wheels.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter aims to lay out the fundamental theory and provide a critical evaluation of the relevant literature in order to advance the research. Additionally, it aims to summarize the key points and writings of various specialists on the topic of two-wheeled robots and control techniques. Additionally, this literature survey's discussions highlight the research deficit.

2.2 Two wheeled robots

One of the scientific topics that is now expanding the quickest is mobile robots. Mobile robots are capable of replacing humans in several professions. Numerous other industrial and nonindustrial applications exist as well, such as those for surveillance, planetary exploration, patrolling, emergency rescue operations, reconnaissance, petrochemical applications, industrial automation, construction, entertainment, museum guides, personal services, intervention in harsh environments, transportation, healthcare, and so forth. The majority of these are already on the market (Rubio et al., 2019).

The concept of balancing robot model has been widely used by researches around the world in controlling a system not only in designing wheeled robot but other types of robots as well such as legged robots. One of the first to patent a gyroscopic stabilizing vehicle was an Irish- Australian inventor named Louis Brennan. Brennan invented a gyroscopically balanced monorail system for use in the military in 1903; he successfully tested the device in 1909 (Highfield, 2010)

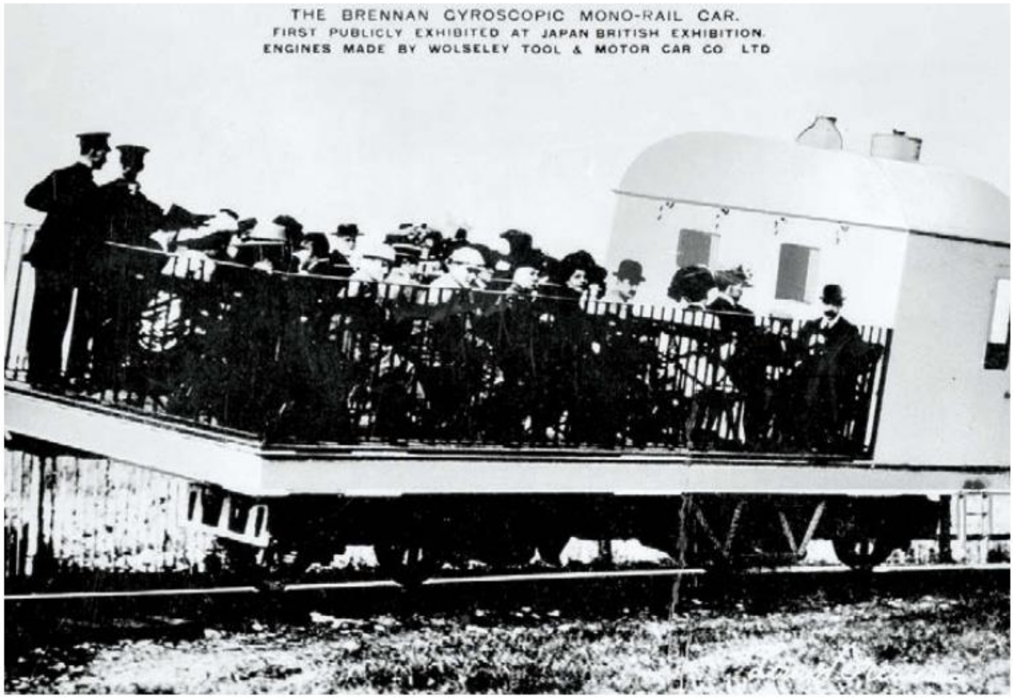

Figure 2: Brennan gyroscopic monorail circa 1909 (Highfield, 2010)

Since then, rapid improvements of technology in the years after led to researchers and inventors developing different configurations of two wheeled robots for research and commercial use. This was as a necessity as human interest grew in the field of control and robotics for autonomous systems.

Advantages of two wheeled robots

Robots with two wheels have a lot of benefits over other mobile robots. Two-wheeled robots are still much easier to handle than legged robots, but being more difficult to manage than statically stable wheeled robots. They can turn on the spot thanks to their wheel layout, which makes them very maneuverable and similar to differential drive robots.

