Institut für Mechatronische Systeme
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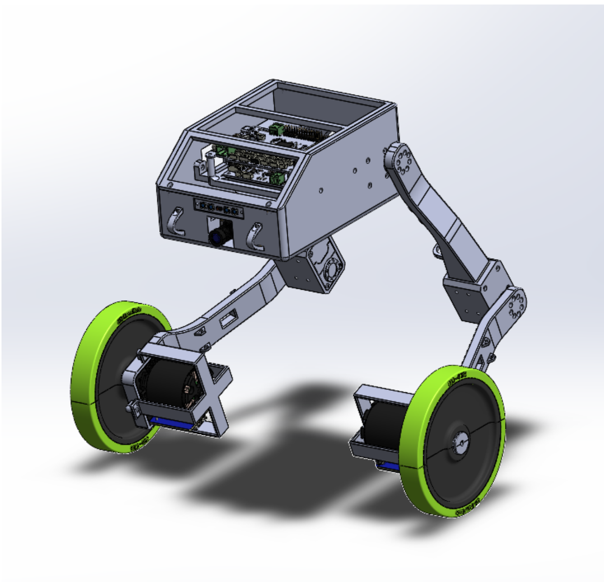
Design and Control of a Multi-Joint Two-Wheeled Inverted Pendulum Robot for Agile Motion Learning



Master's thesis M-MM/JJJJ-XXXXX

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Hannover, 14. January 2024

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I, *Mohamed Barakat*, hereby affirm that the Master's thesis entitled *Design and Control of a Multi-Joint Two-Wheeled Inverted Pendulum Robot for Agile Motion Learning* was written independently, that no references and aids other than those indicated were used, that all passages of the thesis which were taken over literally or analogously from other sources are marked as such and that the thesis has not yet been presented to any examination board in the same or similar form.

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(Mohamed Barakat)

Eigenständigkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und eigenhändig sowie ohne unerlaubte fremde Hilfe und ausschließlich unter Verwendung der aufgeführten Quellen und Hilfsmittel angefertigt habe.

Ort, Datum

Mohamed Barakat

Abstract

This thesis addresses the challenge of input trajectory transfer in heterogeneous multi-agent systems, where each agent has distinct system dynamics.
The concept of transfer learning has been applied to MAS to accelerate the learning process of a target agent by leveraging previously learned trajectories from a different source agent. However, directly transferring input trajectories between agents with dissimilar dynamics can lead to unwanted behaviour. This can be overcome by applying a mapping that transforms the input trajectory of the source system into an appropriate input trajectory for a target system so that their outputs match. Obtaining such an input transfer map from simple experiments is difficult, so previous research often focuses on output transfer, adaptive control or strong similarity assumptions. Those approaches either require extensive model knowledge or have limited usability.

This thesis provides a comprehensive understanding of trajectory transfer, distinguishing the input and output transfer cases and highlighting their similarities. Those insights are then used to propose a simple, data-driven method to estimate a dynamic input transfer map for SISO systems that addresses the aforementioned problem. Structural similarity in the systems is leveraged to simplify the estimation process further. The transfer map is estimated as a lifted system matrix and a transfer function. The performance of the estimated dynamic input transfer map is compared to a static map using a simple gain and to the direct transfer of the input trajectories.

It is shown that input and output transfer are equivalent under certain conditions. An input transfer map based on this assumption was able to significantly reduce the differences between a source and a target system in three simulated scenarios. This even includes scenarios where the systems have nonlinear, non-minimum phase dynamics.
Compared to a static map, the performance of a dynamic input transfer is superior, especially in cases where the estimated transfer map is applied to input trajectories which are not part of the training data. Furthermore, the dynamic input transfer map can have a model order lower than the theoretically expected order of the transfer system, given that the source and target systems are related. Therefore, the expected order only provides an upper limit for the order of an estimated transfer map, and not a recommended choice.
Nonetheless, this thesis alone does not fully explore the potential and limitations of the proposed method. Future research is necessary to address these topics further.

Keywords— input transfer, trajectory transfer, transfer learning, multi-agent systems

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1 Introduction

1.1 Motivation

This section should explore the underlying reasons for undertaking the research. It might include the importance of the topic, the gap in current knowledge, and the potential applications of the research findings.

Robotics has always been a cutting-edge field that combines sophisticated engineering, artificial intelligence, and a comprehension of human-environment interactions. This study is motivated by multiple important elements, all of which highlight the importance and relevance of the research.

Advancements in Robotic Technologies: Robotics has grown at an exponential rate over the past few decades, resulting in improved capabilities and more applications. Previously limited to industrial settings, robots are now being deployed in increasingly dynamic and unpredictable circumstances. The development of robotic systems that are more flexible, nimble, and intelligent is required due to this evolution. Our research is to create a sophisticated multi-legged robotic system that can perform intricate movements and interact with its surroundings.

Filling Knowledge Gaps: Even with significant advancements, there are still many unanswered questions about robotic control and locomotion, particularly in systems that replicate biological structures and processes. Complex dynamic tasks that living beings handle with ease are sometimes difficult for traditional robotic systems to accomplish. This research aims to close these gaps by concentrating on a multi-legged robot that finds inspiration in the natural environment. This will provide insights into more realistic and effective movement tactics.

Potential for Broad Impact: The applications of such advanced robotic systems are vast and varied, ranging from search and rescue operations in hazardous environments to assistive technology in healthcare. By pushing the boundaries of what is currently possible in robotic design and control, this research has the potential to make significant contributions to fields where human intervention is limited, dangerous, or impractical.

Interdisciplinary Collaboration and Innovation: This project is inherently interdisciplinary, integrating concepts from mechanical engineering, computer science, control theory, and even biology. Such cross-disciplinary collaboration is crucial for driving innovation, as it allows for the exchange of ideas and methods from diverse fields. This approach is expected to yield novel solutions and advancements that could extend well beyond the scope of this project.

In summary, the motivation for this project lies in its potential to advance the field of robotics, fill existing knowledge gaps, have a broad societal impact, and foster interdisciplinary collaboration. By developing a multi-legged robotic system with enhanced movement capabilities and control strategies, this research endeavors to set new standards in robotic design and functionality.

1.2 Explanation of the Goals and Requirements

Here, you should clearly outline the objectives and aims of the research. This might include specific technical goals, hypotheses to be tested, or particular research questions to be addressed. Also, detail any specific requirements necessary for the research, such as technological needs, data requirements, or theoretical frameworks.

2 Literature Review

2.1 Overview of Two-Wheeled Inverted Pendulum Robots

2.2 Prior Works and Advances in Multi-Legged Robotic Systems

This section should provide a comprehensive review of existing literature relevant to your research topic. It should cover key theories, models, experiments, and findings in the field, particularly focusing on works that directly relate to your research question or hypothesis. This review not only shows your understanding of the field but also how your work fits into and contributes to the existing body of knowledge.

2.3 State-of-the-Art in Robotic Control Systems

3 Mechanical Design

Modeling In this chapter, the details of the mechanical design are presented. where it goes from the initial conceptual design to the final design showing in the process the design decision-making for each critical point, This chapter emphasis the detailed description of the precise placement and alignment of different components such as the motors, wheels, battery, boards, and others to maintain the seamless integration of all the components into the robot body.

The mechanical design serves as an important pillar to define the new physical form, size, and shape of the TWIPR. Depending on how these criteria are defined, the robot would interact with the environment. taking into account that the design directly influences the center of gravity, which is crucial to consider in our robot due to the inverted pendulum nature to be able to balance and maintain the upright position. In addition to the impact that the design has on the maneuverability of the robot and how it would respond to the control signals to be able to execute a task.

3.1 Design Objectives and Requirements

The main objective is to come up with a new design for a multiple joints Robot to perform complex dynamic movements. this robot would be based on the Two wheeled inverted pendulum robot. The new design would add more degrees of freedom to enable the more complex movements.This enhances the robot capabilities where it can execute more diverse scenarios. Initially, the main requirement was to add two more degrees of freedom where originally it used to have one degree of freedom in the wheels. The new design has three degrees of freedom one in the wheels, one as a knee joint and one as a hip joint. The current design has two identical legs.

