Capstone Project II Report

Design, Simulation, and Validation of a Humanoid Torso for Bipedal Robot Gait Stabilization

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A thesis submitted in part fulfilment of the degree of

BS in Robotics Engineering

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May 30, 2025

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Abstract

This project focuses on the design, simulation, and validation of a humanoid torso for bipedal robot gait stabilization. The primary aim is to improve balance and minimize lateral motion during walking by incorporating two degrees of freedom (DOF) in the waist joint. The project involves developing simulation for different robot configurations and gaits with the focus on comparing their performance in terms of energy efficiency in PyBullet simulation environment as well as early real life prototype tests based on the simulation data. The experiments clearly demonstrate the improvements caused by incorporating the upper body of the bipedal robot as a means of balancing in terms of energy efficiency by reducing the lateral movement in the lower body. Real life prototype tests have shown that closed loop control is necessary to avoid disturbances and effects of unideal conditions which are not present in the virtual environment. With the results acquired during this project, further experiments on the upper body motions can be carried out to improve bipedal walking gaits.

Acknowledgments

We would like to express our sincere gratitude to the following individuals who have provided invaluable support and guidance throughout our project:

- **Timur Umurzakov**, PhD Candidate at Nazarbayev University.

- **Sharafatdin Yessirkepov**, PhD Candidate at Nazarbayev University.

- **Samuel Paul Roshaven**, Humanoid Robotics Laboratory Research Assistant at Nazarbayev University.

Chapter 1: **Introduction**

The development of bipedal robots capable of efficient locomotion has been a longstanding challenge in the field of robotics [1]. One approach is the exploration of gait patterns that ensure stable locomotion by integrating the use of the upper body for balance control.

The existing robot prototype incorporates a robot base, which is similar to pelvis, and the two legs attached to it. This together constitutes what we refer to as the lower body.

The aim of the project is to develop a robotic humanoid torso that aids motion by reducing the need for lateral movement in the lower body, achieving greater stability, energy efficiency and more human-like locomotion of bipedal robot.

Thus, the objectives of this project are as follows:

1. Design the system, including the integration of two Degrees of Freedom (DOFs) in the waist and the mounting of new motors.
2. Export the new model into PyBullet and make a simulation.
3. Adapt an existing gait algorithm to optimize waist joint trajectories, enhancing system balance, reducing lateral motion and consumed energy.
4. Start to realize the real prototype based on the simulation results.
5. Conduct testing and comparison of the prototype to refine the design further.

By following the steps listed above, we will conclude our Capstone Project with a bipedal robot design incorporating a torso for gait stabilization, which could serve as a base for further research on humanoid bipedal locomotion both for the researchers in our university and possibly on a more global scale.

Chapter 2: **Literature Review**

In this chapter, we present a review of developing a gait for the bipedal robot that uses the upper body for balancing. To provide a comprehensive overview of the current state of research in this area, this review will examine a selection of 14 research papers retrieved from the Scopus database. By synthesizing the findings of these papers, we aim to identify key insights, trends, and challenges in the development of bipedal gaits that use upper body dynamics for balance control.

2.1 Methodology

The Scopus database was used to gather research papers on our theme. A comprehensive search was conducted using key terms such as "bipedal robot" and "upper body". Studies were included if they focused on bipedal robots, incorporated upper body elements (e.g., torso or arms) in gait or balance control. Priority was given to works published from 2010 onward. In addition, we used SciSpace AI, which helped quickly summarize and highlight the most relevant details from each paper. After applying the inclusion and exclusion criteria, 14 relevant papers were selected out of an initial pool of 103 identified through the Scopus search. After that, all selected papers were manually reviewed and analyzed to ensure accurate interpretation.

2.2 Bipedal Locomotion

Bipedal locomotion, the ability to move using two legs [2], is a remarkable feature observed in various organisms, including humans. Understanding the fundamentals of bipedal locomotion is essential for the design and control of bipedal robots that aim to mimic human-like movements.

2.2.1 Anatomy and Mechanics of Bipedal Walking

The lower part of bipedal robots typically consists of a complex arrangement of actuators and joints to mimic human locomotion. These robots are designed with various degrees of freedom in multiple dimensions to facilitate dynamic movement and stability. At the hip, they commonly feature yaw, roll, and pitch joints, providing flexibility and range of motion akin to human hips. These joints enable the robot to adjust its orientation and posture while walking or performing tasks. The knee joints, crucial for weight-bearing and stride control, allow for smooth and efficient walking patterns [3].

Some advanced designs also incorporate ankle pitch joints, which could increase their walking capabilities over rough terrain, although their implementation adds complexity due to the additional actuators required [4]. Despite their importance in achieving natural gait and balance, toe joints are relatively rare in bipedal robots, often rendered passive, since the added complexity is generally not worth the change in stability [4].

2.2.2 Integration of Upper Body Dynamics in Gait Control

Recent research highlights the crucial role of upper body dynamics, specifically torso and arm motion, in enhancing the stability of bipedal robots. Ebrahimi et al. [5] showed that incorporating active control into a passive walker significantly improves gait robustness across varying terrains. Similarly, Liu et al. [6] employed a Zero Motion Point based gait control framework with upper body motion, resulting in more natural postures and improved knee extension.

Kamimura and Sano [7] introduced a model with a horizontally oscillating upper body mass, which helped smooth accelerations and stabilize gait. Gao et al. [8] demonstrated that arm swings can effectively counteract yaw disturbances during walking, though this method requires precise control and real-time feedback.

Various strategies, ranging from passive upper body oscillation to active momentum compensation, demonstrate that integrating upper body dynamics can reduce energy consumption and promote more human-like gait patterns [9, 6].

2.2.3 Learning Methods of Bipedal Robots

To achieve stable and efficient walking in bipedal robots, there are a variety of learning and control approaches.

One of the most common strategies is model-based control, where simplified dynamic models like the Linear Inverted Pendulum Model (LIPM) are used to generate walking trajectories. This model treats the robot like a pendulum standing on one leg, helping calculate where and how to move to stay balanced. While this method is fast and works well on flat surfaces, it doesn't adapt easily to uneven ground or unexpected changes [10].

In response to these limitations, optimization-based methods have gained popularity. For example, Clever et al. [10] trained robots to walk by learning from how humans move, using a method called inverse optimal control. This approach helps generate motions that look more natural and adjust to different situations. Ding et al. [11] took another step further with Nonlinear Model Predictive Control (NMPC), a technique that continuously plans and adjusts the robot's steps by considering momentum and changes in body height. This allows the robot to stay balanced even during dynamic walking.

Another important concept is energy efficiency, measured by something called the Cost of Transport (COT). It tells us how much energy the robot uses to move a certain distance. An et al. [12] showed that changing the shape and weight of the robot's upper body can significantly lower energy use without making walking less stable.