Two-wheeled robots are non-holonomic, however this is only a minor drawback given that they can quickly pivot (Ping et al., 2013). Robots with two wheels can be taller and have a smaller overall footprint, which makes them well-suited for indoor settings because they can squeeze through tight spaces like hallways and corners. Two-wheeled robots are able to retain stability on incline by leaning into the hill since they can lean fore and aft to re-stabilize themselves. Similarly, two-wheeled robots can move swiftly without toppling over, even when they have a lofty profile. With only two wheels, there is greater room for larger wheels, which would enable them to travel over more difficult terrain (Ping et al., 2013).

2.3 Previous works

Segway, nBot, Bender, Emiew, and Emiew 2 are examples of two-wheeled balancing robots that have been developed previously. The improved (evolved) Emiew is now known as the Emiew 2. While the Segway was devised and developed by Dean Kamen, who eventually founded Segway Inc., they were both designed and produced by Hitachi (Anderson, 2007).

The remaining robots that were examined were made by robotics enthusiasts who over time enhanced the durability of their designs. These robots share a lot of the same design principles. Each typically makes use of a gyroscope to gauge tilt, shaft encoders to gauge distance, and a microcontroller to handle calculations.

Together, these elements form the foundation for sustaining stability. To counteract the effects of gyroscope drift and provide a more precise input signal for the control system, inclinometers or accelerometers are occasionally incorporated (Shanmugavel, 2018).

The commercially available two-wheeled robot Segway (Segway 2009) is currently in its second generation of models that have been released. With the image shown in the following figure, it is offered to the entire world as a transport option. The robot is marketed as being perfect for adventure, commuting, police enforcement, and general transportation.

Figure 3: A Segway (Segway Inc, 2009)

"Excellent Mobility and Interactive Existence as Workmate" is what EMIEW (Kageyama 2007) stands for. Released in March 2005, it was the first two-wheeled robot made by Hitachi. It weighed more than 70 kg and stood 1.3 meters tall. Emiew 2 was born in November 2007 and is roughly half as big as Emiew, weighing in around 13 kg and 0.8 m. By combining weight and height reductions, it was intended to lessen the safety issues brought on by Emiew's bigger size (Hitachi, 2005).

Figure 4: Emiew 2 by Hitachi (Hitachi, 2005)

In the year 2003, David P. Anderson, developed the nbot a revolutionary small two wheeled robot. On May 19, 2003, this robot was highlighted as NASA's Cool Robot of the Week. The NASA page was subsequently recognized as one of the best 10 engineering and technical web sites for 2003 by Scientific American's online publication, SCI/Tech Web Awards, which included a written reference to nBot. This robot uses a commercially available inertial sensor and position information from motor encoder to balance the system (Anderson, 2003).

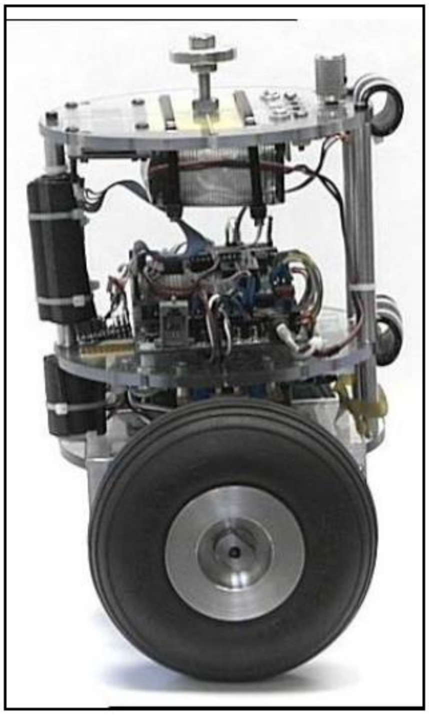

Figure 5: nBot (Anderson, 2003)

2.3 Control strategies

Most experimental data for applications involving two wheels come from linear controllers. PID and other linear controls have the benefit of being simple to implement. As the system is viewed as a black box, it is simple to estimate the PID gain values since all that is needed is the tracking error of the system. A PID controller, however, does presume that the system being controlled is linear. A two-wheeled robot is linear in the area near the equilibrium point despite typically being non-linear. A PID controller can stabilize the two-wheeled robot if it works in this linear zone (den Brandt, 2021).

A PID controller is insufficient to regulate the system outside of the linear range. The emergence of linear matrix controllers as possible options in this field has inspired new non-linear control system methodologies. Numerous researchers have hypothesized that intelligent control approaches, as well as some hybrid control approaches, will enhance the robustness and control stability of two-wheeled robots (Khalil Sayidmarie, 2016).

