“DESIGN AND DEVELOPMENT OF QUADRUPED ROBOT”

Minor Project Report

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Abstract

The limitations of wheeled robots in traversing uneven and unstructured terrains have driven the shift toward legged locomotion, inspired by the adaptability of multi-legged animals. Legged robots, with distinct footholds, overcome the need for continuous paths, making them ideal for challenging environments. This project focuses on the design and development of a quadruped robot that addresses these challenges, emphasizing advanced electronics and control systems.

The quadruped robot is equipped with an STM32 microcontroller to control servo motors via Pulse Width Modulation (PWM), ensuring precise leg movements and enabling adaptive gait cycles. Inspired by quadrupedal animals, the robot can dynamically adjust its movements using Central Pattern Generators (CPGs), which coordinate real-time responses to environmental feedback. The integration of sensors, including encoders, inertial measurement units (IMUs), and position feedback systems, provides comprehensive data for stability and balance. This sensor architecture, combined with the microcontroller's Direct Memory Access (DMA) capabilities, ensures rapid and efficient processing of feedback.

By combining biological inspiration, robust electronics, and adaptive control algorithms, this project advances the capabilities of legged robots. The result is a reliable, efficient, and versatile quadruped robot suitable for applications in hazardous and remote environments, offering significant advantages over traditional wheeled robots in mobility, adaptability, and fault resilience.

Table of Contents

Chapter 1 - Introduction

1.1 Preliminary Remarks

At the very beginning of the 20th century, the concept of a humanoid robot was conceived. However, today it is now possible to witness robots that are the size of humans and possess the capability for human-like thinking and movement. When wheels have dominated the world of robots, they become extremely popular. Experts are under pressure to find a well-behaved alternative for wheels that would function in any type of environment. Integrating legged robots could potentially solve the problem of robots operating on uneven terrains.

Multiple studies have suggested that legged mobility is the most effective form of locomotion across different terrains, as compared to using wheels. The terrain surface may exhibit irregularities, fragility, discomfort, muddiness, and overall lack of structure. Legs in their biological state possess significant advantages in such situations. The explanation for developing a four-legged walking robot is based on the assumption that it can be driven by warm-blooded organisms.

By adopting this approach, other inherently intricate concepts, such as locomotion strategies for overcoming obstacles, may be introduced to facilitate the achievement of the desired objective. Additionally, a thorough analysis of the subsequent challenges would enable such a quadruped to navigate more efficiently.

1.2 Motivation

Researchers have conducted extensive research on legged robots during the past seventy years. Legged robots now have a better level of agility than wheeled and tracked robots. A robot with six legs that possesses task capabilities can be utilized in a wide range of applications. These applications encompass nuclear power plants, volcanic regions, mining operations, interplanetary missions, and other environments that pose similar risks to those faced by human labour. Furthermore, the continuous pandemic has facilitated the development of many uses of robots in the healthcare sector to ensure social distancing and autonomy. Hence, the Fault Tolerant feature of a robot becomes highly significant when it is employed for tasks that are deemed exceedingly perilous. This is because when the robot is used for such operations, it is not feasible to substitute a component or carry out repairs in case of a breakdown. Only a few inquiries have been conducted with the aim of attaining a high level of knowledge in legged robots. Furthermore, it is crucial to highlight that both wheeled and tracked robots are incapable of completing tasks in the event of a malfunction or failure of one of its actuators. This is particularly accurate when it comes to wheeled robots. Legged robots have an advantage over wheeled and tracked robots because they need less area to navigate Due to the presence of redundant degrees of freedom in the system, the robot can still operate effectively even if the actuator is not functioning properly, as long as adequate planning is done.

Development has optimized these systems to ensure survival. The topic of mechanical autonomy has seen significant breakthroughs driven by biological inspiration, with applications ranging from cockroaches to lizards. The consensus is that the inclusion of all animals in a collection serves as an effective foundation for the creation of advanced systems that outperform robots in challenging areas. Felidae members, specifically, do not encounter any issues with velocity. This is particularly true for specific organisms. The Acinonyx jubatus, often known as the cheetah, belongs to this group of fascinating animals. This remarkable creature not only has the ability to reach a maximum speed of 70 miles per hour, but it can also achieve an acceleration from 0 to 60 miles per hour in a few three seconds. The measures are so remarkable that they would leave a car enthusiast astounded. The remarkable speed of this creature can be attributed to the immense muscles in its hind legs, as well as to a common feature found in all highly evolved animals, to varying degrees. When studying the cheetah's hunting behaviour, it becomes clear that its spine is not inflexible, but rather a highly adaptable part of its anatomy. The main goal of the study is to create a quadrupedal model with a faulttolerant gait. This model will be articulated to assess changes in speed, adaptability, and energy consumption. The aim is to enhance the working performance of the quadruped.

1.3 Objective

The objective of this project is to design and develop a quadruped robot capable of navigating challenging terrains through adaptive and fault-tolerant locomotion. Inspired by quadrupedal animals, the robot aims to overcome the limitations of wheeled mobility by implementing biologically inspired gait cycles for enhanced stability and adaptability. The project integrates advanced electronics, including an STM32 microcontroller, to control precise leg movements, process real-time sensor feedback, and ensure efficient gait adjustments. Through mathematical modeling, dynamic simulations, and prototype development, the robot is validated for applications in hazardous environments, search and rescue, and exploration, demonstrating reliability and versatility

1.4 Types of Legged Robots

We can classify legged robots on the following basis:

- On the basis of Leg Configuration
- On the basis of Numbers of Legs
- On the basis of Legs orientation

1. On the basis of legs configuration

(a) **Mammal Type**

- These robots are highly versatile for movement because to their leg structure. Specifically, the parallel movement of the legs and body ensures that the robot's hip and head always move in sync with its leg action.

(b) **Insect Type**

- These robots are highly versatile for use with six or more legs because to their stable leg-based locomotion. The robot's body is hinged on its legs, ensuring that its movement remains parallel to the ground and perpendicular to the position of its legs.

2. On the basis of legs orientation

There are three major important types of legs orientation which are as follows:

(a) Frontal legs orientation

- The orientation of the robot's body is perpendicular to the position of its legs.

(b) Sagittal legs orientation

- The robot's body moves in alignment with the motion of its legs.