Learning-based approaches, such as trajectory imitation from human motion, offer another way to generate realistic walking patterns. However, these methods often lack flexibility unless combined with adaptive feedback mechanisms.

2.2.4 Challenges in Achieving Stable Bipedal Locomotion

Achieving stable bipedal locomotion is a challenging task in the fields of robotics and biomechanics [13]. Unlike quadrupeds or wheeled robots, bipeds must constantly maintain balance through complex interactions between their mechanical structure, sensory feedback, and control algorithms.

According to research articles, it was revealed that problems in achieving stable bipedal locomotion in robots are due to various factors:

1. Research about a behavior-based reinforcement learning approach[14] shows that the relatively small body mass of bipedal robots affects balance of it.

2. Robots do not have complex sensors to perceive the environment like humans do [13]. This deficiency hinders their ability to effectively navigate various landscapes and environments.

3. Hardware limitations, such as joint motor torque limitations, reduce the effectiveness of arm rotation in compensating for changes in momentum during locomotion [8].

In conclusion, achieving stable bipedal locomotion requires addressing challenges related to balancing the robot design, improving sensory capabilities for perceiving the environment, and overcoming hardware limitations that affect upper body coordination.

2.3 Conclusion

2.3.1 Summary of Key Findings

This review highlighted the importance of integrating upper body dynamics to enhance the stability of bipedal locomotion. While lower body control is central to movement, the upper body through arm motion, torso rotation, and mass distribution plays a critical role in maintaining balance, especially in response to external disturbances.

Various control strategies have been explored, including model-based, optimization-based, and learning-based approaches. Model-based methods are efficient but less adaptable, optimization offers flexibility and energy efficiency, and learning-based techniques provide lifelike motion yet often lack generalization. Hybrid strategies that combine these methods are emerging as a promising direction for robust locomotion.

Key challenges include hardware limitations (e.g., low joint torque), coordination complexity between upper and lower body, and limited adaptability of learned behaviors in varied environments.

2.3.2 Suggestions for Future Research

Future research should focus on developing integrated control frameworks that combine feedback, predictive, and learning-based strategies. Enhancing sensory capabilities and addressing hardware limitations will also be essential for achieving more resilient and adaptive bipedal robots capable of operating in real-world, dynamic environments.

Chapter 3: **Methodology**

3.1 System Design

The methodology involves a systematic approach to design, simulation, and validation, ensuring optimal performance in both virtual and real-world environments. Thus, it is divided into three key phases: Upper Body Design, Gait Algorithm Development, and Prototype Development. Each phase is critical to ensuring the final product meets the desired performance criteria.

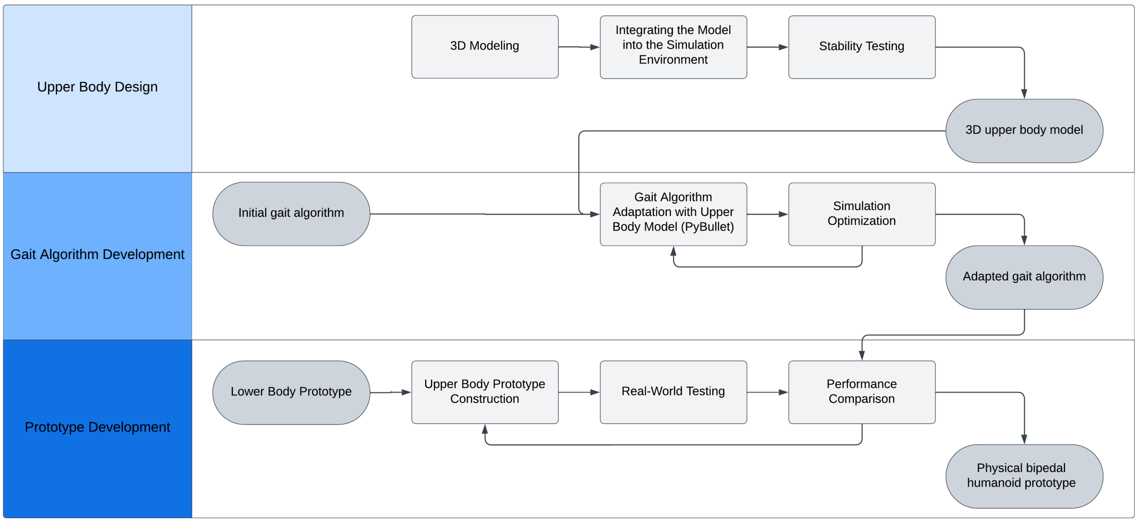

Figure 3.1: System Design

1. **Upper Body Design**
    - **3D Modeling**: FreeCAD software is used to design the new upper body, focusing on incorporating additional motors and joints.
    - **Integration with Simulation Tool**: The designed model is exported from FreeCAD to CoppeliaSim for simulation and testing.
2. **Gait Algorithm Development**
    - **Adaptation of Existing Algorithms**: Modify a pre-existing gait algorithm to optimize waist joint trajectories for balance.
    - **Simulation Testing**: Validate the gait algorithm through iterative simulations, adjusting based on performance.
3. **Prototype Development**
    - **Real-World Testing**: A physical prototype will be built and tested to compare with simulation results.

During each phase of development, the following software tools are utilized accordingly:

- **FreeCAD**: Used for modeling and designing new components for the robot.
- **Spyder**: Installed as the primary Python development environment to facilitate coding and debugging.
- **CoppeliaSim**: Initially used for simulation, particularly in the early stages of the project, as the lower body design is already available on this platform.
- **PyBullet**: Utilized for simulating bipedal robot dynamics, chosen for its robust simulation capabilities, ease of integration with Python, and support for detailed physics-based simulations.

3.2 Justification of Methods

The methodologies and tools selected for this project are critical to effectively designing a humanoid robot torso for bipedal gait stabilization:

1. **Phased Approach**: The project is divided into three stages—Upper Body Design, Gait Algorithm Development, and Prototype Development. This structure enables focused development, thorough testing, and iterative improvements at each phase.
2. **Simulation Tools**: CoppeliaSim is initially used for its user-friendly interface and compatibility with existing lower body designs. Transitioning to PyBullet enhances our ability to simulate complex dynamics and integrate Python-based algorithms efficiently.
3. **Gait Algorithm Adaptation**: Modifying existing algorithms enables us to build on established methodologies while tailoring them to our design, promoting reliability and reducing development time through iterative testing.
4. **Prototype Development**: Building a physical prototype allows for real-world validation of our designs and algorithms, ensuring practical applicability and performance reliability.

This combination of methods ensures that the project effectively meets its objectives of optimizing bipedal gait stabilization.