3.2 Conceptual Design

As for the initial design concepts the body was that main point of focus as shown in the figure 3.1.Three initial designs where considered mainly for the body. Symmetrical vertical body in figure A, symmetrical horizontal body in figure B and leaning forward body in figure C. For the three designs, two independent legs where considered. two designs where considered for the legs, the normal joint leg and the compliant leg

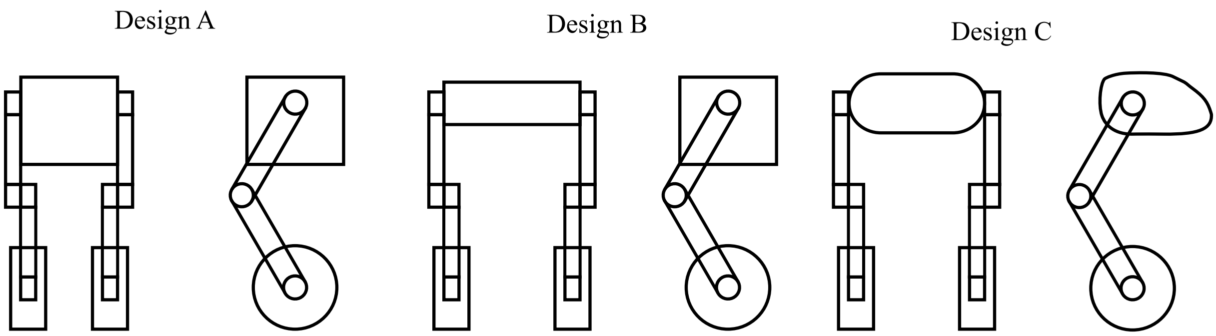


Figure 3.1: Three initial Design Concepts for the robot body

Two main designs where considered for the legs, the normal joint leg and the compliant leg. The compliant leg is more flexible and can be used to absorb the shock from the ground. The normal joint leg is more rigid and can be used to generate more torque.in addition, the normal is more relative to our use-case as it can precisely control the position of the leg.

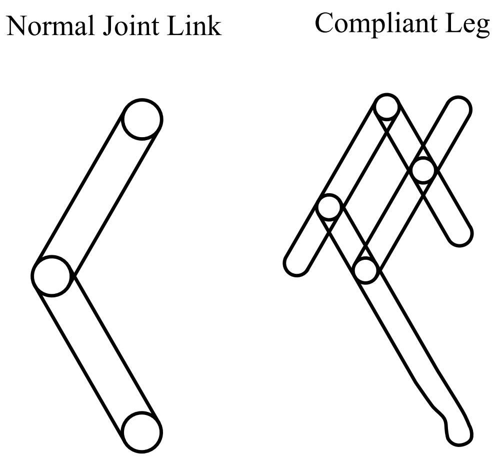


Figure 3.2: Leg Design Concepts

3.3 Initial Calculations

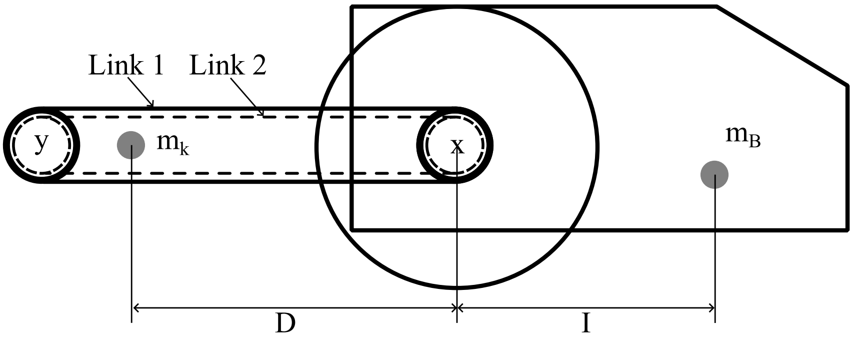


Figure 3.3: Initial Calculations

One of the main critical positions for the robot, as shown in the figure 3.3 is the position where the center of mass of the body and the center of mass of the legs are the furthest away from point x on the horizontal axis.It is important to make the initial torque calculations to be able to select the right motors for the robot. Starting from that position first, the robot should be able to balance itself and maintain the upright position. secondly, the robot should be able to change the knee angle to lift the body while maintaining its balance. The calculations are based on some assumptions and simplifications, Considering only half the body weight and one leg joint. As shown in the figure, The Wheel motor shaft is aligned with the hip joint, the minimum torque required to balance the robot is calculated as follows:

The summation of the torques around point x should be equal to zero to maintain the balance with minimum motor torque.

$$\sum_{i=1}^{n} \tau_i = 0 \tag{3.1}$$

$$\sum_{i=1}^{n} \tau_i = m_B * g * D - m_K * g * I \tag{3.2}$$

$$\sum_{i=1}^{n} \tau_i = 0.5 * 9.81 * 0.03 - 0.2 * 9.81 * 0.5 * 0.15 = 0Nm \tag{3.3}$$

The Lengths of D and I can be modified to make sure that the summation of the torques around point x is equal or approximately equal to zero. This will make sure that the robot can balance itself with minimum wheel motor torque. The torque required to lift the body is calculated as follows:

$$\sum_{i=1}^{n} \tau_i = m_B * g * (D + I) - m_K * g * L_1 \tag{3.4}$$

$$\sum_{i=1}^{n} \tau_i = 0.5 * 9.81 * (0.03 + 0.15) - 0.1 * 9.81 * 0.5 * 0.15 = 0.9555Nm \tag{3.5}$$

0.9555 Nm is the minimum torque required to hold the body in position. The motor should be able to generate more torque to be able to lift the body and change the knee angle.

table for the assumptions

Table 3.1: Assumptions

Parameter	Value	Description
m_B	0.5 kg	Mass of the body
m_K	0.2 kg	Mass of the Knee including the two legs
L_1	0.15 m	Length of Link 1
L_2	0.15 m	Length of Link 2
d	0.3 m	distance from the hip joint axis to the center of mass of the body

Note 3.1

To reduce the needed torque to lift we can:

- shorten the links then calculate position 4 again
- reduce the body weight then calculate position 4 again
- use gearbox then calculate position for again

3.4 Detailed Design Development

Throughout the design process, modularity and ease of assembly were considered. The design was broken down into three main parts: the body, the hip-knee joint, and the knee-wheel joint. Print iterations were made to ensure that the parts fit together and that the robot could be assembled with ease. Modifications were made to simplify the printing process and reduce the support material used.

3.4.1 Body Design

The body design is the main part of the robot, it is the main structure that holds all the components together. The components that are mounted on the body are the hip motors, the battery, camera, sensor, a rack that includes the power distribution board, the microcontroller board attached to the Raspberry Pi.The optimization of the body design is crucial to be able to fit all the components in a compact form and at the same time distribute the weight equally to maintain the balance of the robot. Different design features were considered, such as the cable management, the fastening features specifically designed to easily mount the battery, organize the cable between the boards and the rest of the robot parts.

3.4.2 Hip Knee Joint Design

This joint connects the hip body axis to the knee axis. The design of this joint includes the knee motor housing form one-side and a frame to attach to the output horn of the hip motor. The motor housing is designed to ensure the fixed placement of the motor inside the joint, As shown in the figure, 3.7 Cable management is also considered in the design of this joint to make sure that the cables are not interfering with the movement of the joint.The curvature of the joint creates enough clearance so that when the hip axis is aligned with the wheel axis, they would not touch with each other even when considering the elastic bending of the legs.

3.4.3 Knee Wheel Joint Design

This joint connects the knee axis to the wheel axis.