(c) Circular legs orientation

- The legs are arranged in a radial configuration, enabling the mechanism to move in any direction.

3. On the basis of number of legs

On the basis of number of legs, we can classify legged robots like as-

(a) One-legged robot

According to this technique, the minimum number of legs required for a robot to maintain contact with the ground is one. Typically, one-legged robots are designed for jumping, as there are no other means of locomotion available to them. A jumping robot must continuously leap to maintain balance, as stopping would cause it to topple over. These kinds of robots are dynamically stable and alter their center of gravity and apply corrective forces to prevent falling when they are unsteady. The primary advantage of having a single leg is its ability to leap and navigate across many types of terrain by taking a running start and jumping over obstacles, even those larger than its maximum stride. Since there is only one leg. Planners can carefully examine leg coordination as there is just one leg that can be controlled. Similarly, robots with only one leg are more energy efficient compared to robots with a greater number of legs. The obstacle lies in their intricate strategy and authority.

(b) Two-legged robot (Biped)

The construction of a bipedal walker, which has only two legs, is significantly more challenging compared to other types of walkers. During walking, just one foot will be in contact with the ground, and the center of gravity must shift significantly to prevent the robot from falling over. Although not as efficient or uncomplicated as a wheeled or tracked vehicle, the ability to navigate challenging terrain is essential. A check can only be passed over by going between the legs. Regardless, there is no surplus in the legs. If one leg fails, the robot is completely unable to walk.

Figure 1.4.1 : Bipedal Robot Michigan University

(c) Four-legged robot (Quadruped)

An industrially available quadruped robot, such as the Sony Aibo, is a straightforward and often used example of a four-legged robot. Controlling a quadruped is easier than controlling a bipedal robot, as long as only one leg is off the ground at a time, eliminating the need for sophisticated adjustments. Regardless, a quadrupedal robot lacks leg redundancy. If one of the legs fails, the robot loses its ability to walk.

Figure 1.4.2 : Quadruped Robot ETH Zurich

(d) Six-legged robot (Hexapod)

The hexapod, a walker with six legs, has exceptional stability. The designer can devise a gait in which three legs are simultaneously lifted off the ground, resulting in a stable tripod configuration. A hexapod is a very advantageous robotic platform designed for navigating intricate terrain. It is widely recognized as one of the most prominent types of legged robots, along with quadrupeds.

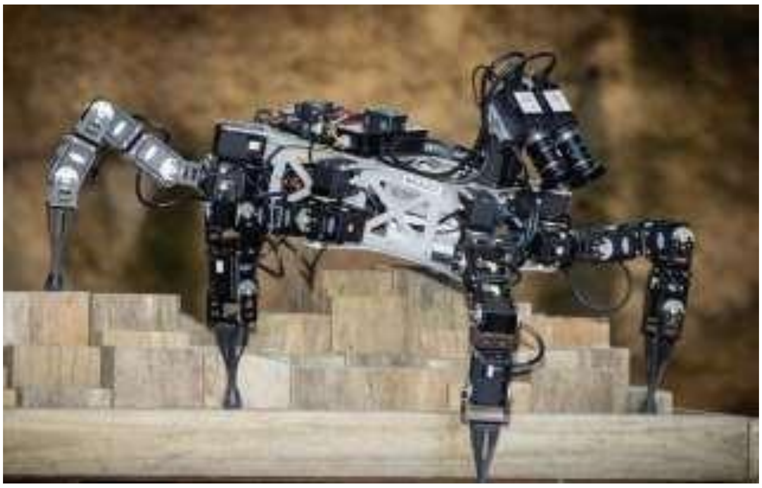


Figure 1.4.3 : Hexapod Robot CISRO

Figure 1.4.4 : Octapod Robot

1.5 Comparison of Legged Robots with Wheeled Robots

The main distinction is in the fact that legged robots excel in terms of mobility and adaptability over uneven terrains, whereas wheeled robots exhibit insufficient maneuverability in such environments. Legged robots have a greater potential to traverse a larger range of terrains compared to wheeled robots, similar to how animals with biological legs can access almost all of the earth's land surfaces. Legged robots exhibit more flexibility and efficiency in walking compared to wheeled robots. Engage with universally applicable physical surroundings that are specifically created for bipedal/quadrupedal movement (humans). Wheels do not necessarily follow the same path as feet. Wheeled systems achieve remarkable speeds, surpassing all other objects in terms of velocity. However, speed is not necessarily the sole criterion for measuring performance. The velocity of linear motion does not directly correspond to the rate of change in position or orientation. The legged robot exhibits more agility compared to the wheeled robot.

1.6 Comparison of Quadruped Robots with other Legged robots

Comparison is made on the basis of the four important criteria

- Maneuverability
- Stability
- Load carrying Capacity
- Control Simplicity

Parameters	2-Legged Biped	4-Legged Quadruped	6-Legged Hexapod	8-Legged Octopod
Maneuverability	★★★	★★	★	★
Stability	★★	★★	★★★	★★★
Load Carrying Capacity	★	★★	★★★	★★★
Control Simplicity	★	★★	★	★

Figure 1.5.1 : Comparison between Legged Robots

A quadrupedal robot is well-suited for navigating difficult terrain. It has the ability to ascend steps, traverse gaps that are equal to or less than its stride, and walk on highly irregular terrain where the use of wheels would not be practical due to the unevenness of the ground. In order to create a mobile legged robot, it is necessary for each leg to possess a minimum of one degree of freedom (DOF). Each degree of freedom requires one joint, typically operated by a single servo. The leg mechanism, often referred to as the locomotion mechanism of legged robots, is a collection of linkages and joints that allows for the replication of the walking motion observed in people or animals. Mechanical legs can be equipped with one or more actuators that are capable of executing either simple two-dimensional or complex and diverse movements. Bionics and biomimetics involve incorporating the structure and movement techniques of animals into the design of robots.

1.7 Advantages of the Quadruped Robot

- It exhibits greater adaptability.
- It has improved in stability.
- It possesses the capacity to traverse difficult terrain.
- It is capable of moving even if one of its legs fails.
- The object has the ability to distribute its weight evenly and adjust its center of mass without altering the placements of its supports.