Chapter 4: **Implementation & Execution with Results**

4.1 Bipedal Robot Design for Simulation

4.1.1 Inverted Pendulum Design

With supervision from the instructor, we decided on the architecture and design of the 2 DOF inverted pendulum. The upper body is an open kinematic chain which consists of 2 actuated joints with a mass attached as the end effector (Figure 4.1 and 4.2). The first element is the motor which rotates the upper body around the roll axis, and the second is the one that rotates around the pitch axis. The joint axes intersect, thus achieving better control and stability of the system. Additionally, this way the motors are located as close to each other and the lower part of the body as possible, which results in less torque required to hold the joints in a required position, thus reducing energy consumption and mechanical wear.

Additionally, a bearing, shown in blue in Figure 4.3, is included in the design to provide smooth rotational motion and structural support. It is positioned symmetrically to the pitch motor, ensuring balanced load distribution and enhancing the stability of the system.

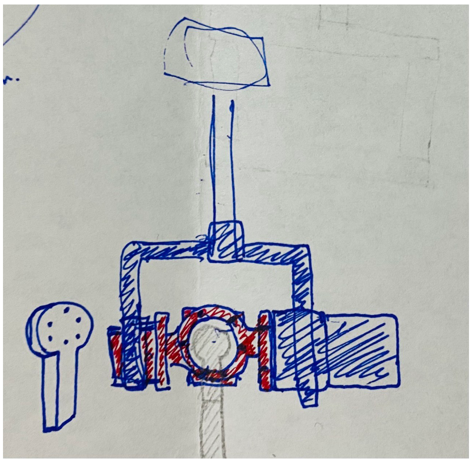

Figure 4.1: Sketch of the Upper Body Design

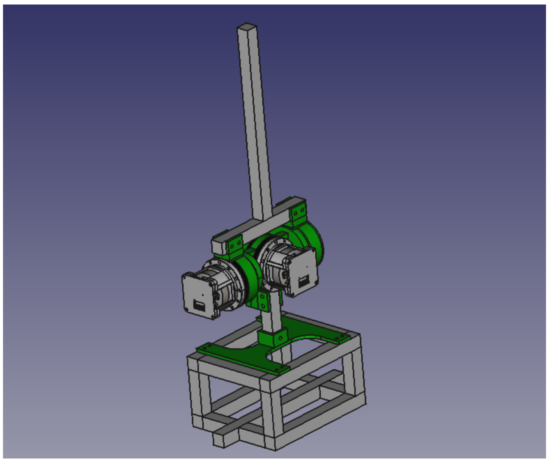

Figure 4.2: 3D model of the Upper Body

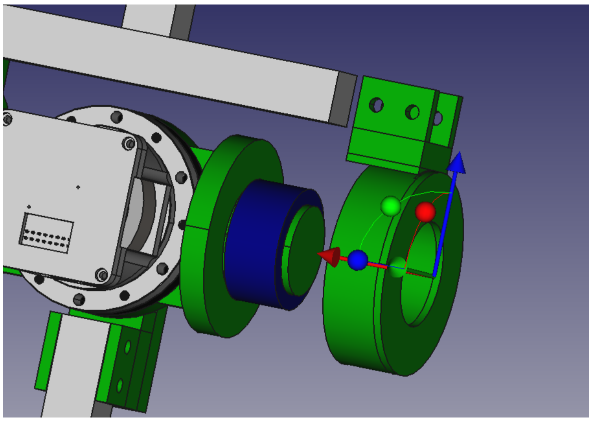

Figure 4.3: Bearing Part of the Upper Body

Also, the motors use harmonic gearing as a reduction drive. Harmonic gearing (or strain wave gearing) reduction drives experience less backlash, which is the primary reason to use them over the more common planetary reduction drives, which suffer from this issue. This is crucial in our application, as control over the position of the center of mass must be precise, and uncontrollable motion introduced by the backlash is unacceptable. According to the datasheets, changing actuators resulted in a reduction of the maximum backlash angle by a factor of 15, from planetary gearbox's 5 arc minutes to harmonic drive's 20 arc seconds.

4.1.2 Lower Body Prototype and CAD Model Update

As part of the ongoing development of the humanoid robot, several design modifications were made to enhance both functionality and aesthetics. These changes include the integration of harmonic drives across the hip joints and narrower robot base which resulted in decrease in backlash and reduction of the width between the robot's legs.

Backlash introduces uncontrollable motion, which must be avoided in order to achieve smooth and reliable movement. Given the length of the legs, reducing backlash from hip joints is especially important, as just 1 degree off in hip joint's roll angle would offset the foot position by more than 1 cm, which is not a negligible error.

$$\text{Horizontal offset} = \tan(\text{backlash angle}) \times \text{leg length} = \tan(1^\circ) \times 95\,\text{cm} = 1.66\,\text{cm}$$

Making the legs closer together reduces the need for extensive lateral motion and makes the gait more natural and human-like.

The entire lower body of the bipedal robot was modeled in FreeCAD according to real-life dimensions. Precise measurements were taken, ensuring that the simulated model closely matches the physical prototype. This accurate representation allows for realistic simulations, making it easier to test and refine gait algorithms before real-world implementation. Figure 4.4 shows the physical prototype, while Figure 4.5 presents the corresponding 3D model used in the simulation environment.