Linear matrix inequalities

It has been more than a century since LMIs were first used to analyze dynamical systems. About 1890 saw the publication of Lyapunov's major paper, which introduced what is now known as Lyapunov theory, and that is when the story really starts. He showed that the differential equation, $\frac{dy}{dt}x(t) = Ax(t)$ is stable f and only if there exists a positive definite matrix P such that, $A^T P + PA < 0$. The requirement $P > 0$, $A^T P + P A < 0$ is what we now call a Lyapunov inequality on P, which is a special form of an LMI. Lyapunov also showed that this first LMI could be explicitly solved (Herrmann et al., 2007).

An effective method for resolving linear and convex quadratic programming models is the Linear Matrix Inequalities (LMIs). Few common convex or quasi-convex optimization issues utilizing LMIs can be used to solve a wide range of optimization problems in identification, signal processing, identification and system and control theories. Many problems that lack analytical solutions can be resolved by using LMIs (Masehian & Habibi, 2007).

LMIs have been used in the case of self-balancing robots. (Lima, et al., 2019) in the research of a ball balancing robot with omni wheels used LMI approach to control and stabilize the robot. The method proved effective in mitigating uncertainties and was able to keep the angular positions of the body within range within -5◦ and +5◦, which represents a variation almost imperceptible by eye. This ensured the robot was accurately stabilized.

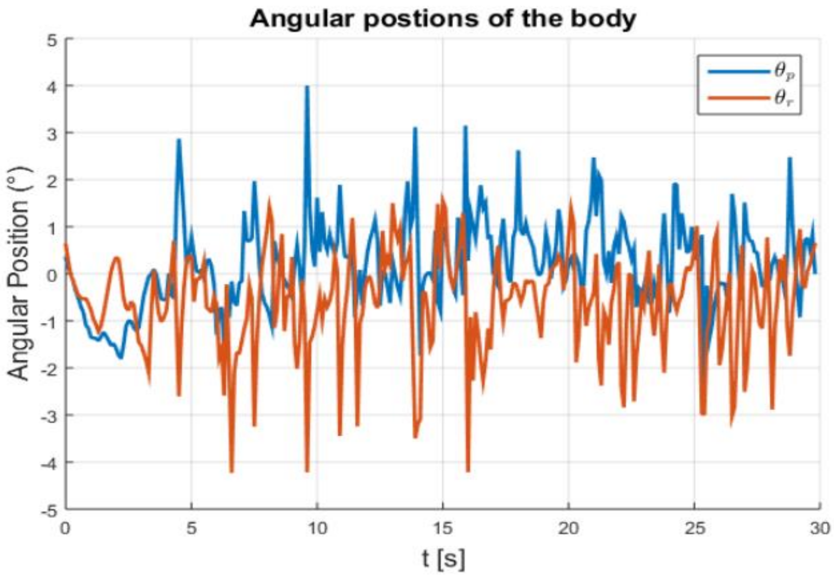

Figure 6: Angular positions of the body under LMI control (Lima, et al., 2019)

(Wang et al., 2017) used LMI approach during their research on the free operation of a magnetically levitated rotor. They introduced LMI to help mitigate drawbacks encountered by PID and the results were astounding. Rotor displacement was greatly mitigated when LMI was introduced into the system as shown in the figure below.