1.8 Limitations of the Quadruped robot

- The design will become increasingly intricate and incorporate a greater number of components in motion.
- Challenging to maintain stability due to the position of the center of mass.
- Establishing a gait pattern might be challenging.
- It is challenging to manipulate actuators to achieve the desired motion.

Chapter 2 - Literature Review

2.1 Literature Review

❖ **Early Development of Robots**

The history of robots dates back to ancient times, with significant progress during the Industrial Revolution when advanced machinery and electricity revolutionized manufacturing. By the early 20th century, the concept of humanoid robots emerged, paving the way for the development of modern robots that can simulate human-like thinking and movement.

❖ **Evolution of Robotic Locomotion**

Wheels became the dominant form of robotic movement, yet researchers sought alternatives for navigating complex environments. Legged robots emerged as a promising solution due to their ability to traverse diverse terrains. Richard Lovell Edgeworth's early attempt with a "Wooden Horse" in 1770 and Pafnuty Chebyshev's 1878 "Plantigrade Machine" exemplified early efforts in legged robotics. However, designing functional robotic legs proved to be challenging, drawing inspiration from the learning process of human walking.

Figure 2.1.1 : Wooden Horse

❖ **Advances in Quadruped Robots**

Research on dynamic quadruped locomotion gained momentum in the 1980s, particularly with Marc Raibert's work at MIT, where he developed robots with hopping capabilities and various gaits. His work laid the foundation for later designs like Boston Dynamics' "BigDog," a quadruped robot developed in 2005. Robots like "Collie-1" and "Collie-2" built at the University of Tokyo demonstrated advancements in dynamic walking gaits.

❖ Control Strategies and Dynamic Walking

Key contributions in gait control for quadruped robots were made by Snaith and Holland (1990), who proposed methods for controlling gait using centralized systems, reflexive neural clusters, and training algorithms. This was followed by research in the 1990s by Kimura et al. on Central Pattern Generators (CPGs) for adaptive walking. Developments in dynamic stability for robots, like the Scout II quadruped robot, further enhanced running performance.

❖ Fault Tolerance in Legged Robots

Fault tolerance in legged robots has become essential, especially for hazardous tasks. Methods such as locked joint fault-tolerant gaits and stability margin calculations enable legged robotsto continue functioning after partial mechanical failures. Studies by Martins-Filho (2000) and recent research by Chen et al. (2016) have focused on developing robust fault-tolerant gaits that maintain stability even in challenging conditions.

❖ Modern Quadruped Robotics and Practical Applications

The 21st century has seen significant advancements in quadruped robotics, with sophisticated algorithms enabling robots to navigate rough terrain, avoid obstacles, and adapt to unexpected environmental changes. Boston Dynamics' LS3, for instance, funded by DARPA, was designed to carry heavy loads across difficult terrains autonomously. Algorithms like the Kinetic Momentum Management Algorithm (KMMA) have further refined leg movement and energy efficiency, ensuring robots can operate effectively even with a single malfunctioning actuator.

Chapter 3 - Electronics and Control System

3.1 STM32 Architecture

The **STM32 Architecture** refers to the design and structure of STM32 microcontrollers, produced by STMicroelectronics. These microcontrollers are based on ARM Cortex-M cores, which provide a range of capabilities for embedded systems applications. Here's a brief overview of key elements within STM32 architecture:

1. Core Processor (ARM Cortex-M)

- STM32 microcontrollers use ARM Cortex-M cores, typically Cortex-M0, M3, M4, or M7, each suited for different performance and power requirements.
- The core handles the main processing tasks and supports features like low-power modes, high-speed operation, and efficient interrupt handling.

2. Memory Architecture

- **Flash Memory**: Non-volatile memory used to store program code and non-changing data. STM32 devices have integrated Flash memory for firmware storage.
- **SRAM**: On-chip Static RAM provides temporary data storage, faster than Flash for runtime variables.
- **EEPROM** (in some models): Used for storing non-volatile data that can change, such as configuration parameters.
- Memory Mapping: STM32 supports a flat memory space with address mapping for Flash, SRAM, and peripheral registers, making access efficient.

3. Peripherals

- **GPIO (General Purpose Input/Output)**: Configurable pins for digital input/output operations.
- **Communication Interfaces**: Includes USART, SPI, I2C, and CAN for serial communication with other devices.
- **Timers and PWMs**: Multiple general-purpose and advanced timers support pulse-width modulation (PWM) generation, signal measurement, and delay functions.

4. Interrupt System

- **NVIC (Nested Vectored Interrupt Controller)**: Manages interrupts with nested prioritization, allowing high-priority tasks to interrupt lower-priority ones.

- Cortex-M processors use a fast interrupt handling system that quickly switches between tasks, essential for responsive applications.