Figure 3.4: TOP view of the Body Design

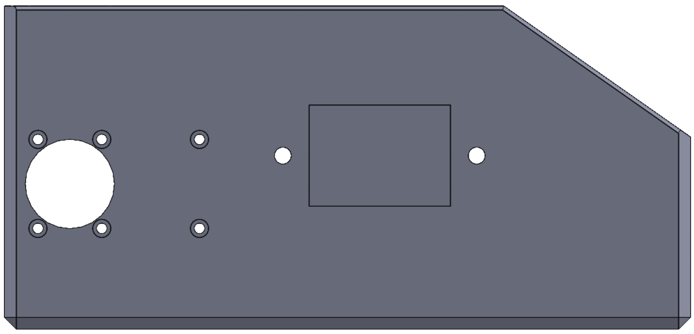


Figure 3.5: side view of the Body Design

3.4.4 Full Design

3.4.5 safety considerations

3.5 Design for Manufacturability and Assembly

3.6 Prototyping and Iterative Design

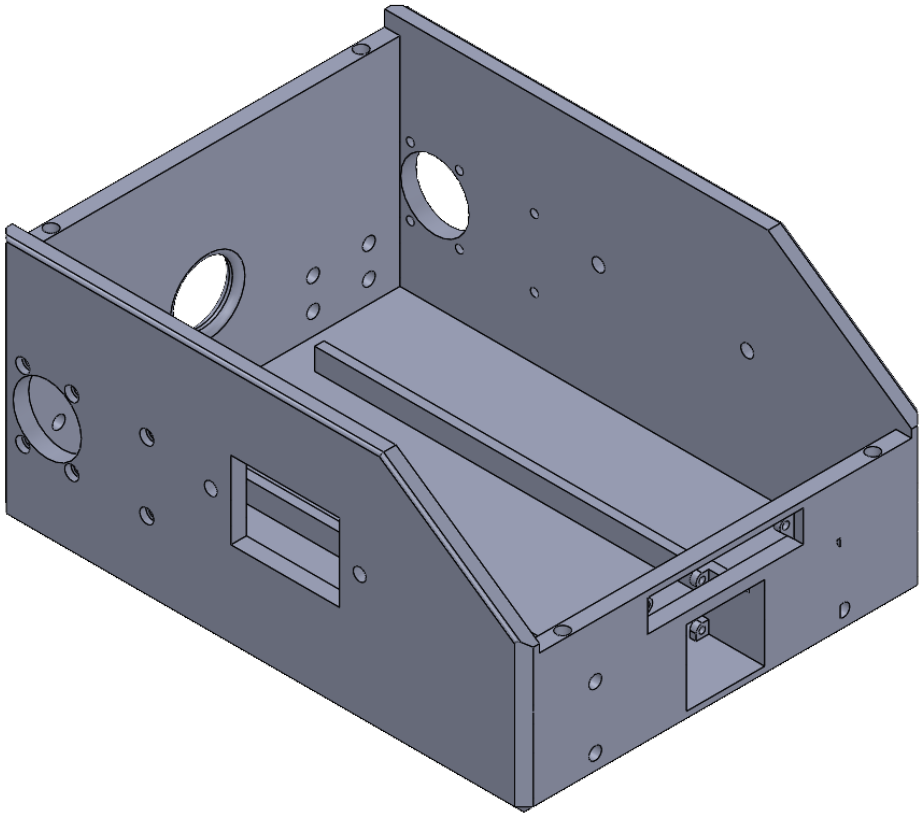


Figure 3.6: 3D view of the Body Design

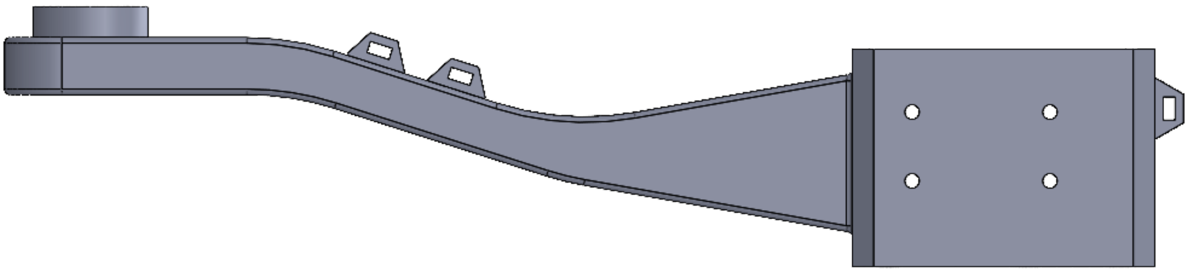


Figure 3.7: TOP view of the Body Knee Joint

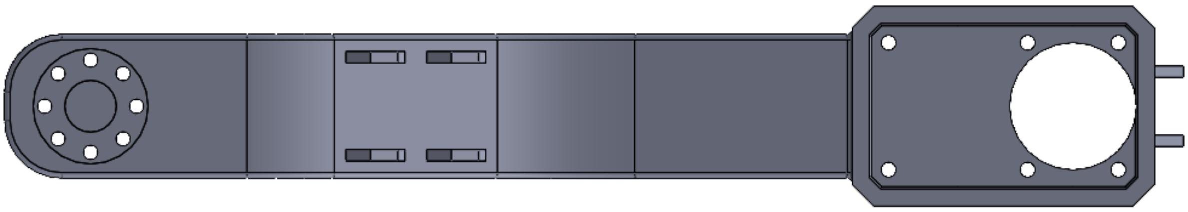


Figure 3.8: side view of the Body Knee Joint

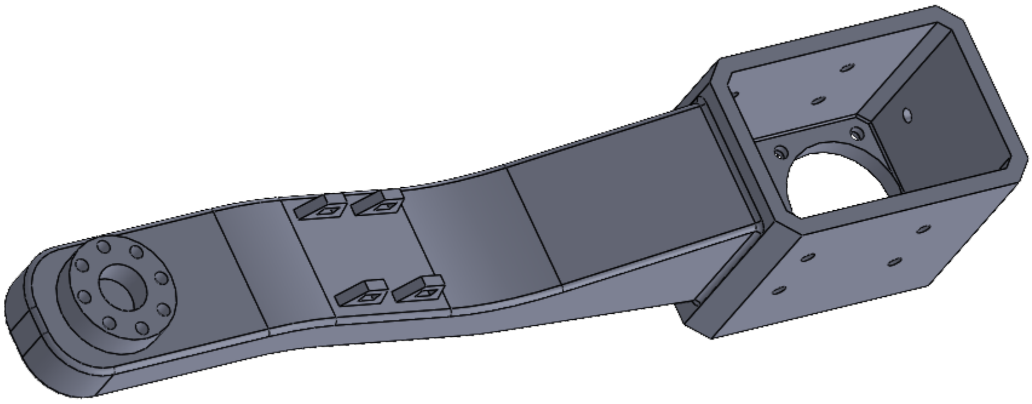


Figure 3.9: 3D view of the Body Knee Joint

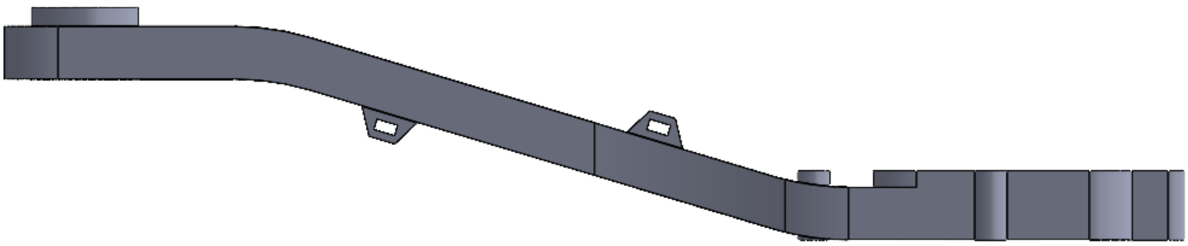


Figure 3.10: SIDE view of the Knee Wheel Joint

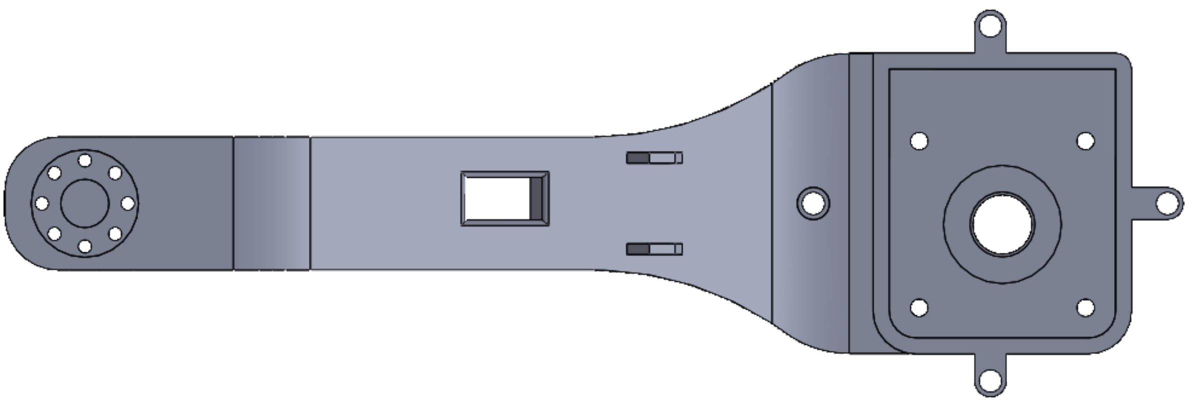


Figure 3.11: TOP view of the Knee Wheel Joint

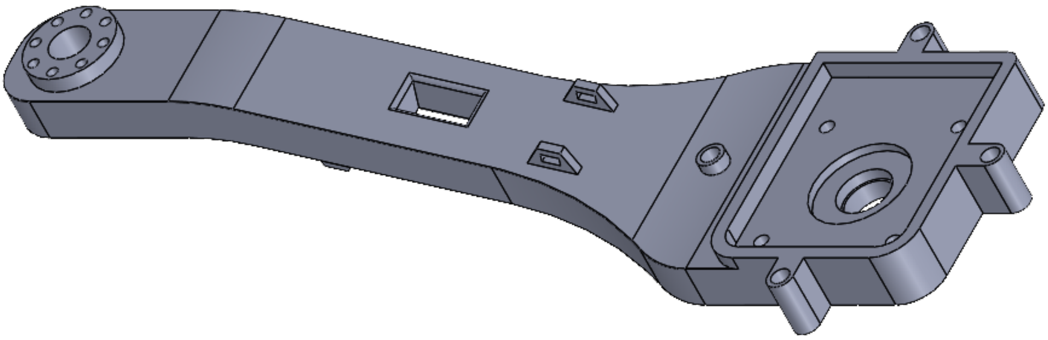
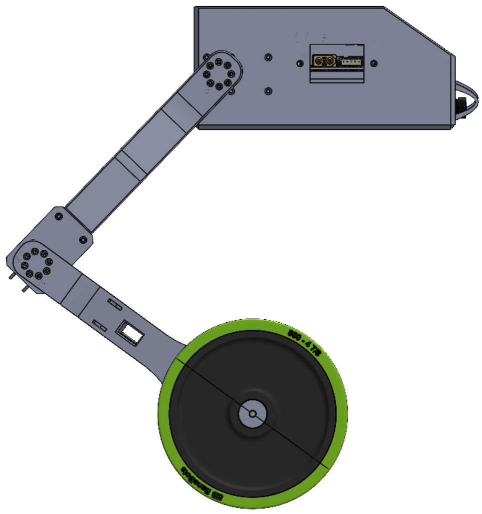
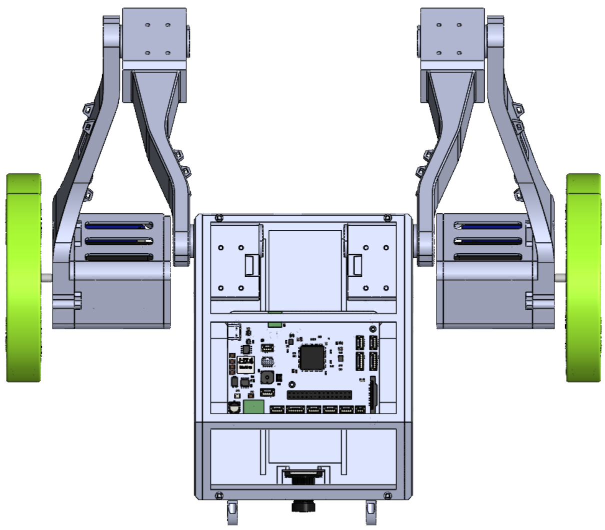


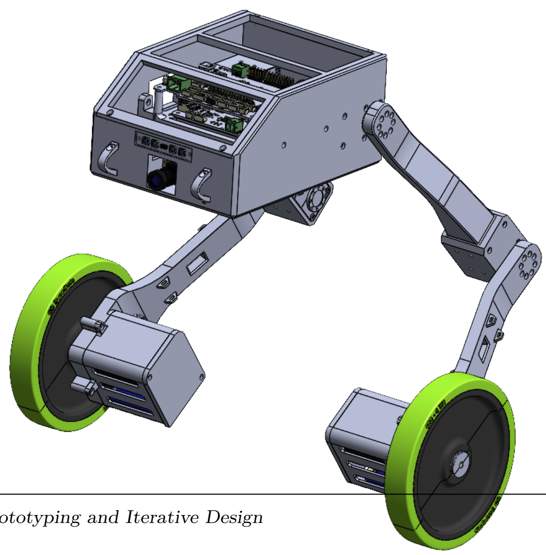
Figure 3.12: 3D view of the Knee Wheel Joint



(a) Training error for trajectory transfer with and without output noise in the training data



(b) Test error for trajectory transfer with and without output noise in the training data



4 Electronic Design

In this chapter, the details of the electronic design are presented. Where it emphasizes the details of the components' technical specifications and the selection process. The chapter also discusses the circuit design and the PCB design. In addition, the chapter discusses the power management and the power distribution.

The electronic design serves as a critical link between the robitic conceptual framework and the physical implementation of the robot.The electronic design translates the abstract control algorithm into tangible action and responses. The electronic design directly influences the performance, responsiveness, adaptability to various scenarios.

4.1 Design Objectives and Constraints

The main objectives of the electronic Design are to connect the different components and enable them to perform the desired tasks. The electronic design is responsible for controlling the motors. Robust communication between the electronic components is needed to ensure reliable operation of the robot. The electronic design is constrained by the power requirements of the motors. The motors require a high current to operate, and the electronic design should be able to provide the required current. In addition, the electronic design is constrained by the size of the components and their placement in the robot body.

4.2 Component Selection