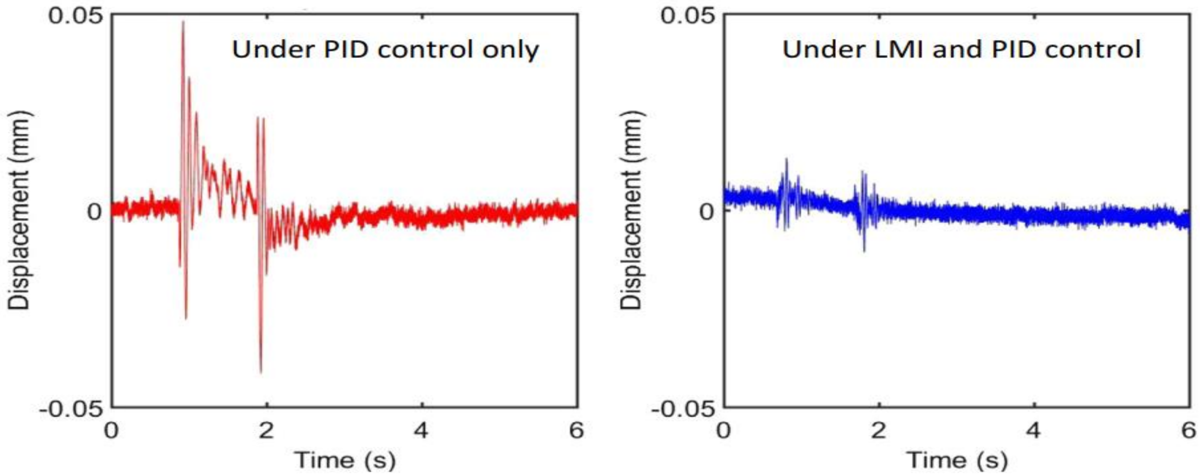

Figure 7: Rotor displacement under PID and LMI (Wang et al., 2017)

2.4 Research gap and Direction

The concept of two wheeled robots is still under intensive research with different methods and approaches still being considered. The fact that stability of the two wheeled robot is still a problem in many applications researchers are constantly trying different control methods. Two wheeled robots come in different configurations and are unique therefore control algorithms will be different. A comparative analysis of PID and LMI on a two wheeled robot is yet to be established and this present a research gap yet to be filled. This research aims at introducing an LMI control method for the stabilization and control of a two wheeled robot which is affected by a non-minimum phase load.

CHAPTER THREE: RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

This chapter highlights the processes that will be undertaken for the realization of the said objectives. This project will be carried out in the Mechatronic department labs in Dedan Kimathi University of Technology. To evaluate the LMI controller applicability in a two wheeled self-balancing robot it is necessary to compare it with existing and highly comparative controllers in this case PID controller. An existing two wheeled robot will be used as a test bench for the controller applicability. The two wheeled robot will be incorporated with a simple non minimum phase load to investigate effects of applying more disturbances on its stability and control. The simulation results of the controllers will be developed from standardized tests of various performance parameters touching on stability and control. The results will then be compared with physical experiments on the two wheeled robot to ascertain validity of the LMI controller. State of the art will involve reading materials that are related to the research topic. In addition, I will be looking at previous works in detail since research is progressive and this will be done throughout the research period. The figure below outlines the steps to be undertaken in realization of stability and control of a two wheeled robot.

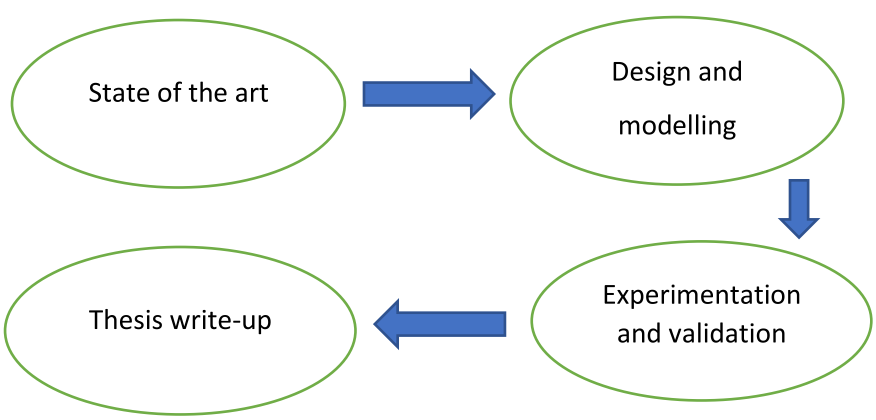

Figure 8: Project flowchart

3.2 Design and modelling

A computer Aided Design (CAD) software will be used to model the proposed two wheeled robot. This will entail detailed structure and hardware design present on the model will accuracy to dimensions. CAD allows a designer to build a virtual replica of the physical model and allows alterations on the intended parameters therefore producing results by combining it with another software. The figure below shows the proposed two wheeled robot for this research purpose.