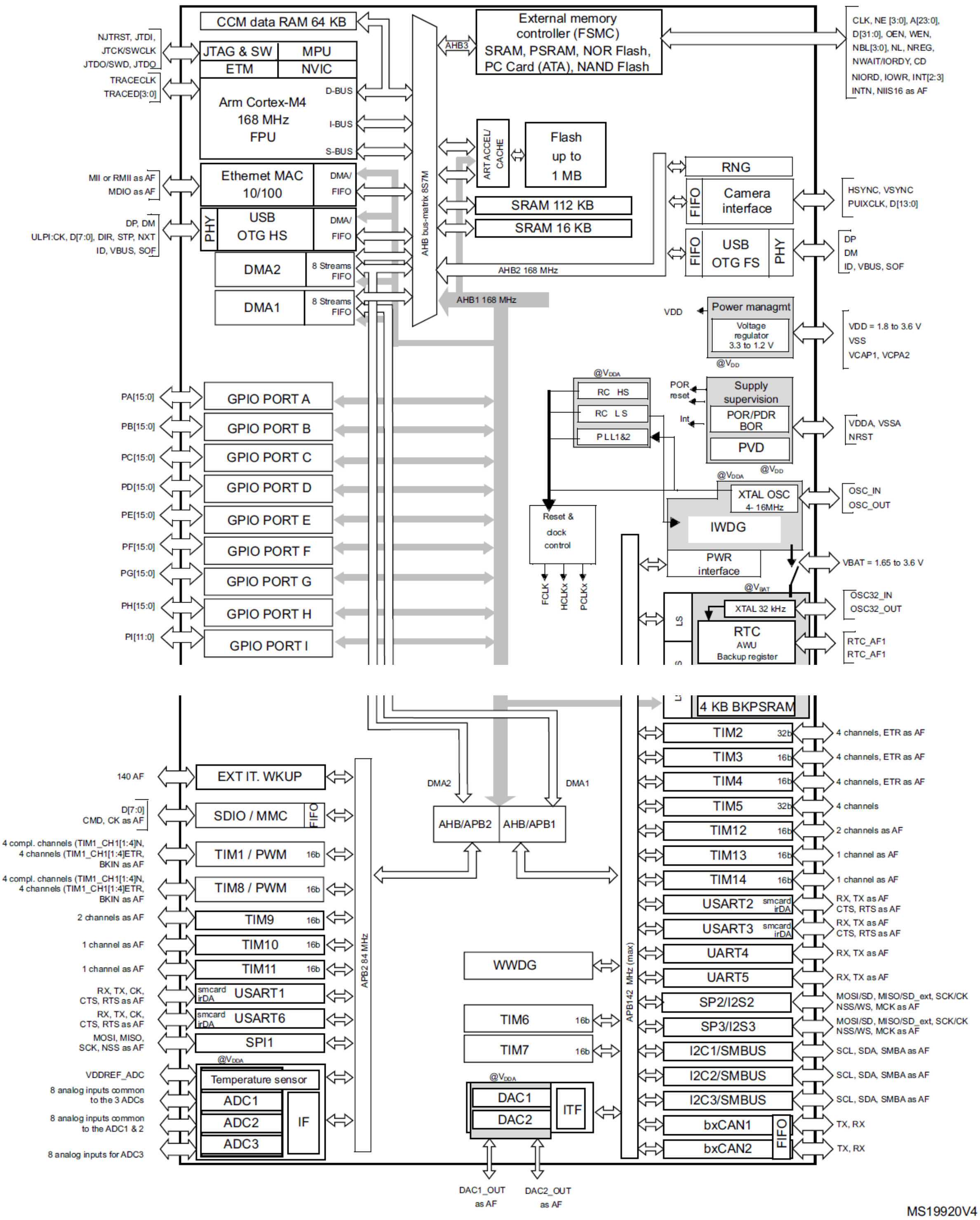


Figure 3.1.1 : STM32 Architecture

5. Clock and Power Management

- **RCC (Reset and Clock Control)**: Provides a flexible clock system to manage the speed of the core and peripherals, with options for low-power operation.
- **Low-Power Modes**: STM32 offers various modes like sleep, stop, and standby to optimize power consumption in battery-powered applications.

6. Debugging and Programming Interfaces

- STM32 microcontrollers support debugging and programming interfaces like **JTAG** and **SWD (Serial Wire Debug)**, providing essential tools for code development and troubleshooting.

7. Direct Memory Access (DMA)

- DMA controllers allow peripherals to transfer data directly to/from memory without CPU intervention, freeing up the core for other tasks and enhancing data handling efficiency.

3.2 Serco Motors Working

The working principle of a servo motor relies on a closed-loop control system, where feedback is constantly monitored and adjustments are made to achieve the desired position or speed. The process generally follows these steps:

1. **Input Signal**: The control system (like a microcontroller) sends a command to the servo motor in the form of a Pulse Width Modulation (PWM) signal. This signal determines the desired position by encoding it as a specific pulse width.
2. **Comparison and Error Calculation**: The servo motor’s control circuit receives feedback on the current position from the potentiometer or encoder. It then compares the actual position with the desired position set by the input signal.
3. **Error Correction**: If there is a difference (or error) between the actual and desired positions, the control circuit adjusts the motor's rotation to minimize this error. For example, if the actual position is less than desired, the motor will rotate in the positive direction to match the desired angle.
4. **Positioning**: Once the desired position is reached, the motor stops, maintaining its position until a new command is received.

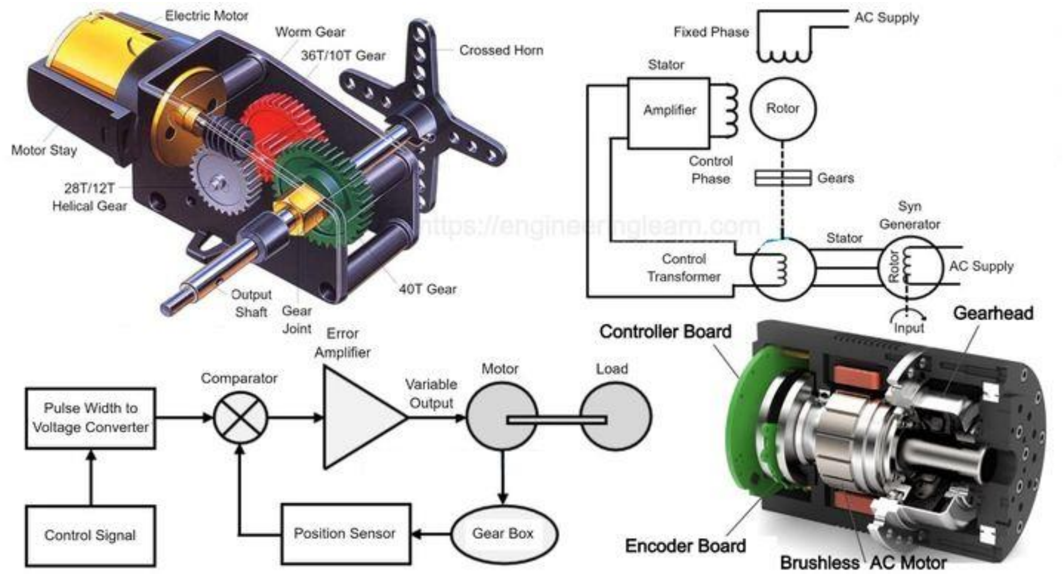


Figure 3.2.1 : Servo Motor Working

3.3 Control of Servo Motors Using PWM

Servo motors are typically controlled by a PWM signal, where the duty cycle (length of the pulse) corresponds to a specific angle:

- **Pulse Width Range**: A standard PWM signal for servo motors has a pulse width that varies between 1 ms to 2 ms, where:
  - A 1 ms pulse often represents the 0° position.
  - A 1.5 ms pulse represents the neutral or mid-point, usually around 90°.
  - A 2 ms pulse represents the maximum position, usually around 180°.
- **Duty Cycle**: By adjusting the duty cycle of the PWM, the position of the servo motor can be set accurately.