The component diagram is shown in a figure 4.1shows the different components and their relationship with each other. The main components are the microcontroller, rassberry pi, the motors, Distance sensor, Camera, the battery. The motors are chosen based on the calculations done in the mechanical design chapter. The microcontroller is chosen based on the complixity of the control algorithm and the processing power needed to run the control algorithm.

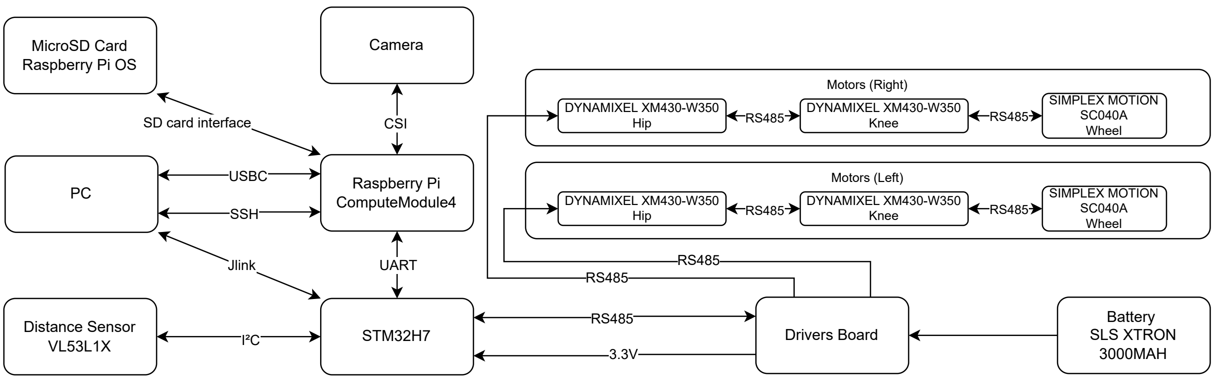


Figure 4.1: Components Diagram and there realationship with each other

4.2.1 Hip and Knee Motors

The DYNAMIXEL XM430-W350 is chosen as a motor for the hip joint and the knee joint. The motor is chosen because it has a high torque to weight ratio and it has a high resolution of 4096 steps per revolution. The motor has a built-in driver and it can be controlled using a serial communication protocol. The motor has a built-in encoder that can be used to measure the position of the motor. The motor has a maximum torque of 3.5 Nm and a maximum speed of 46 RPM. The motor has a maximum current of 2.1 A and a maximum voltage of 12 V. The motor has a weight of 82 g and a size of 28.5 x 46.5 x 34 mm.

Figure 4.2: DYNAMIXEL XM430-W350

4.2.2 Wheel Motors

The SIMPLEX MOTION SC040A is chosen as a motor for the wheels. The motor is chosen since it has a output of 120W and 280 mNm torque at 4000rpm. The motor has a built-in driver and it can be controlled using RS485 serial communication protocol. The motor has position and speed control with torque limit. The motor has a maximum torque of 800 mNm.

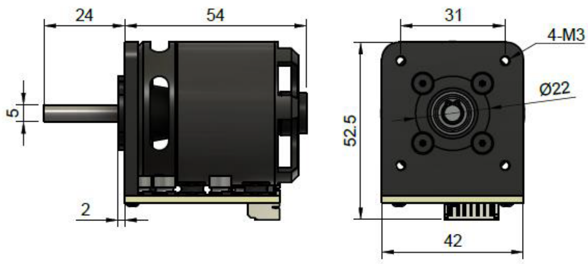


Figure 4.3: SIMPLEX MOTION SC040A

4.2.3 Microcontroller

The STM32H7 is chosen as a microcontroller for the robot. The microcontroller is chosen because it has a high processing power and it has a high number of input and output pins. The microcontroller has a 32-bit ARM Cortex-M7 core running at 400 MHz. The microcontroller has 2 MB of flash memory and 1 MB of RAM. The microcontroller has 16-bit ADCs with 3.2 MSPS in interleaved mode. The microcontroller has 16-bit DACs with 2.5 MSPS. The microcontroller has 2 CAN interfaces. The microcontroller has 3 I2C interfaces. The microcontroller has 4 SPI interfaces. The microcontroller has 6 USART interfaces. The microcontroller has 4 UART interfaces. The microcontroller has 2 USB OTG interfaces. The microcontroller has 2 SDMMC interfaces. The microcontroller has 2 SAI interfaces. The microcontroller has 2 DFSDM interfaces. The microcontroller has 2 FMC interfaces. The microcontroller has 2 QUADSPI interfaces. The microcontroller has 2 SWPMI interfaces. The microcontroller has 2