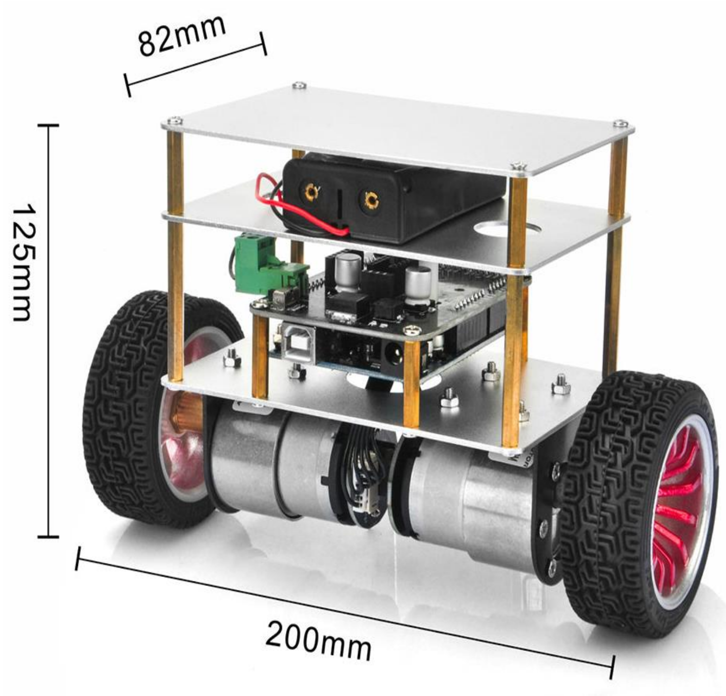

Figure 9: Proposed model

3.2.1 Hardware design

The two wheeled robot has an array of components to enable controller application. These include:

Inertial measurement unit MPU-6050

Six degrees of freedom are available in this extremely accurate inertial measurement unit (IMU) (DOF). IMUs can measure a variety of factors, including acceleration, inertia, and others, to help you calculate the spatial position and velocity of an object (Hub, 2021).

Figure 10: MPU 6050 (electronics, n.d.)

Arduino Uno R3

A detachable, dual-inline-package (DIP) ATmega328 AVR microcontroller serves as the foundation for the Arduino Uno R3 microcontroller board. There are 20 digital input/output pins (of which 6 can be used as PWM outputs and 6 can be used as analog inputs). It can have programs loaded onto it from the user-friendly Arduino computer application (Pololu, 2020).

Figure 11: Arduino Uno R3 (Pro, 2019)

DC motors with encoders

It will be required to use motors to provide the robot movement. Because they provide good torque and speed control, DC motors are widely used. Their torque is 127.4 mN.m, and their rated speed is 130 rpm. This is thought to be enough to keep the robot balanced (electronics, n.d.).

Figure 12: DC motor with encoder (Vordeo, 2022)

Voltage regulator LM2596S

The monolithic integrated circuits that make up the LM2596 series of regulators are capable of driving a 3-A load with excellent line and load regulation. They are step-down (buck) switching regulators. These devices come in versions with adjustable output voltages as well as fixed output voltages of 3.3 V, 5 V, and 12 V(Components, 2019).

Figure 13: LM2596S (Nerokas, 2020)

Motor Driver TB6612FNG

Up to two DC motors can be managed by the TB6612FNG Motor Driver at a constant current of 1.2A. (3.2A peak). The motor can be controlled in one of four function modes: CW, CCW, short-brake, and stop, using two input signals (IN1 and IN2). A PWM input signal with a frequency of up to 100kHz controls the speed of each motor, and the two motor outputs can be independently regulated. (electronics, n.d.).

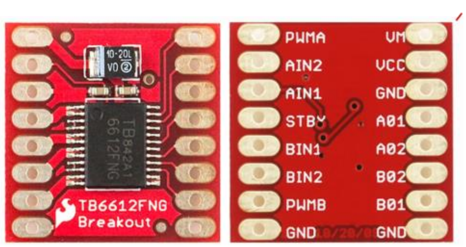

Figure 14: Motor Driver TB6612FNG (ArtisTechMore, 2019)

Modelling: Matlab/Simulink software will be used for the mathematical representation of the structure to enable parameters to be varied. Linear matrix Inequality solvers present in the Matlab tool box will be used to generate required equations during experimentation. Matlab/Simulink will also be used in proportional, integral and derivative controller development and tuning. This is important as PID will provide the benchmark for LMI testing.

An interactive, graphical interface for modeling, simulating, and evaluating dynamic systems is provided by Matlab/Simulink. It makes it possible to quickly and easily build virtual prototypes to explore different design concepts.