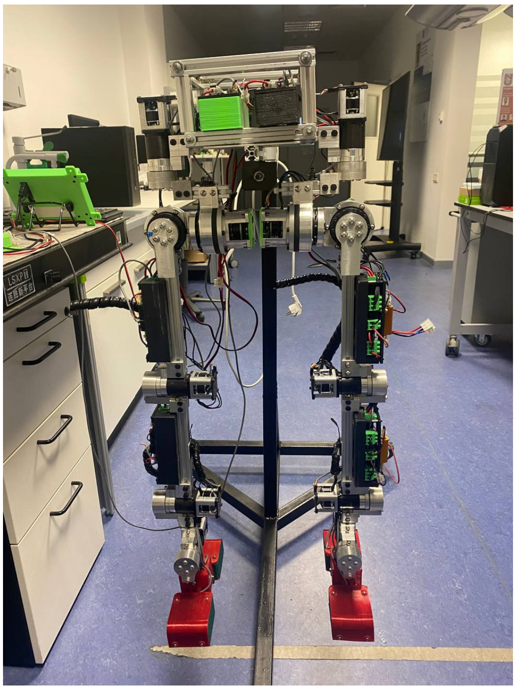

Figure 4.4: Real-life robot prototype

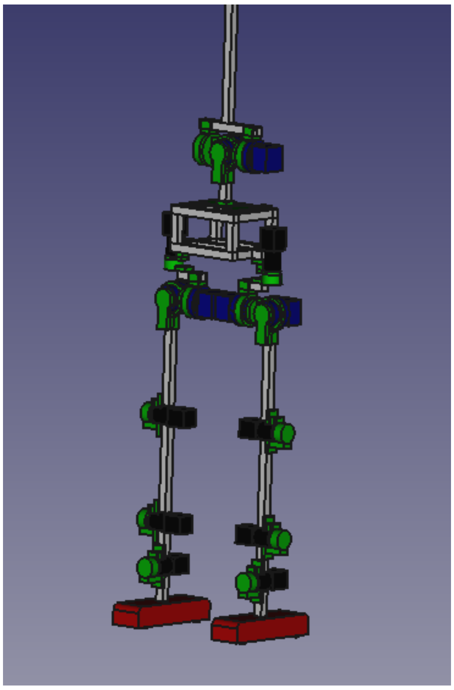

Figure 4.5: 3D model of the humanoid robot

Furthermore, the upper body design was also incorporated into the CAD model, maintaining consistency with the lower body dimensions. This detailed modeling ensures that the humanoid robot behaves as expected in the simulation environment, providing valuable insights before moving to the physical assembly stage.

4.1.3 Model Preparation for Simulation Environment

Joint Configuration

The humanoid robot is equipped with a total of 14 revolute joints, strategically placed to provide the necessary range of motion for lifelike movement and flexibility. These joints are designed to mimic the articulation of the human body.

Joint	**Direction**	**Degrees of Freedom**
Waist	x, y	2 d.o.f. × 1 = 2 d.o.f.
Hip	x, y, z	3 d.o.f. × 2 = 6 d.o.f.
Knee	y	1 d.o.f. × 2 = 2 d.o.f.
Ankle	x, y	2 d.o.f. × 2 = 4 d.o.f.
	Total	**14 d.o.f.**

Table 4.1: Degrees of freedom of the humanoid robot

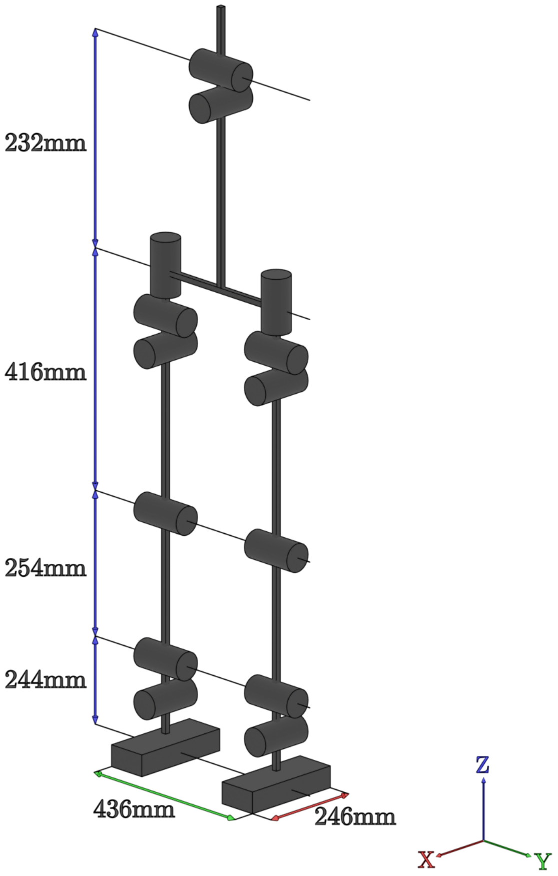

Figure 4.6: Kinematic Architecture [*Proportions are not to scale*]

Dimension	**Value**
Height	1614 mm
Width	436 mm
Depth	246 mm
Length of thigh (hip to knee)	416 mm
Length of shin (knee to ankle)	254 mm
Length of ankle (ankle to foot)	244 mm

Table 4.2: Physical dimensions of the humanoid robot

Assigning Physical Properties

Subsequently, the constructed 3D model of the bipedal robot was imported into the CoppeliaSim simulation environment. Within this environment, a hierarchical structure was implemented by establishing parent-child relationships between the consecutive robot's links, thereby ensuring accurate representation of its kinematic chain. This setup enables realistic dynamic simulation and control of the robot's motion. The complete kinematic structure is illustrated in Figure 4.7.

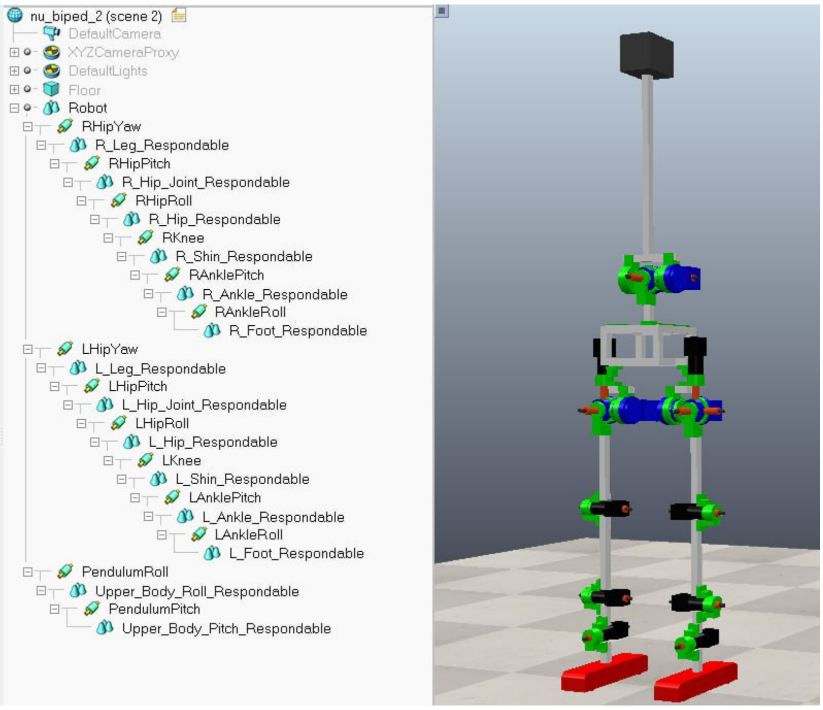

Figure 4.7: Updated model and Scene Hierarchy in CoppeliaSim

Additionally, realistic physical properties were assigned to each part of the robot. The masses of the motors were measured directly from the physical hardware and manually entered into the simulation. For the structural components, such as the aluminum extrusions and connecting parts, we specified a uniform material density for aluminum. Using this density along with the known geometry, CoppeliaSim was able to automatically calculate their masses. To simplify the simulation and and due to their relatively low contribution to overall system dynamics, we chose to neglect the masses of smaller auxiliary components, including electronic control boards (PCBs), wiring, motor drivers, and fasteners like bolts and screws. Despite these simplifications, the physical model remains sufficiently accurate to represent the robot's dynamic behavior in simulation.