LPTIM interfaces. The microcontroller has 2 MDIOS interfaces. The microcontroller has 2 OCTOSPI interfaces. The microcontroller has 2 SPDIFRX interfaces. The microcontroller has 2 HDMI-CEC interfaces. The microcontroller has 2 RNG interfaces. The microcontroller has 2 HRTIM interfaces. The microcontroller has 2 MDMA interfaces. The microcontroller has 2 JPEG interfaces. The microcontroller has 2 FDCAN interfaces. The microcontroller has 2 DFSDM interfaces. The microcontroller has 2 USB OTG interfaces. The microcontroller has 2 SDMMC interfaces. The microcontroller has 2 SAI interfaces. The microcontroller has 2 DFSDM interfaces. The microcontroller has 2 FMC interfaces. The microcontroller has 2 QUADSPI interfaces. The microcontroller has 2 SWPMI interfaces. The microcontroller has 2 LPTIM interfaces. The microcontroller has 2 MDIOS interfaces. The microcontroller has 2 OCTOSPI interfaces. The microcontroller has 2 SPDIFRX interfaces. The microcontroller has 2 HDMI-CEC interfaces. The microcontroller has 2 RNG interfaces. The microcontroller has 2 HRTIM interfaces. The microcontroller has 2

4.2.4 Raspberry Pi

The Raspberry Pi 4 compute module is chosen

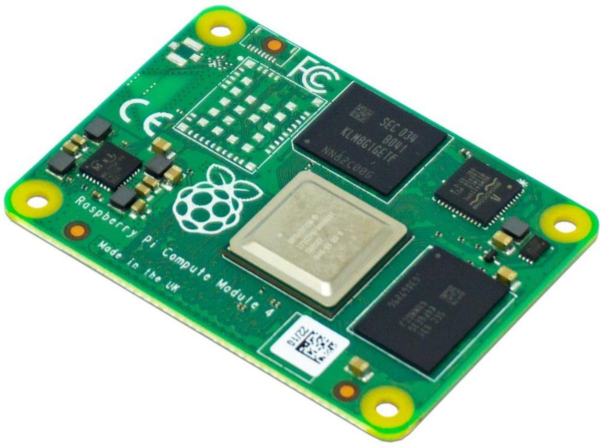


Figure 4.4: Raspberry Pi 4 compute module

4.2.5 Distance Sensor

The VL53L1X is chosen as a distance sensor for the robot. The sensor is chosen because it has a high accuracy and it has a high range. The sensor has a maximum range of 4 m. The sensor has a maximum accuracy of 1 mm. The sensor has a maximum field of view of 27 degrees. The sensor has a maximum current of 20 mA. The sensor has a maximum voltage of 3.6 V. The sensor has a weight of 1.6 g and a size of 4.4 x 2.4 x 1.0 mm.

4.2.6 Camera

The Raspberry Pi Camera Module V2 is chosen as a camera for the robot. The camera is chosen because it has a high resolution and it has a high frame rate. The camera has a resolution of 8 MP. The camera

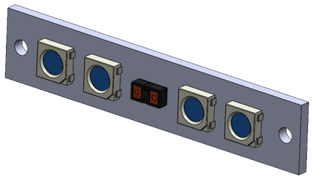


Figure 4.5: VL53L1X

has a frame rate of 30 fps. The camera has a maximum current of 250 mA. The camera has a maximum voltage of 3.3 V. The camera has a weight of 3.4 g and a size of 25 x 23 x 9 mm.

Figure 4.6: Raspberry Pi Camera Module V2

4.2.7 Battery

The SLS XTRON 3000MAH 4S1P 14.8V 35C LIPO BATTERY is chosen as a battery for the robot. The battery is chosen because it has a high capacity and it has a high discharge rate. The battery has a capacity of 3000 mAh. The battery has a discharge rate of 35 C. The battery has a maximum current of 105 A. The battery has a maximum voltage of 16.8 V. The battery has a weight of 300 g and a size of 135 x 42 x 30 mm.

4.3 Circuit Design

The wiring tree of the electronic components is shown in figure 4.8 where it shows the connection between the different components and the microcontroller.The first motor of each leg is connected to the microcontroller and the rest of the motors are connected in series to the first motor of using daisy chain connection. the motors have the drivers board intigrated so they only need the control signal comimg from the microcontroller.

Figure 4.7: SLS XTRON 3000MAH 4S1P

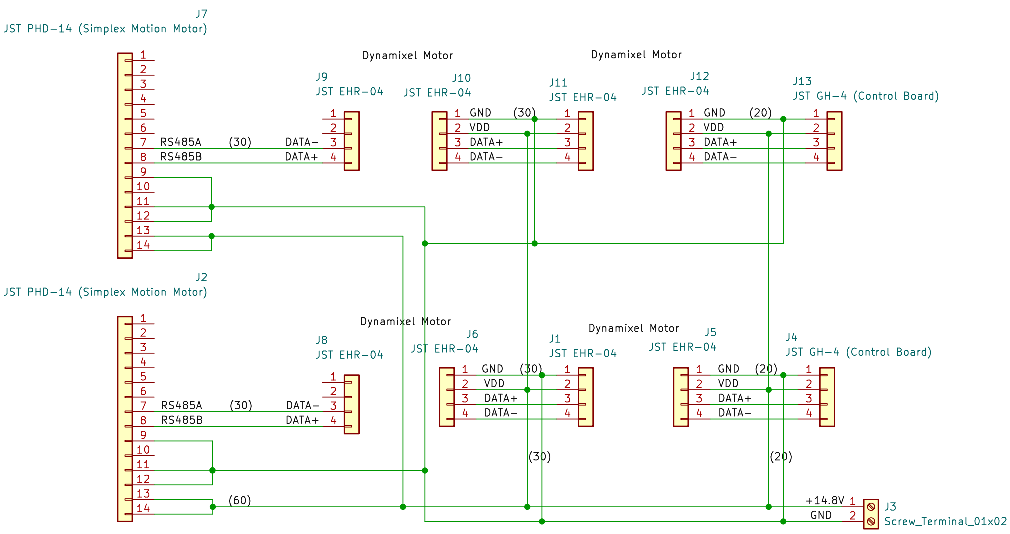


Figure 4.8: Electronic Design

- Provide comprehensive information about the circuit design, including schematic diagrams.
- Explain the functionality and interaction of different circuit components.
- Discuss the design considerations for signal integrity, power distribution, and noise reduction.

4.4 PCB (Printed Circuit Board) Design

- Describe the layout and design of any custom PCBs used in the project.
- Include information about PCB fabrication and assembly processes.

4.5 Power Management

- Discuss how power is managed and distributed within the system.
- Include details on battery management, voltage regulation, and power efficiency considerations.

5 Modelling and Simulation

In this pivotal chapter, we meticulously derive the center of gravity and the moment of inertia for the two-wheeled self-balancing robot. These parameters are the linchpins of our dynamic analysis, serving as the critical variables within the equations of motion that govern the robot's behavior. By calculating these values with precision, we can substitute them into our dynamic equations, thereby tailoring the model to reflect the true dynamics of the robot. This process not only enhances the accuracy of our simulations but also ensures that the control strategies developed are based on a robust and representative model of the robot's physical capabilities. The careful derivation of these parameters is a testament to the thoroughness of our approach, ensuring that the resulting model is both reliable and predictive of the robot's real-world performance.

5.1 Mathematical Modelling

- **TWIPR Model:** Explanation of the Two-Wheeled Inverted Pendulum Robot (TWIPR) model.

  The two wheeled Inverted Pendulum robot model is as shown in the figure where it consist of two legs that include a hip and knee joints as well as wheels at the end of each leg. the robot needs to constantly adjust it posture to be able to maintain the balance, just like how the humanbeing balance when standing on the feet.

- **Focus on 2D Dynamics:** Discussion on the scope limited to 2D dynamics and plans for future expansion to 3D dynamics and controller synthesis.
- **Assumptions and Parameters:** Detailing assumptions such as considering motor angles as parameters.
- **Model Derivation for *l_cg* and *I_y*:** Derivation of the models for center of gravity length (*l_cg*) and inertia around the y-axis (*I_y*).
- **Integration into TWIPR Model:** Integration of derived models into a new TWIPR framework.
- **Linear Model Derivation:** Derivation of the linear model from the integrated TWIPR model.
- Modeling allows for predictive analysis and understanding of the robot's behavior.

  In order to predict the behavior of the robot under different settings, the modeling procedure entails constructing mathematical representations of the robot's dynamics and control systems.

Center of Gravity calculations

5.1.1 Center of Gravity

• in that section the calculations of the overall center of gravity

• Significance in Dynamics:The stability of an object is directly impacted by the COG position, which also affects how it reacts to forces and moments from the outside world.