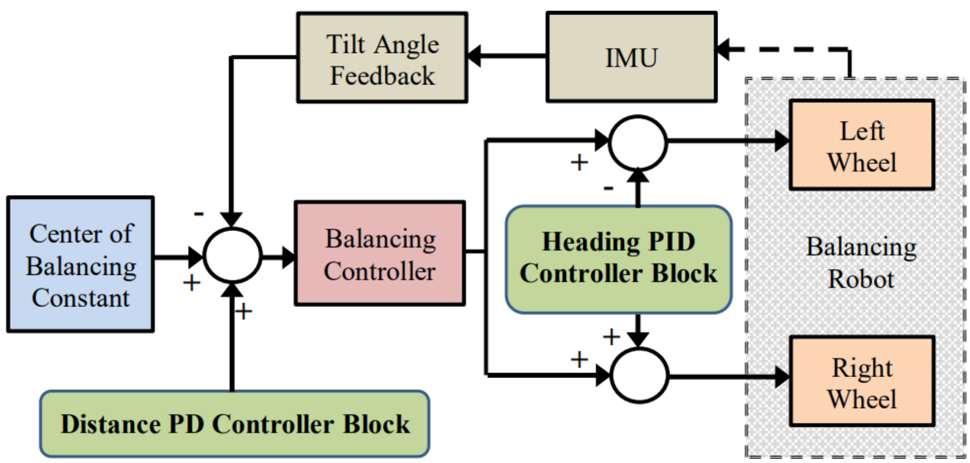

Figure 15: Proposed PID balancing block (Pratama et al., 2015)

3.3 Experimentation and validation

Upon completion of mathematical modelling of the controllers, the model will be setup for preliminary and actual experimental runs. Experiments done on the controllers through a series of performance parameters that touch on control and stabilization of the two wheeled robot will be conducted. Through experimentation, data will be collected throughout the runs and will be analyzed to enhance the validation of this research. Validation aides in comprehending the veracity of the outcomes of the two-wheeled robot simulation model and genuine or physical performance.

CHAPTER FOUR: EXPECTED RESULTS

At the end of the research the following outcomes are expected;

- MatLab simulation data for the suggested control strategies under different performance indexes.
- Physical demonstration of the two wheeled robot tracking and upright stability under the proposed control methods.
- Tracking and upright stabilization of the two wheeled robot under a non-minimum phase load.
- A case study demonstrating the performance of the linear matrix inequality controller.

APPENDICES: WORK SCHEDULE

Activity	Duration (Weeks)	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan
Literature review	32								
Proposal writeup	3								
Cad modelling	8								
Mathematical modelling	8								
PID integration	7								
LMI integration	8								
Validation	8								
Thesis writing	28								
Thesis defense	1								

REFERENCES

1. Anderson, D. P. (2003). nBot balancing robot. In http://www.geology.smu.edu/~dpa-www/robo/nbot/ (Issue 2007). Internet.
2. ArtisTechMore. (2019). Driving small motors with the TB6612FNG. Instructables. https://www.instructables.com/Driving-Small-Motors-With-the-TB6612FNG/
3. Baskaran Shanmugavel. (2018). Development of self balancing robot.
4. Components. (2019). LM2596 switching regulator datasheet, pinout, features & equivalents. Components101. https://components101.com/regulators/lm2596-3a-step-down-voltage-switching-regulator
5. Derry Pratama, Eko Binugroho, & Ardilla, F. (2015). Movement control of two wheels balancing robot using cascaded PID controller (pp. 94–99). https://doi.org/10.1109/ELECSYM.2015.7380821
6. Ellips Masehian, & Habibi, G. (2007). Motion planning and control of mobile robot using Linear Matrix Inequalities (LMIs) (pp. 4277–4282). IEEE International Conference on Intelligent Robots and Systems. https://doi.org/10.1109/IROS.2007.4399641
7. Ghani, A., Mat, I., & Azmi, N. A. (2010). Comparative assessment for two wheels inverted pendulum mobile robot using robust control. 562–567. https://doi.org/10.1109/ICCAS.2010.5669926
8. Gong, Y., Wu, X., & Ma, H. (2015). Research on control strategy of two-wheeled self-balancing robot. 281–284. https://doi.org/10.1109/CSMA.2015.63
9. Highfield, R. (2010). Zeros to heroes: The invention that’s best hidden. New Scientist, 207, 36. https://doi.org/10.1016/s0262-4079(10)62212-9