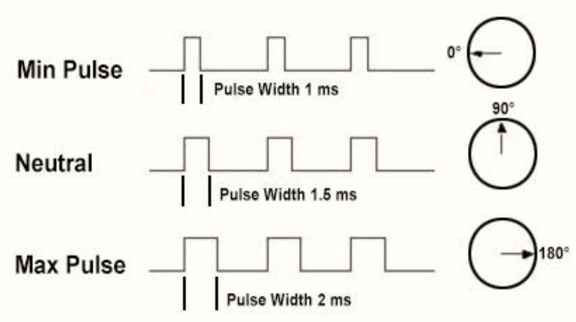


Figure 3.3.1 : Servo angle at different pulse width

3.4 PWM Generation in STM32

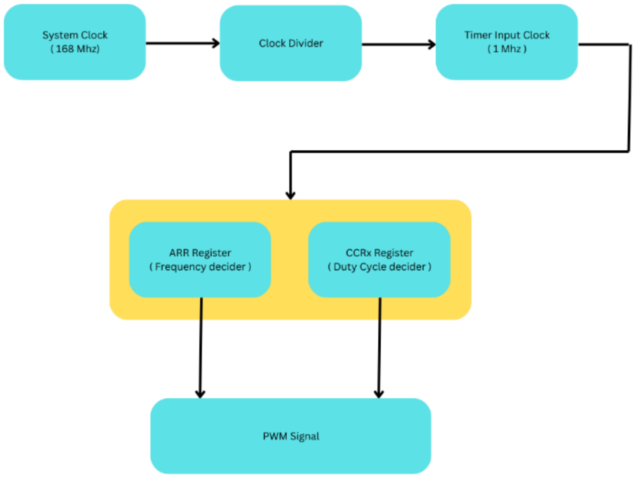


Figure 3.4.1 : PWM Generation Block Diagram

1. Enable the Timer Clock

- Enable the clock for the timer you want to use for PWM by setting the appropriate bit in the RCC (Reset and Clock Control) register.

2. Configure the Timer Mode for PWM

- Set the timer mode to PWM mode 1 (OCxM = 110) or PWM mode 2 (OCxM = 111) by configuring the OCxM bits in the TIMx_CCMRx register.
- Enable the preload register for the output compare channel by setting the OCxPE bit in the TIMx_CCMRx register.

3. Set the Auto-Reload Register (ARR)

- Set the TIMx_ARR register to determine the PWM frequency.
- Frequency of PWM = Timer Clock Frequency / (TIMx_PSC * TIMx_ARR)

4. Set the Duty Cycle Using the Capture/Compare Register (CCR)

- Set the duty cycle of the PWM by writing a value to TIMx_CCRx. This determines how long the PWM signal stays high within each period.

5. **Enable the Counter and Auto-Reload Preload Register**

- Enable the auto-reload preload register by setting the ARPE bit in the TIMx_CR1 register.
- Start the timer counter by setting the CEN bit in the TIMx_CR1 register.

6. **Initialize the Timer Registers**

- Force an update event to transfer the preload register values to the shadow registers by setting the UG bit in the TIMx_EGR register.

7. **Configure the Output Polarity and Enable Output**

- Set the output polarity (high or low) by configuring the CCxP bit in the TIMx_CCER register.
- Enable the output by setting the appropriate bits (CCxE, MOE) in TIMx_CCER and TIMx_BDTR registers.

```
void PWM_1()
{
  GPIO_Handle_t GPIO_Btn;
  GPIO_Btn.pGPIOx=GPIOB;
  GPIO_Btn.GPIO_PinConfig.GPIO_PinMode=GPIO_MODE_OUT;
  GPIO_Btn.GPIO_PinConfig.GPIO_PinMode=GPIO_MODE_ALE;
  GPIO_Btn.GPIO_PinConfig.GPIO_PinPuPdControl=GPIO_NPULL;
  GPIO_Btn.GPIO_PinConfig.GPIO_PinAltFunMode=3;
  GPIO_Btn.GPIO_PinConfig.GPIO_PinNumber=GPIO_8;
  GPIO_Init(&GPIO_Btn);

  TimerPeriClock(TIM10,ENABLE);
  TIM10->PSC=0xA8;
  TIM10->CCMR1|=(0<<0);//O/P FIRST CANNEL
  TIM10->CCER|=(1<<1);//Active Low
  TIM10->CCMR1|=(7<<4);
  TIM10->ARR=0x4E1F;
  TIM10->CCMR1|=(1<<3);
  TIM10->CR1|=(1<<7);
  TIM10->CCER|=(1<<0);
  TIM10->CR1|=(1<<0);
}
```