• maintain equilibrium,

• accurately determining the COG is crucial for predicting and controlling dynamic behavior

in the above figure in order to simplify the deriviation of the center of

$$x_{CG} = \frac{m_{L1} \cdot 0 + m_K \cdot 0 + m_{L2} \cdot L_{C2} \cdot \sin(\phi_2) + m_B \cdot (L_2 \cdot \sin(\phi_2) + L_{C3} \cdot \sin(\phi_2 + \phi_3))}{m_{L1} + m_{L2} + m_K + m_B} \tag{5.1}$$

$$y_{CG} = \frac{m_{L1} \cdot L_{C1} + m_K \cdot L_1 + m_{L2} \cdot (L_1 + L_{C2} \cdot \cos(\phi_2)) + m_B \cdot (L_1 + L_2 \cdot \cos(\phi_2) + L_{C3} \cdot \cos(\phi_2 + \phi_3))}{m_{L1} + m_{L2} + m_K + m_B} \tag{5.2}$$

$$L_G = \sqrt{x_{CG}^2 + y_{CG}^2} \tag{5.3}$$

$$\theta = \arctan\left(\frac{x_{CG}}{y_{CG}}\right) \tag{5.4}$$

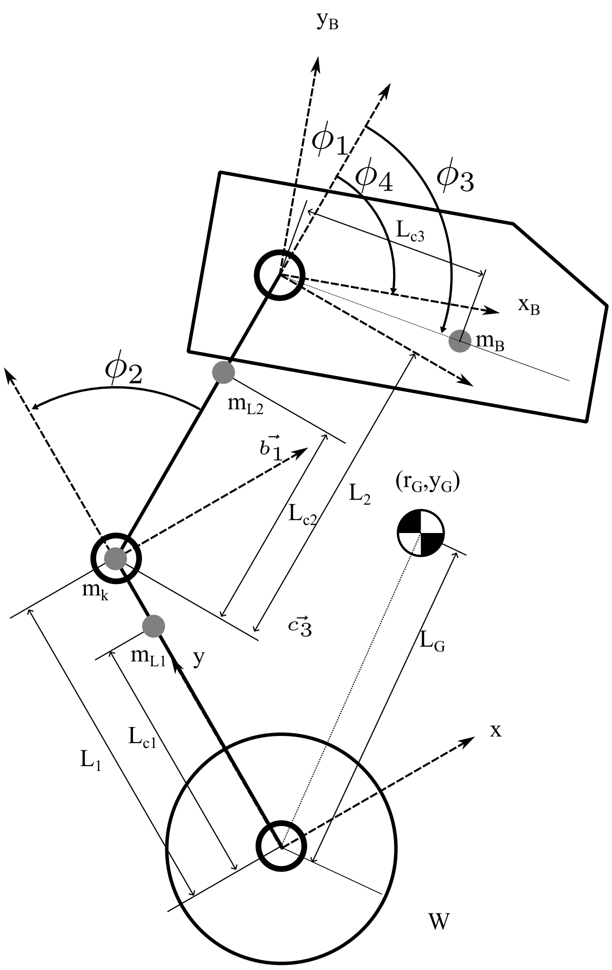


Figure 5.1: Figure illustrating the mechanical model with the local coordinate system to determine the center of gravity.

5.1.2 Moment of inertia

Moment of inertia calculations

$$L_m = \sqrt{L_1^2 + L_{C2}^2 - L_1 L_{C2} \cos(180 - \phi_2)} \tag{5.5}$$

$$L_x = \sqrt{L_1^2 + L_2^2 - L_1 L_2 \cos(180 - \phi_2)} \tag{5.6}$$

$$\alpha = \cos^{-1}\left(\frac{l_2^2 + l_x^2 - l_1^2}{2 l_2 l_x}\right) \tag{5.7}$$

$$L_b = \sqrt{L_x^2 + L_{C3}^2 - LxL_{C3} \cos(180 - \alpha - \phi_3)} \tag{5.8}$$

$$I_{L1} = \frac{1}{12} m_{L1}(a_1^2 + b_1^2) \tag{5.9}$$

$$I_{L2} = \frac{1}{12} m_{L1}(a_2^2 + b_2^2) \tag{5.10}$$

$$I_K = \frac{1}{2} m_K R_m^2 \tag{5.11}$$

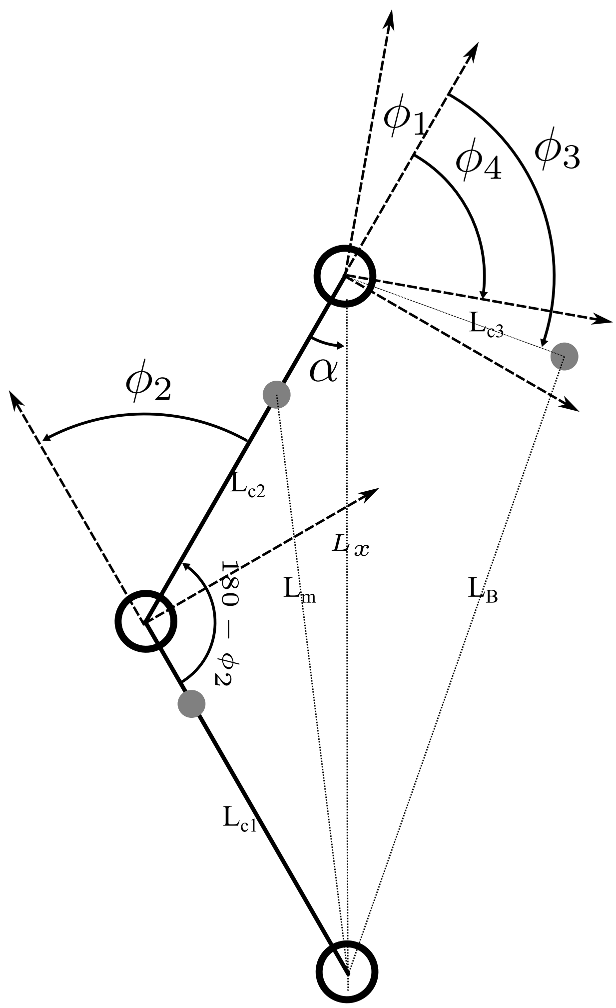


Figure 5.2: Schematic representation detailing the requisite angles and lengths for calculating the moment of inertia.

$$I_B = \frac{1}{12} m_B (a_B^2 + b_B^2) \tag{5.12}$$

$$I = I_{L1} + m_{L1} L_{C1}^2 + I_K + m_K L_1^2 + I_{L2} + m_{L2} L_m^2 + I_B + m_B L_b^2 \tag{5.13}$$

5.1.3 Equation of motion

Equation of motion

5.1.4 Dynamics of the Two-Wheeled Inverted Pendulum Robot

Given the functions $B_i : \mathbb{R} \to \mathbb{R}$, $C_{ij} : \mathbb{R} \to \mathbb{R}$, $D_{ij} : \mathbb{R} \to \mathbb{R}$, and $V_i : \mathbb{R} \to \mathbb{R}$, $i,j \in \{1,2,3\}$, the equations of motion are given by:

$$\ddot{s} = \frac{\sin(\Theta)}{V_1(\Theta)} \left(-C_{11}(\Theta) + C_{12}\dot{\Theta}^2 + C_{13}(\Theta)\dot{\psi}^2\right) - \frac{D_{11}(\Theta)}{V_1(\Theta)}\dot{s} + \frac{D_{12}(\Theta)}{V_1(\Theta)}\dot{\Theta} + \frac{B_1(\Theta)}{V_1(\Theta)}(\tau_L + \tau_R) \tag{5.14}$$

$$\ddot{\Theta} = \frac{\sin(\Theta)}{V_1(\Theta)} \left(C_{21} - C_{22}(\Theta)\dot{\Theta}^2 - C_{23}(\Theta)\dot{\psi}^2\right) + \frac{D_{21}(\Theta)}{V_1(\Theta)}\dot{s} - \frac{D_{22}(\Theta)}{V_1(\Theta)}\dot{\Theta} - \frac{B_2(\Theta)}{V_1(\Theta)}(\tau_L + \tau_R) \tag{5.15}$$

$$\ddot{\psi} = \frac{\sin(\Theta)}{V_2(\Theta)} \left(C_{31}(\Theta)\dot{\Theta}\dot{\psi} - C_{32}(\Theta)\dot{\psi}\dot{s}\right) - \frac{D_{33}(\Theta)}{V_2(\Theta)}\dot{\psi} - \frac{B_3}{V_2(\Theta)}(\tau_L - \tau_R) \tag{5.16}$$