10. Hitachi Ltd. (2005). EMIEW : Robotics : Research & development : Hitachi. www.hitachi.com. https://www.hitachi.com/rd/research/mechanical/robotics/emiew1_01/index.html
11. Hub, P. (2021). MPU-6050 sensor module: A friendly introduction. Arduino Project Hub. https://create.arduino.cc/projecthub/RucksikaaR/mpu-6050-sensor-module-a-friendly-introduction-ec7a1c
12. Iwendi, C., Alqarni, M. A., Joseph Henry Anajemba, Alfakeeh, A. S., Zhang, Z., & Ali Kashif Bashir. (2019). Robust navigational control of a two-wheeled self-balancing robot in a sensed environment. IEEE Access, 7, 82337–82348. https://doi.org/10.1109/access.2019.2923916
13. Lima, B., Poleze, E., das, P., Angélico, B. A., Lima, Poleze, E., Gabriel, & Angélico, B. A. (2019). LMI based robust H2 control of a ball balancing robot with omniwheels. 2090–2095. https://doi.org/10.23919/ECC.2019.8795789
14. Minh, G., Duong Hoai Nghia, & Nguyen Huu Phuc. (2010). A PID backstepping controller fortwo-wheeled self-balancing robot. 76–81. https://doi.org/10.1109/IFOST.2010.5668001
15. Nerokas. (2020). LM2596S-5.0 LM2596 TO-263 3A Step-Down 5V Regulator. Nerokas Online Store. https://store.nerokas.co.ke/index.php?route=product/product&product_id=2171
16. Nor Maniha, Ghani, A., Naim, F., & Tan Piow. (2011). Two wheels balancing robot with line following capability.
17. Omar Khalil Sayidmarie. (2016). Design and real-time control of a new structure two-wheeled robot (p. Pg 21-24).

18. Pinetree electronics. (n.d.). OSOYOO two wheel bluetooth balance robot car kit for arduino. OSOYOO.Store. https://osoyoo.store/products/osoyoo-rc-two-wheel-self-balancing-robot-car-kit-with-uno-r3-board-diy-educational-programmable-starter-kit-for-arduino-bluetooth-remote-control-by-android-smart-phone?variant=19316632486006
19. Ping, R., Stol, K. A., & C Roger Halkyard. (2013). Review of modelling and control of two-wheeled robots. Annual Reviews in Control, 37(1), 89–103. https://doi.org/https://doi.org/10.1016/j.arcontrol.2013.03.004
20. Pololu. (2020). Pololu - arduino uno R3. www.pololu.com. https://www.pololu.com/product/2191#:~:text=The Arduino Uno R3 is
21. Pro, E. (2019). Arduino UNO R3 microcontroller, specifications, and pin diagram. ElProCus - Electronic Projects for Engineering Students. https://www.elprocus.com/what-is-arduino-uno-r3-pin-diagram-specification-and-applications/
22. Qiu, C. (2015). The design of fuzzy adaptive PID controller of two-wheeled self-balancing robot. International Journal of Information and Electronics Engineering, 5. https://doi.org/10.7763/ijiee.2015.v5.529
23. Rubio, F., Valero, F., & Llopis-Albert, C. (2019). A review of mobile robots: Concepts, methods, theoretical framework, and applications. International Journal of Advanced Robotic Systems, 16, 172988141983959. https://doi.org/10.1177/1729881419839596
24. Segway Inc, S UPPILL, & Cazzolato, B. (2009). 899: BALLBOT.
25. Sun, L., & Gan, J. (2010). Researching of two-wheeled self-balancing robot base on LQR combined with PID. 1–5. https://doi.org/10.1109/IWISA.2010.5473610
26. Van. (2021). Two-wheeled robot stabilization and motion control.

27. Vordeo. (2022). BIG DISCOUNT - machifit 25GA370 DC 12V micro gear reduction motor with encoder speed dial reducer - VORDEO. Vordeo. https://vordeo.com/shop/tools/machine-tools-accessories/gear-motor/

28. Wang, M., Cole, M. O. T., & Keogh, P. S. (2017). New LMI based gain-scheduling control for recovering contact-free operation of a magnetically levitated rotor. Mechanical Systems and Signal Processing, 96, 104–124. https://doi.org/10.1016/j.ymssp.2017.04.008