Figure 3.4.2 : Pin Configuration for PWM Generation

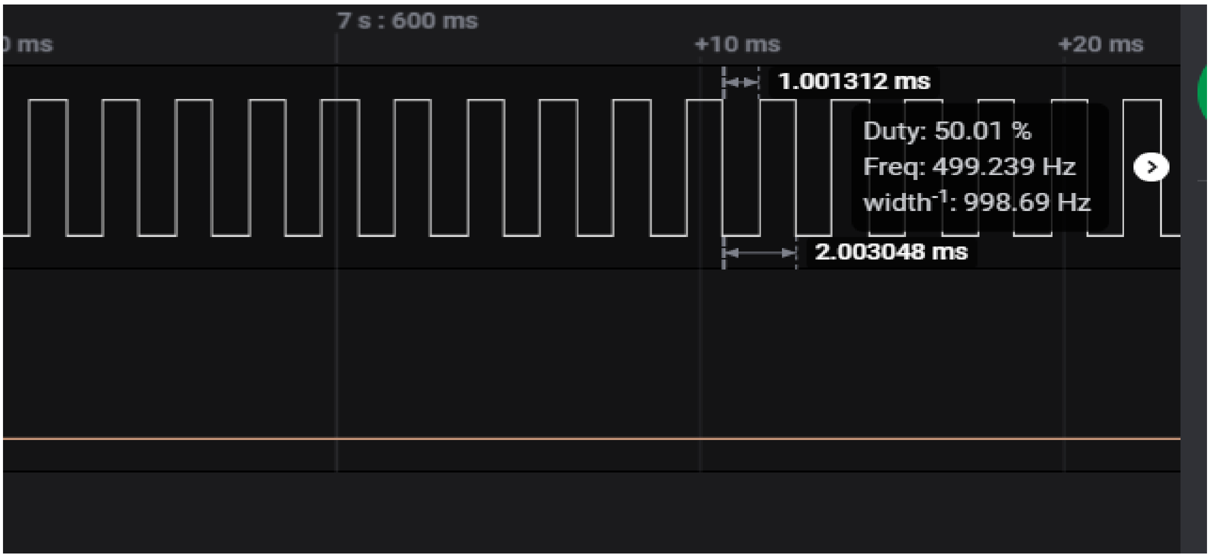


Figure 3.4.3 : PWM Signal

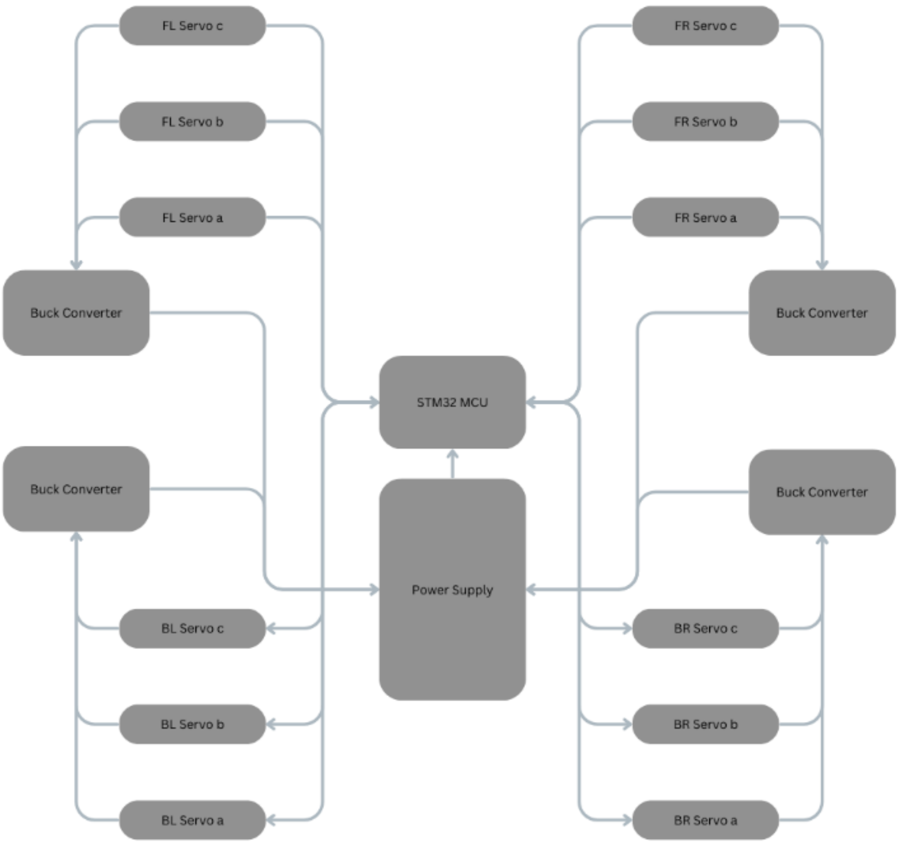


Figure 3.4.4 : Block Diagram

Chapter 4 - Gait Pattern in 3 DOF Quadruped robot

A quadruped robot model as shown in figure 6, is prepared in Simscape Multibody. Database of joint angles for all 12 joints is prepared as per the procedure stated in the previous section with cubic trajectory planning in time step of 0.01 second for the gait cycle of 28 seconds. Figure 5 shows the overall flow chart of the procedure. Length (L) and Width (W) of the body of the simulated model are 20 and 10 cm respectively. Length of the upper and lower links of the legs is 10 cm. and the Length of the legs' workspace (R_x) is considered as 14 cm. The robot performs the locomotion while keeping 15 cm height of the torso from the ground. The trajectory of legs while in the swing phase is considered as rectangular as shown in figure 7. And the cubic trajectory has been considered for the swing as well as the support phase.

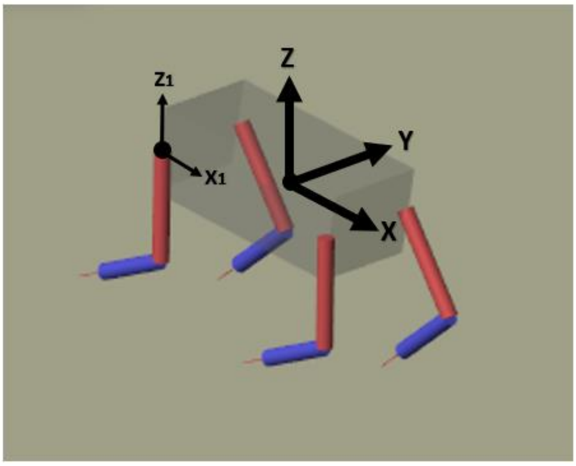
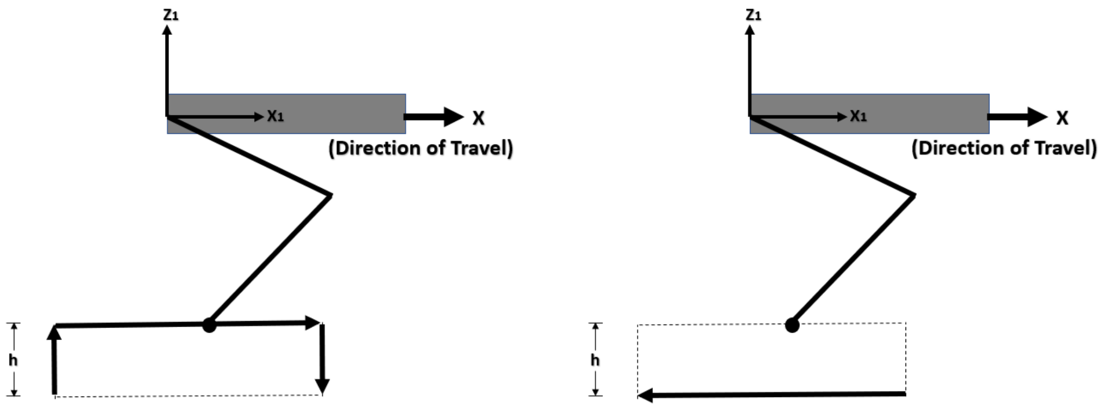