Estimation of Mass and Length of Upper Body

To estimate the mass distribution of our bipedal humanoid robot, we began with the known mass of one leg, which is approximately 4.8 kg. This value was determined from the model in CoppeliaSim. According to the human body mass distribution model presented in [15], each leg accounts for 15% of the total body mass, and the upper body accounts for 70%. Using this reference, we reverse-calculated the total mass of the robot and the corresponding upper body mass.

Given that one leg (15%) is 4.8 kg, the total mass of the robot is:

$$\text{Total mass} = \frac{4.8\ \text{kg}}{0.15} = 31\ \text{kg}$$

From this, the mass of the upper body is:

$$31\ \text{kg} \times 0.70 = 21.7\ \text{kg}$$

For the simulation, we modeled the upper body as an inverted pendulum and attached a point mass at its top. To determine this pendulum mass, we subtracted the masses of other upper body components, including the waist joint motors and structural parts, from the total upper body mass. As a result, the pendulum mass was set to approximately 8 kg. We then adjusted the pendulum length manually on CoppeliaSim environment so that the height of its center of mass (COM) matched the estimated COM height of the human body visually.

This distribution ensures that our robot maintains a similar balance and dynamic behavior to a human body, which is crucial for stable bipedal locomotion. The final mass distribution used in our design is summarized in Table 4.3.

Table 4.3: Mass Distribution of the Bipedal Humanoid Robot

Component	**Mass (kg)**
Legs (30%)	9.6
Upper Body Total (70%)	21.7
Other Components	13.4
Inverted Pendulum Mass	8.0
Total Body Mass	**31.0**

Export URDF(Unified Robot Description Format)

Once the design and mass distribution were finalized, we exported it as a URDF file. This URDF file, containing all relevant parameters such as joint types, positions, and link configurations, was then imported into PyBullet for further simulation and testing(Figure 4.9).

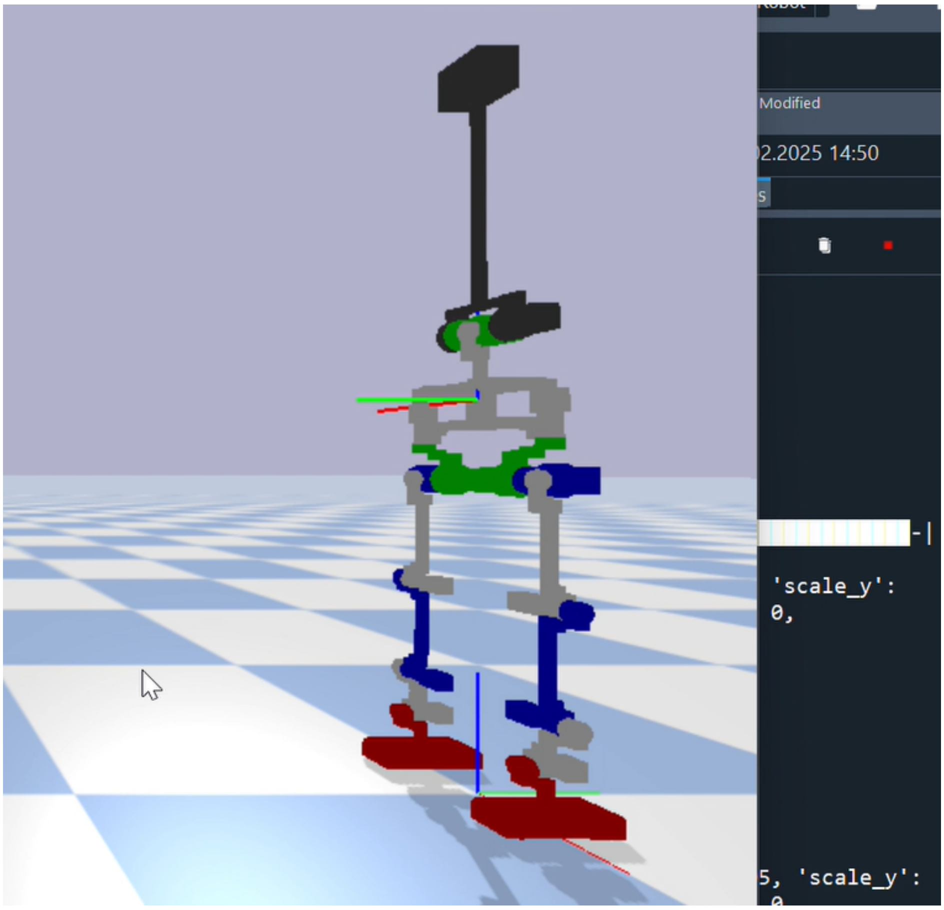

Figure 4.8: Robot Simulation in PyBullet

4.2 Gait Algorithm Development

4.2.1 Random Grid Search Based Hyperparameter Optimization

Having updated the model once again and verified the inverted pendulum's performance in the early tests, our next step is making the robot walk.

Our supervisor provided us with a base for a gait optimization script that involves random grid search. The idea is to have the robot's gait predefined and altered in different ways by a manually specified range of values that serve as scaling multipliers to joint movements, known as hyperparameters, which define a hyperspace in which an optimal set is found by trying different random combinations and evaluating them, which allows us to quickly find a functional one without going through all of them.

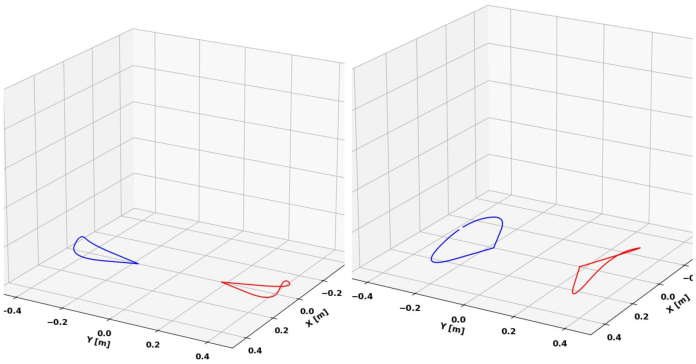

Figure 4.9: The effect of scaling parameters on the foot trajectory

4.2.2 Integrating Hyperparameter Optimization with the 14-DOF Robot Model

As the script was developed to control a 12 DOF robot with no upper body, we needed to make it work with our new robot and its additional upper body joints. By modifying some lines in the code to account for the new joints and correcting the model itself to interact with the script the intended way, we could run the optimization algorithm with the new model.