The equations of motion are derived in [44]. The functions $B_i : \mathbb{R} \to \mathbb{R}$, $C_{ij} : \mathbb{R} \to \mathbb{R}$, $D_{ij} : \mathbb{R} \to \mathbb{R}$, and $V_i : \mathbb{R} \to \mathbb{R}$, $i,j \in \{1,2,3\}$, are given by:

$$C_{11}(\Theta) = m_B^2 l^2 \cos(\Theta), \tag{5.17}$$

$$C_{12} = (I_2 + m_B l^2) m_B l, \tag{5.18}$$

$$C_{13}(\Theta) = (I_2 + m_B l^2) m_B l + m_B l (I_3 - I_1 - m_B l^2) \cos^2(\Theta), \tag{5.19}$$

$$C_{21} = (m_B + 2m_W + \frac{2J}{r^2}) m_B l, \tag{5.20}$$

$$C_{22}(\Theta) = m_B^2 l^2 \cos(\Theta), \tag{5.21}$$

$$C_{23}(\Theta) = m_B^2 l^2 + (m_B + 2m_W + \frac{2J}{r^2})(I_3 - I_1 - m_B l^2) \cos(\Theta). \tag{5.22}$$

$$C_{31}(\Theta) = 2(I_3 - I_1 - m_B^2) \cos(\Theta), \tag{5.23}$$

$$C_{31} = m_B l, \tag{5.24}$$

$$D_{11}(\Theta) = \frac{(I_2 + m_B^2) 2c_\alpha}{r^2} - \frac{m_B \cos(\Theta) 2c_\alpha}{r}, \tag{5.25}$$

$$D_{12}(\Theta) = \frac{(I_2 + m_B^2) 2c_\alpha}{r} - 2m_B \cos(\Theta) c_\alpha, \tag{5.26}$$

$$D_{21}(\Theta) = \frac{(m_B + 2m_W + \frac{2J}{r^2}) 2c_\alpha}{r} + \frac{m_B \cos(\Theta) 2c_\alpha}{r^2}, \tag{5.27}$$

$$D_{22}(\Theta) = \frac{(m_B + 2m_W + \frac{2J}{r}) 2c_\alpha + m_B \cos(\Theta) 2c_\alpha}{r}, \tag{5.28}$$

$$D_{33}(\Theta) = \frac{d^2}{2r^2 c_\alpha}, \tag{5.29}$$

$$B_1 = \frac{(I_2 + m_B^2)\frac{1}{r} + m_B \cos(\Theta)}{r}, \tag{5.30}$$

$$B_2 = \frac{m_B l}{r} - \cos(\Theta) + m_B + 2m_W + \frac{2J}{r^2}, \tag{5.31}$$

$$B_3 = \frac{d}{2r}, \tag{5.32}$$

$$V_1 = (m_B + 2m_W + \frac{2J}{r^2})(I_2 + m_B^2) - m_B^2 \cos^2(\Theta), \tag{5.33}$$

$$V_2 = I_3 + 2K + (m_W + \frac{J}{r^2})\frac{d^2}{2} - (I_3 - I_1 - m_B^2) \sin^2(\Theta). \tag{5.34}$$

5.2 Numerical Simulation

- **Discrete Numerical Simulation:** Elaboration on the process of discrete numerical simulation, including the discrete double integration method to arrive at the state vector.

5.3 Simulation Environment

- **Overview of the Simulation Environment:** A brief overview of the simulation environment, referencing David's Bachelor Thesis for details.

Table 5.1: Parameters of the mechanical system

Parameter	Value	Description
m_B	2.5 kg	mass of the pendulum body
m_W	0.636 kg	mass of a wheel
l	0.026 m	distance between the wheel axis and the pendulum's center of gravity
d	-	distance between the two wheels
J	$5.175e^{-4}$ kgm^2	moment of inertia of a wheel w.r.t. reference frame {C} in direction of c_2
K	-	moment of inertia of a wheel w.r.t. reference frame {C} in direction of c_3
I_1	-	moment of inertia of pendulum's body w.r.t. reference frame {B} in direction of b_1
I_2	0.0165 kgm^2	moment of inertia of pendulum's body w.r.t. reference frame {B} in direction of b_2
I_3	-	moment of inertia of pendulum's body w.r.t. reference frame {B} in direction of b_3
c_α	$4.630e^{-4}$ Nms	viscous friction coefficient

- **Integration of the Model:** Description of integrating the new TWIPR model into the simulation environment and a summary of the individual components of the model.

5.4 Controller Synthesis

- **State-Space Controllers:** Introduction to two state-space controllers: Linear Quadratic Regulator (LQR) and Pole-Placement.
- **Configuration Specificity:** Explanation of how these controllers are specific to one configuration (knee angle and hip angle) of the robot.
- **Controller Retuning Algorithm:** Presentation of an algorithm for retuning the controllers as the configuration changes.

5.5 Simulation Analysis

- **Controller Responses:** Analysis of step response and responses to other inputs using one of the controllers in different configurations.
- **Impact of Non-Retuning:** Discussion on the effects of not retuning the controllers.
- **Influence of Leg Configuration:** Analysis of how leg configuration influences the robot's behavior.
- **Controller Setting Comparisons:** Comparative study of different controller settings and a comparison between LQR and Pole-Placement controllers.
- **Optimal Controller Configuration:** Conclusion on which controller configuration might be best suited for such a robot.

6 Mechanical Assembly

- Intro Overview of the chapter.
- Importance of mechanical assembly in the overall project.

6.1 Components Overview

- Detailed description of all mechanical components used in the robot.
- Source or method of fabrication for each component (e.g., machined parts, 3D printed elements).

6.2 Assembly Process

- Step-by-step explanation of the assembly process.
- Tools and techniques used in the assembly.
- Assembly sequence and rationale behind it.

6.3 Integration of Mechanical and Electronic Systems

- Discussion on how mechanical components interface with electronic systems.
- Challenges faced in integration and strategies employed to overcome them.

6.4 Troubleshooting and Problem Solving

- Discussion of any unexpected challenges or issues faced during assembly.
- How these issues were diagnosed and resolved.

6.5 Safety Considerations

- Safety measures taken during the assembly process.
- Design considerations for ensuring the operational safety of the robot.
- **Discrete Numerical Simulation:** Elaboration on the process of discrete numerical simulation, including the discrete double integration method to arrive at the state vector.

Note 6.1
the bolts used the problem to shorten them so that it wouldn't touch the motor

7 Firmware and Testing

- Overview of the chapter's content and its significance in the context of the overall project.
- Briefly state the objectives of firmware development and testing procedures.

7.1 Firmware Development

- Discuss the development environment and tools used for firmware programming.
- Detail the architecture and design of the firmware, including flowcharts or state diagrams if applicable.
- Explain the implementation of key functionalities such as control algorithms, sensor integration, and actuator management.

7.2 Programming Languages and Tools

- List and describe the programming languages used for firmware development.
- Mention any specific software tools, libraries, or frameworks employed.

7.3 Integration with Hardware

- Discuss how the firmware interacts with and controls the hardware components.
- Explain any challenges encountered in integration and how they were resolved.

7.4 Testing Framework and Methodology

- Outline the testing framework used to validate the firmware.
- Describe the methodology for functional testing, including unit tests, integration tests, and system-level tests.

7.5 Test Cases and Scenarios

- Present the results of the testing procedures.
- Analyze these results, highlighting successful areas and identifying any issues or bugs discovered.

7.6 Debugging and Troubleshooting

- Discuss the process of debugging and troubleshooting encountered problems.
- Explain how issues were diagnosed and resolved.

Note 7.1
the bolts used the problem to shorten them so that it wouldn't touch the motor

8 Safety

- hardware.
  - motors
    - Hip motor is enclosed in the body.
    - the knee motors are enclosed in cover.
    - the wheels motors have a
  - wiring
    - where the wires are neatly fastened in a predetermined route so that it wouldn't be caught in the robot movement which would cause damage to the robot and also to protect them from damage.
    - the correct type were used to avoid overheating upon the draw of current from the divers.
    - Rs-485 connection between motors where used to avoid additional cables.
  - proximity sensor
    - placed in the front and back side of the robot would help to detect crashing in trivial positions such as running into a wall and that could be easily prevented by proximity sensor monitoring the distance between the robot the and the obsticals in it direction.
  - body safety additional parts in case of impact to protect the internal components.
- software.

Questions to answer in each section

1. what is going to be in here?
2. how long or how elaborate?
3. what is the purpose (the take home message)?