Figure 4.0.1 : Simulated Quadruped Model



(a) Swing Phase *(b) While Robot Travels Forward*

Figure 4.0.2 : Trajectory of the foot tip

1) Omni-Directional Gait Control :

Using the above Standard Gaits, Gait Scheme for Omni-Directional travel is proposed, which uses successive gait transitions and standing posture transformation to plan the walk in any direction in the least possible steps and time. Figure 5 shows an omnidirectional gait pattern.

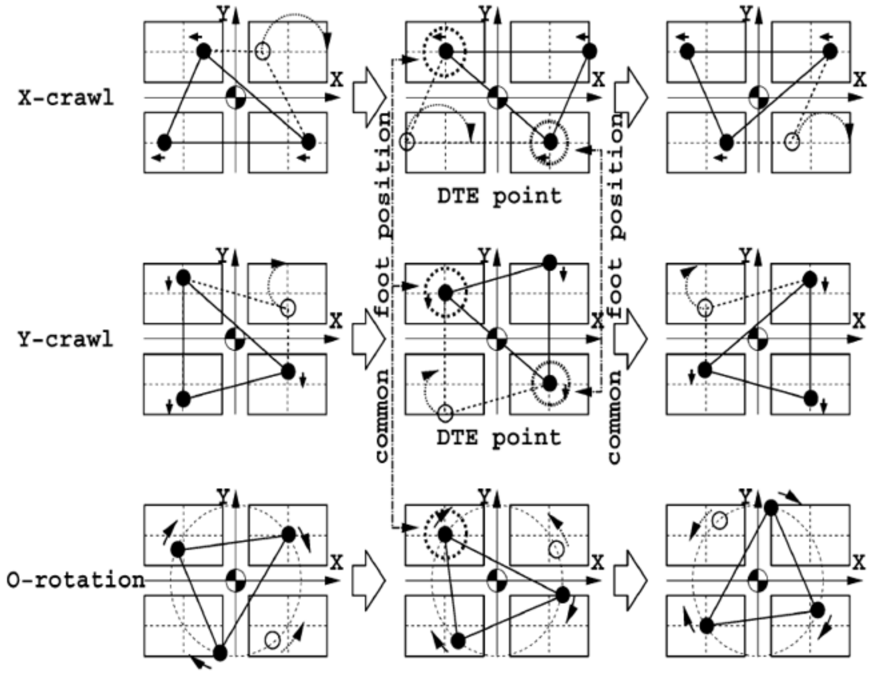


Figure 4.1.1 : Omni Directional gait

2) Body Sway Motion

All the Continuous and Discontinuous Gaits discussed so far have unidirectional body motion, i.e., the body will travel in a straight line, inclined line, or spin around an arbitrary point. Calculation of Stability and maximum possible stride (distance traveled in a cycle) are discussed in previous studies. But the search for a more stable gait led the researchers to discover some novel gaits which may not be biologically inspired and not found in nature but might be more suitable for the robots. The basic idea was to keep the COG of the Robot at the most stable position in the support triangle. It needed to move the robot in a lateral direction, known as COG Adjustment or Body Sway Motion. which increases the stability. It also proposes solutions for the straightforward gait and solutions for the turning gait. This method of Gait Planning is validated by an experiment with a TITAN VII robot while walking on a 15-degree slope. Figure 6 highlights the body sway motion pattern.

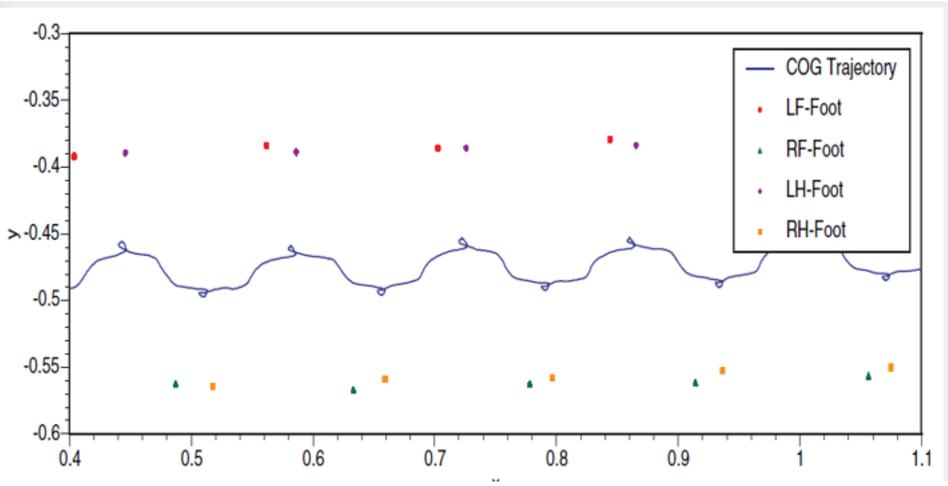


Figure 4.2.1 : Body sway motion

Crocodile inspires the performance of the quadruped robot on a static walk gait pattern. Novel algorithms were proposed in, which first demonstrated the benefits of Body Sway motion, i.e., body movement in the lateral direction. The gait planning shown in this paper is based on regular Wave Gait. It can be used on a slope and flat terrain to considerably increase stability with the same configuration without losing speed. One of the methods is Y-Sway Motion, in which the y-component of COG is always taken to the y-component of the center of the Support Polygon without worrying about the stability margin.

In contrast, in E-Sway Motion, considering the Energy Stability Margin, the y-component of COG is brought to the point where energy stability is equal. The former is comparatively easier to implement and generates a better stable walk than regular wave gaits, and the latter gives extra stability. Both the planning methods are simpler enough to be implemented in a robot in realtime and are validated through simulations for their effectiveness on even and slope terrain.