At this point, however, the upper body joints are set to maintain initial position, essentially replicating an unactuated upper body. As we want to use the upper body as a means of balancing the robot's gait, we need to come up with and implement some motion pattern for the new joints as well, which requires a deeper look into the inner workings of the script and its thorough modification.

Theoretical Considerations of Upper Body Movement

Before experimenting with different movement patterns, we concluded the following considerations:

- Periodic nature of walking. Similarly to how humans' arms swing at the same rate as stepping when walking, the upper body movement cycle must have the same time period as the legs' walking pattern to assist in balancing instead of causing out-of-sync instability.

- Proper alignment of upper body's COM and the lower body's instantaneous pose. Drawing analogy with humans' gait once more, the arms need not only to swing with the same period as stepping, but to also be in correct phase (two synchronized pairs, left leg and right arm, right leg and left arm, in antiphase to each other) to aid in walking. The same way, the robot's upper body movement must have a specific phase offset. Finding it is not easy, though, so adding a new hyperparameter may be necessary.

Extending the Hyperparameter Optimization Method to the Newly Added Joints

Having these theoretical considerations in mind, we proceeded to implement the gait that involves using the upper body for balancing. To do so, we created the sinusoidal function that controls the joint positions and introduced four new hyperparameters: phase offset and amplitude for both the roll and pitch joints of the upper body.

```
pendulum_roll_angle = scale_Roll_P * math.sin(t_norm + phase_Roll_P)
pendulum_pitch_angle = scale_Pitch_P * math.cos(t_norm + phase_Pitch_P)
```

After establishing these, we manually specified the range of possible values, initially aiming at small, safe angles, as we expect the pendulum to be effective without bending dramatically, maintaining a natural human-like movement. The initial phase offset parameter values selected have both positive and negative values, as both could result in success, and it is difficult to predict exactly which phase offset would be the most effective.

$$\begin{aligned}
\texttt{scale\_Roll\_P} &= [0.05,\ 0.075,\ 0.1,\ 0.125,\ 0.15] \\
\texttt{scale\_Pitch\_P} &= [0.05,\ 0.075,\ 0.1,\ 0.125,\ 0.15] \\
\texttt{phase\_Roll\_P} &= [-0.5,\ -0.3,\ -0.1,\ 0,\ 0.1,\ 0.3,\ 0.5] \\
\texttt{phase\_Pitch\_P} &= [-0.5,\ -0.3,\ -0.1,\ 0,\ 0.1,\ 0.3,\ 0.5]
\end{aligned}$$

4.2.3 Gait Testing with Different Upper Body Configurations

Through testing, we modified the set of hyperparameters based on results of experiments, trying different strategies such as narrowing down on good values by focusing on values closer to the successful ones and ignoring the extreme ones that were never chosen by the algorithm, or trying to find new optimal values by creating new values outside of the range to not miss other potentially successful values.

We would repeat this process of searching for optimal gait parameters across three possible configurations for future performance comparison and validation. The three configurations are: the robot without the upper body, the robot with an upper body fixed in its home position, and an active upper body. To avoid redundancy and for greater clarity, the following examples focus only on the configuration with the active upper body. However, the same data collection and analysis procedures were applied to all three configurations.

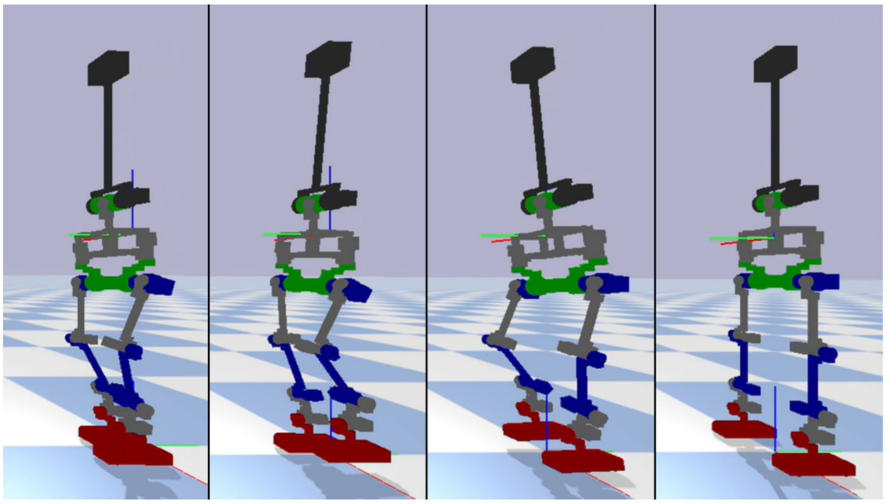

Figure 4.10: Gait Execution Result at Different Time Steps

The bipedal robot's gait execution was analyzed through a sequence of time-sampled snapshots, illustrating the movement cycle. Figure 4.10 presents the robot at different gait phases, showing leg lifting, weight transfer, and step completion. The upper body adjustments, particularly in the torso, help maintain stability while minimizing lateral deviations. The gait cycle includes the following phases:

- **Stance Phase:** One foot remains grounded while the other prepares for a step.
- **Swing Phase:** The lifted leg moves forward, preparing for the next contact with the ground.
- **Double Support Phase:** A brief period where both feet are in contact before transitioning to the next step.

In addition to this, we plotted graphs to clearly see the joint positions and torques during these gait phases.