Table of content Draft

1. Introduction
   a) Background and Motivation
      i. Discuss the evolution and significance of robotics in various industries.
      ii. Emphasize the need for advancements in robotic stability and mobility.
   b) Problem Statement
      i. Define the specific challenges in designing a legged self-balancing robot.
   c) Objectives(Outline the primary goals of the thesis)

2. Literature Review
    a) Overview of Robotics
    b) Previous Work in Self-Balancing Robots
    c) Control Strategies
        i. what is going to be in here? a comparison of the control strategies used.
        ii. how long or how elaborate? not too detailed but with more explanation of the control theory used in the project
        iii. what is the purpose (the take home message)? pros and cons of the different and why would we prefer one of them over the other depending on the applications
3. Design and Development of the Robot
    a) Mechanical Design
        i. Initial calculations
            A. what is going to be in here? -> torque initial calculations
            B. how long or how elaborate? -> two or three scenarios
            C. what is the purpose (the take home message)? for choosing the correct motors
        ii. design
            A. what is going to be in here?-> CAD design and the explanations of the challenges
            B. how long or how elaborate? detailed explanations of the reason behind the design decision
            C. what is the purpose (the take home message)? assembling the robot with fitting parts to match the new model requirements
        iii. Modeling
            A. what is going to be in here?-> the figures for the new model and the new COG and MOI calculations and the equations of motion.
            B. how long or how elaborate? 4 to 5 pages explaining the equations in details
            C. what is the purpose (the take home message)? showing the calculations for the new model and it would influence the equations of motion.
    b) Electrical Design
        i. what is going to be in here? Component diagram showing the choice of all the components and there intended use and why we chose each of these components
        ii. how long or how elaborate? detailed explanation of the requirement boards for operating the robot, the choice of components based calculations for the motors.
        iii. what is the purpose (the take home message)? show how the Electrical design is configured in the optimal way to operate the robot
    c) Software and Control
        i. Control Algorithm

A. what is going to be in here?->flowchart of the Control Algorithm

B. how long or how elaborate?-> detailed explanation of the used control theory

C. what is the purpose (the take home message)? -> how the control is implemented

ii. Firmware

d) Safety

i. what is going to be in here? different design changes for safety measures(motors covers, wire routing, body bumper, distance sensor , algorithm safety, electrical safety)

ii. how long or how elaborate? 1 or two pages max that include the

iii. what is the purpose (the take home message)? the safety measures taken to minimize crashes, failure

4. Experimental Setup and Methodology
   a) Simulation Environment
   b) Physical Prototype Testing
   c) Data Collection and Analysis
5. Results and Discussion
   a) Simulation Results
   b) Real-world Performance
   c) Comparison and Analysis
6. Conclusion and Future Work
   a) Summary of Findings
   b) Contributions
   c) Recommendations for Future Research

content..

9 Random(Erase)

This comprehensive chapter unfolds the intricate details of the new design of our two-wheeled self-balancing robot, an advanced piece of engineering that incorporates additional degrees of freedom to enhance its movement capabilities. Through an exploration of the various motions the robot can perform, we delve into the intricate design considerations of each component, ensuring that they align with the overall functional and aesthetic vision.

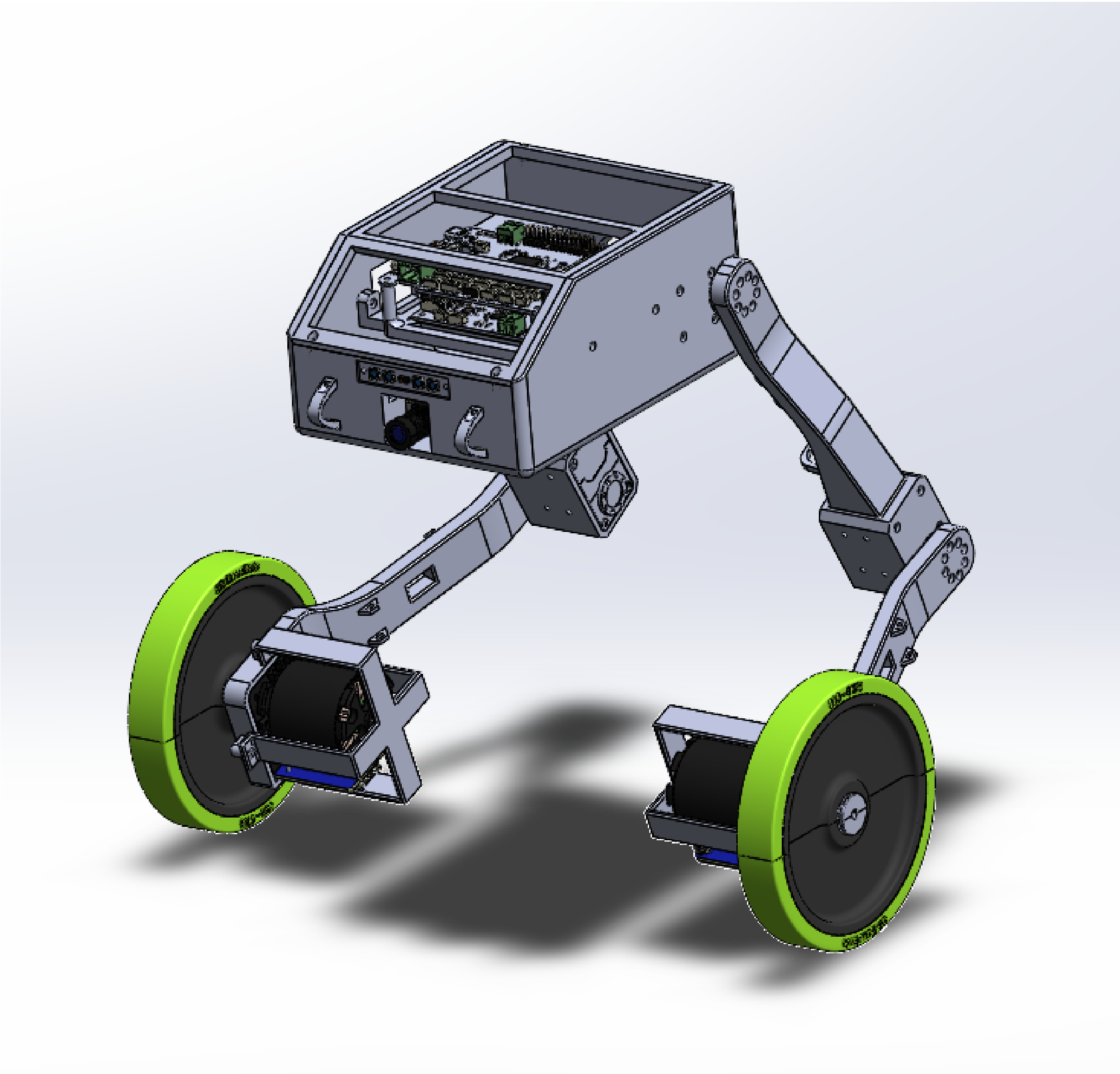


Figure 9.1: Schematic representation detailing the requisite angles and lengths for calculating the moment of inertia.

- The Robot new design.
- The added degrees of freedom.
- Different motions that can be performed.
- Discussing each component of the robot and things taken into account while designing it.
  - Body
    - overall design inspiration
    - For the body: the consideration for including all the necessary components in a compact form is to optimize the use of space and at the same time distribute the weight equally.
    - The body includes the hip motors, the battery, camera, sensor, a rack that includes the motors drivers board, the micro-controller board attached to the Raspberry Pi.
    - fastening features that were specifically designed in order to easily mount the battery, organize the cable between the boards and the rest of the robot parts.
    - Features for modular design and easy printing.
  - Thigh
    - curvature of that joint to give room for the motors
    - cable management
    - motor cover to insure its fixation.
  - Calf
    - curvature of that joint and the thigh joint combined make enough room for the wheel motor so the it have clearance from the body.
    - cable management
    - motor mount and additional frame.

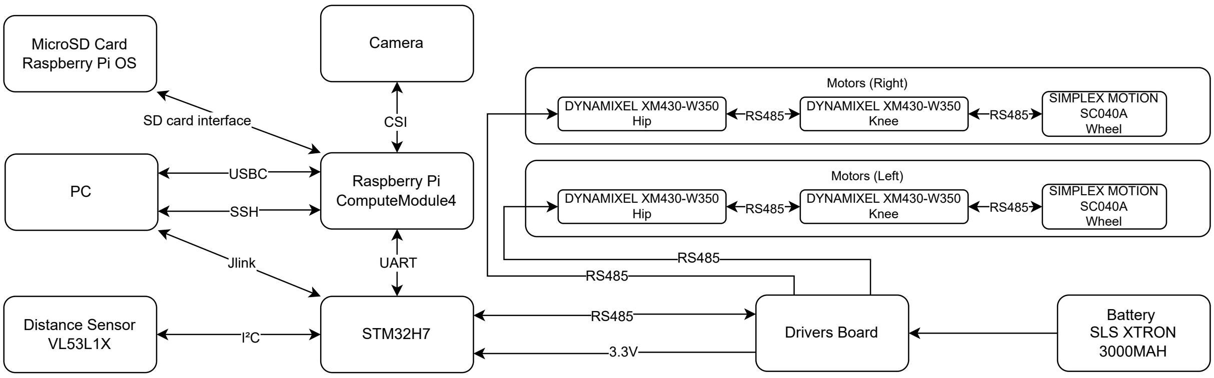


Figure 9.2: Schematic representation detailing the requisite angles and lengths for calculating the moment of inertia.

- electronic components
  - Motors taking into count the needed torque and speed
  - comparison between the BLDC and Geared Robotic
  - RS-485 communications protocol compared to others
    - for the knee and hip motors high torque and low speed is needed.(calculations the show the weights and the needed torques)
    - for the wheel motors high speed and low torque is needed.
  - Boards
    - STM high performance h7 constum board connected with rasberrypi
    - driver board that provide the power for 6 motors.
  - modules
    - camera module.
    - distance sensor.

Bibliography