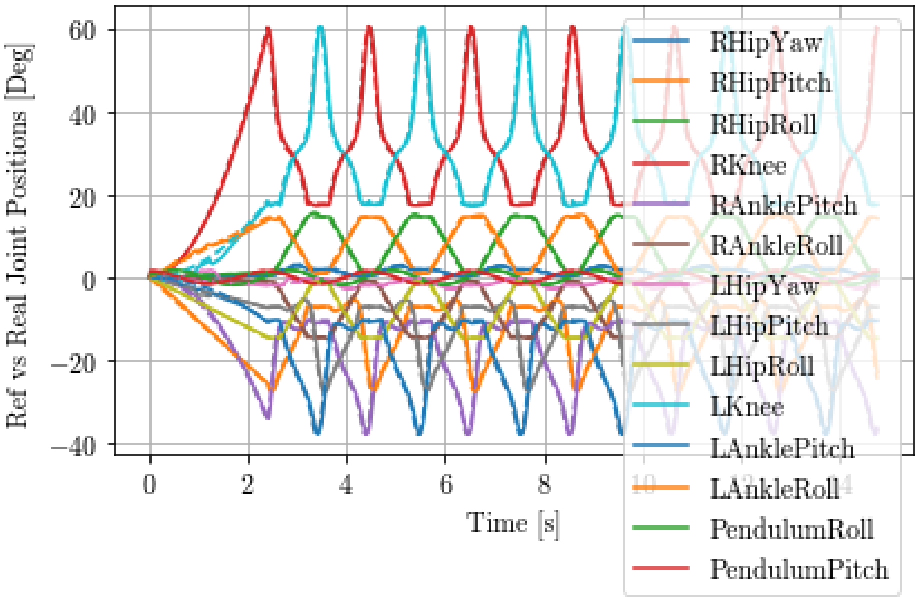

Figure 4.11: Joint Positions Plot

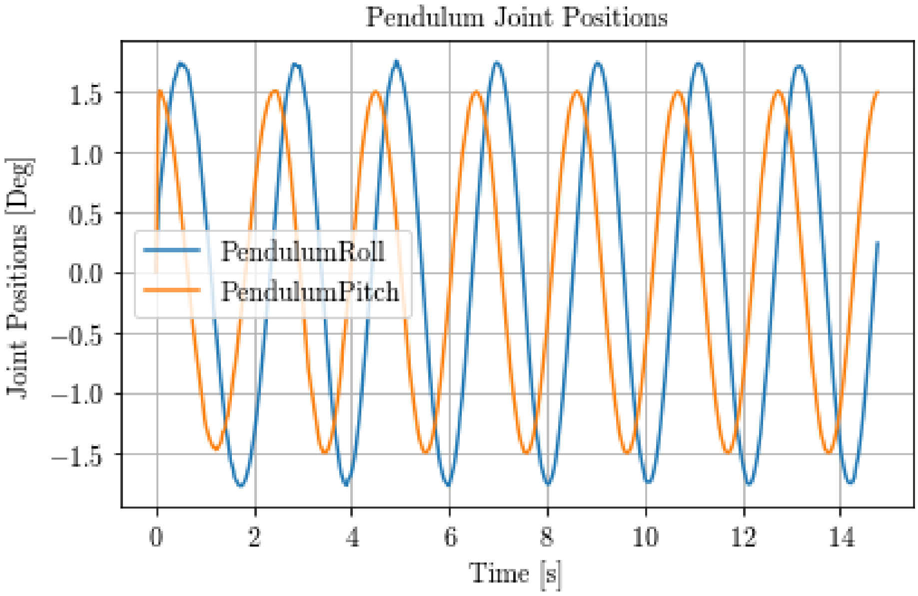

Figure 4.12: Position Plot for the Upper Body. Isolated for clarity due to low amplitude compared to other joints

The joint position graphs allow us to thoroughly review the behavior of the system, along with the video recordings of the gait. We can clearly see a transient period in the beginning followed by the desired periodic pattern of the walking gait.

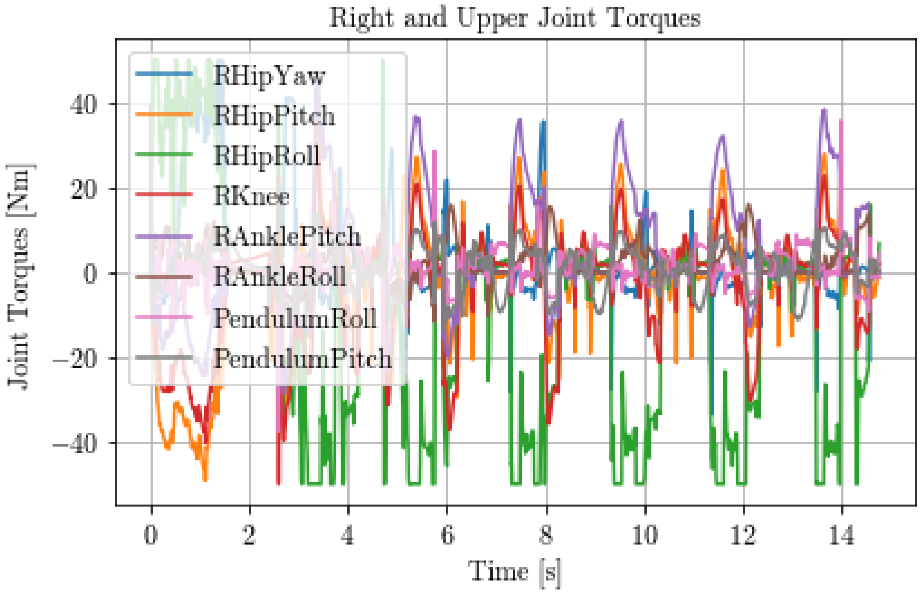

Figure 4.13: Joints Torque Plot. Only right part of the upper body is shown for clarity

The joints' torque in particular is very important for energy consumption analysis. The figure 4.13 clearly shows that the most torque is developed in the Hip Roll Joint, which is responsible for lateral movement of the lower body, further proving the claim that its reduction should lead to better energy efficiency.

Evaluation of Performance

To choose an optimal gait of many that resulted from different hyperparameter combinations, they were compared on the basis of energy consumption. However, this caused an unexpected and undesirable effect of the robots often opting to move less distance, thus conserving energy. This makes sense, as some hyperparameter combinations allow for such a choice, which the evaluation system favors. Therefore, we decided to keep the {`scale_x`} at a constant value to force the robots to cover a consistent distance across the experiments.

The amount of energy consumed is a great figure to evaluate performance when the experiments are done on the same robot in the same conditions, but we quickly realized that it falls short as a metric for performance once we started comparing the energy used by different configurations of the robot. Obviously, the configurations that utilized the upper body consumed far more energy simply due to the additional mass introduced by the pendulum. Thus, we needed a way to fairly compare the performance of different robots with varying mass and behavior.

This is where the concept of Cost of Transport (CoT) plays a key role as a powerful tool for fairly evaluating and comparing different architectures and behaviors. It is defined as a dimensionless quantity which represents how much energy is used by the robot of a certain weight to move a certain distance [12]. This means that a lower value of CoT indicates greater energy efficiency in the robot.

$$\text{CoT} = \frac{\text{Energy consumed}}{\text{Mass} \times \text{Gravitational acceleration} \times \text{Distance traveled}} = \frac{E}{mgd}$$

Having adapted CoT as a metric used for comparison, here are the results of three gait types:

gait without the pendulum, gait with the pendulum's position fixed at home position, and the one with the actuated pendulum.

(Table 4.4).

Parameter	Without Pendulum	Fixed Pendulum	Active Pendulum
scale_x	1.5	1.5	1.5
scale_y	1.0	0.7	0.65
scale_z	1.8	1.5	1.4
KneeBendDist	-0.08	-0.08	-0.08
scale_Roll_P	–	–	1.25
scale_Pitch_P	–	–	1.5
phase_Roll_P	–	–	0.225
phase_Pitch_P	–	–	0.0
Energy Consumed (E)	361.5 J	479.8 J	437.3 J
Distance Covered (d)	1.44 m	1.31 m	1.32 m
Robot's Mass (m)	17.7 kg	30.8 kg	30.8 kg
CoT	**1.45**	**1.21**	**1.09**

Table 4.4: Comparison of simulation parameters for different walking gaits and architectures.

The results clearly indicate that the addition of the upper body leads to more energy efficient gait. Even unactuated, the upper body shifts the center of mass higher, which makes moving the center of mass projection to the supporting leg require less lateral motion. Though it is clear that the superior approach is when the upper body is allowed to sway and actively contribute to the shift of center of mass projection. Video recordings of the gait in simulation environment can be found in the appendix 7.

4.3 Real Prototype Development

4.3.1 Upper Body model for Manufacturing

The detailed upper body model was designed specifically for manufacturing and differs from the simulation model in key aspects. While the simulation model focused on the robot's dynamics, the manufacturing model includes the necessary details for actual construction, such as:

- **Structural Components:** Lightweight aluminum extrusions to ensure strength and ease of assembly.
- **Bolts and Fastening:** Holes for bolts and screws have been added to securely fasten components. These details are shown in Figure 4.14.
- **Bearing Selection:** As mentioned in section 4.1.1, a bearing was integrated into the pitch axis to reduce friction and ensure smooth movement. For the robot prototype, we selected the 6807RS bearing (35x47x7 mm, sealed), in Figure 4.15, for its compact size and load-handling capabilities. To ensure sufficient support and stability in the joint mechanism, three of these bearings are installed in series.

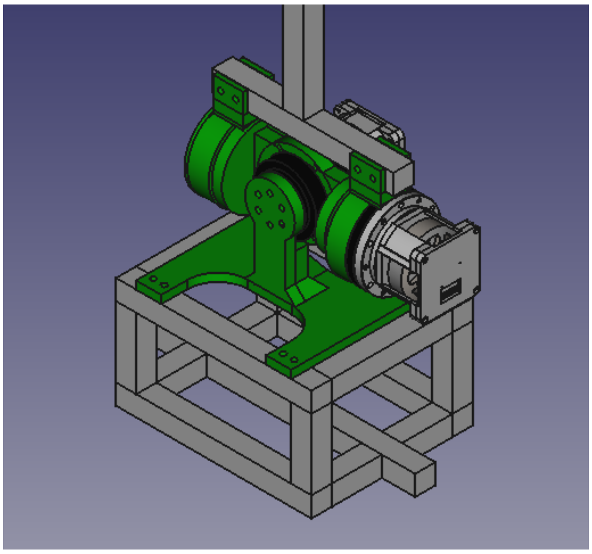

Figure 4.14: Detailed Upper Body model for Manufacturing

Figure 4.15: Enter Caption

This manufacturing model is now ready for 3D printing and will be used to assemble the final prototype.

4.3.2 Manufacturing of Upper Body Prototype

Initially, we planned to 3D print the upper body components in metal at Technopark, where lower body prototype components were produced. However, due to time constraints and long processing times for metal printing, it was realized that there is not much time left for real prototyping.

As a result, it was suggested to manufacture the prototype using plastic 3D printing(Figure 4.16). Unfortunately, this approach turned out to be ineffective. The plastic components were not strong enough to support the weight of the actuators, which are approximately 1 kg each. Additionally, some parts did not print correctly due to their geometry, as shown in Figure 4.17. These issues highlighted the limitations of plastic 3D printing for structural parts under load and the importance of material selection.

Figure 4.16: 3D printed Upper Body parts

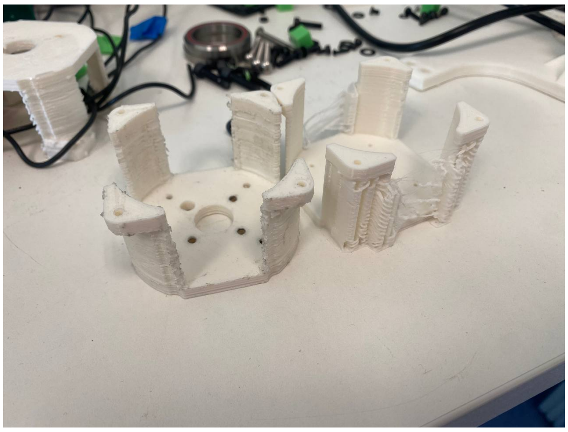

Figure 4.17: Motor Casings

4.3.3 Preliminary Gait Validation without Upper Body

The gait algorithm was validated using the existing lower body prototype to ensure that the basic walking functionality was working as expected. Thus, we simulated the robot without the upper body and used this simulation data to test the robot's walking capability in real life.

As shown in the test video (Chapter 7), the robot maintained a generally stable gait. However, it tends to turn to one side and slide. These issues are due to the open-loop nature of the system, meaning it lacks feedback to correct its movements during walking.

Also, it is important to note that the robot was standing and walking on its own during the test. The assistant visible in the video kept their hands nearby purely as a safety precaution and did not physically support the robot. Overall, the gait algorithm was successfully validated in real-life conditions.

Chapter 5: **Conclusion**

In this project, we successfully designed and validated a humanoid torso with two degrees of freedom to enhance gait stability in bipedal robots. A comprehensive simulation framework was developed in PyBullet, enabling dynamic testing of gait patterns and systematic hyperparameter optimization via random grid search. Our results clearly demonstrated that introducing a movable upper body significantly improved balance by reducing unnecessary lateral motion and enhancing the robot's center of mass control.

We achieved stable and energy-efficient gait patterns in simulation and validated our gait algorithm on a real lower-body prototype. Despite facing manufacturing challenges, including material limitations for the upper body, we were able to conduct successful real-world testing that confirmed the robot's ability to walk independently. The robot demonstrated its capacity to maintain balance and walk stably even in the absence of an actuated upper body, proving the robustness of our gait control algorithm.

Overall, this work lays a strong foundation for future full-body humanoid integration and highlights the vital role of upper body dynamics in achieving human-like locomotion.

Chapter 6: **Future Work**

Several promising directions remain for future development and research to improve the humanoid robot's performance and reliability. These include:

1. **Full-System Integration:** Mechanically and electronically integrate the upper body prototype with the existing lower body to enable complete system testing and coordinated motion.
2. **Closed-Loop Control with Sensory Feedback:** Incorporate sensors such as IMUs and force sensors to enable closed-loop control, improving stability, reducing drift, and allowing responsive adaptation to internal and external disturbances.
3. **Real-Time Gait Adaptation:** Develop real-time gait adjustment algorithms that adjust the gait based on terrain and balance, enhancing the robot's ability to navigate varying environments.

Chapter 7: **Appendix A**

7.1 GitHub Repository

The full project, including simulation videos, 3D models, real-life robot test footage, and other resources, can be found on the GitHub repository:

GitHub Repository Link

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