The advantages of Quadruped Robots increase with the roughness of the terrain. It becomes important to generate a smooth walking pattern even in a rocky environment with continuous velocity and acceleration profiles. In , a Flexible Walking Pattern Generation is demonstrated, which moves the body like numeric eight by implementing sinusoidal sway in lateral and longitudinal directions using 5th-order spline curves. The algorithm is tested in the LittleDog robot and is proven to have enough balance as well as smooth movement.

To compensate for the drop in the stability of periodic gait, the researcher worked on different gaits. (Intermittent Crawl Gait, E-Sway , Zigzag Gait). Even after applying these gaits, a similar level of motion was not attained as that of the animals. And one of the main reasons for that was the use of waist-joint in animals to revolve their front and rear part concerning each other as per the requirement. A passive 1 DoF joint is added in the box, and the COG and waist joint relationship is studied. Also, the proposed Discontinuous Zigzag gait was implemented in a simulation environment and on an ELIRO-II robot, and its superiority against a single-body robot, in terms of extra stride and higher stability, is demonstrated on a flat surface.

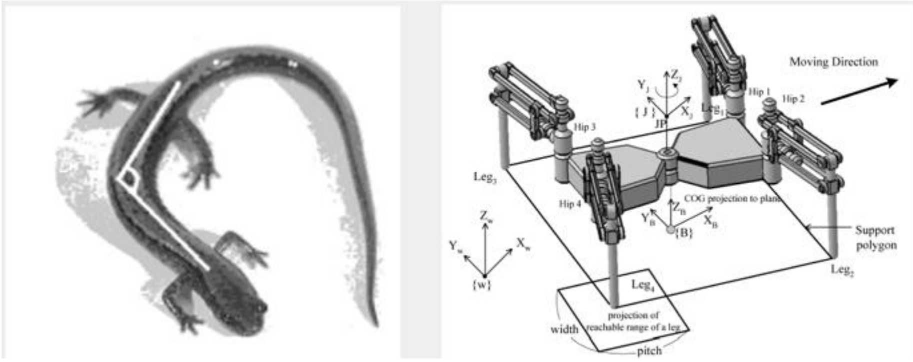


Figure 4.2.2 : Discontinuous zig-zag gait

COG trajectory was generated based on the ZMP stability criterion, represented as a series of Quintic Spline Segments, and COG trajectory generation was formulated as an optimization problem to minimize the squared acceleration along the trajectory, subject to continuity and ZMP stability constraint.

Different researchers proposed Various Adjustment Strategies, but in all of them, either the stability margin is reduced, or the Body retrieval, i.e., movement of the body in opposite to forward direction, takes place, which ultimately reduces the forward speed and increases the energy consumption that leads to a decrease in efficiency of the robot. In a Discontinuous Crawl Gait is proposed, which is good for irregular terrain with grass or asphalts. In this method, the duty factor is more than 0.75, and the body only moves when all four legs are on the ground, similar to the traits of ordinary Discontinuous Gait. The only difference is that the direction of movement of the body and the stability criterion will be different as per the next swing leg. Before the front legs swing, the body moves sideways and reaches the point per the modified Longitudinal Stability Margin criterion. On that, when the next supporting swing leg is on the hind side, the body moves forward following the Static Stability Margin criterion. This planning method is sophisticatedly designed to avoid the retrieval of COG and maintain maximum stability.

In an optimized Discontinuous Crawl Gait is proposed in which the movement of the COG is broken into two types. While making a Lateral Motion, the COG searches for a minimal distance in the lateral direction, which can ensure a stability margin, and while in Forward Motion, it searches maximum moving distance in the forward direction. This improves the forward velocity by reducing unnecessary lateral movement. The proposed method is validated in the simulation environment of websites and it has proven to be faster than the previous method while maintaining a predefined stability margin value.

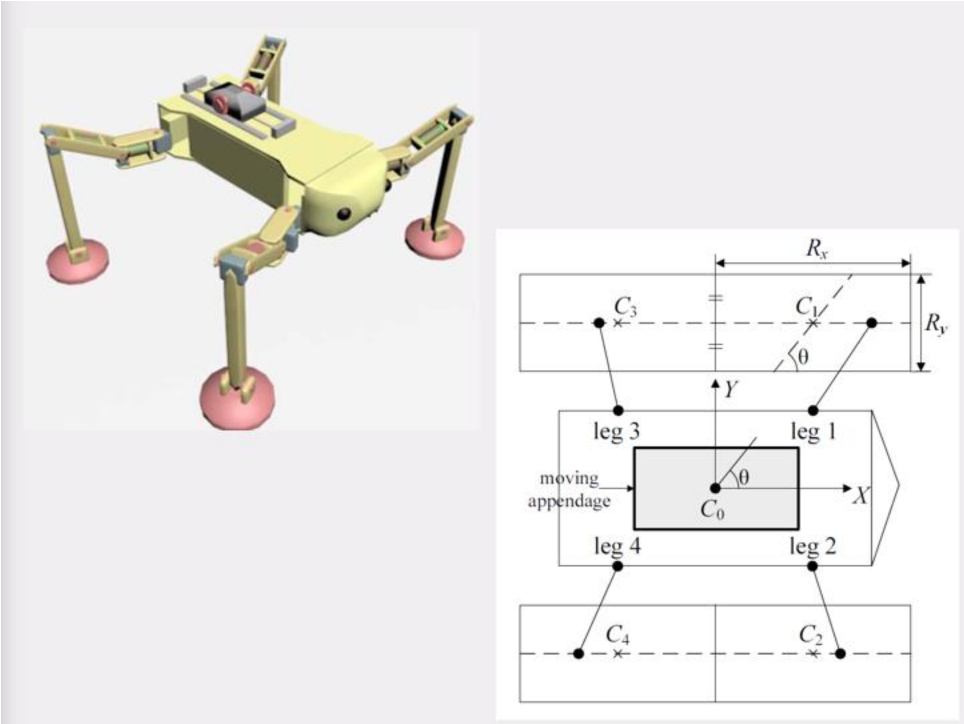


Figure 4.2.3 : Simulated Robot

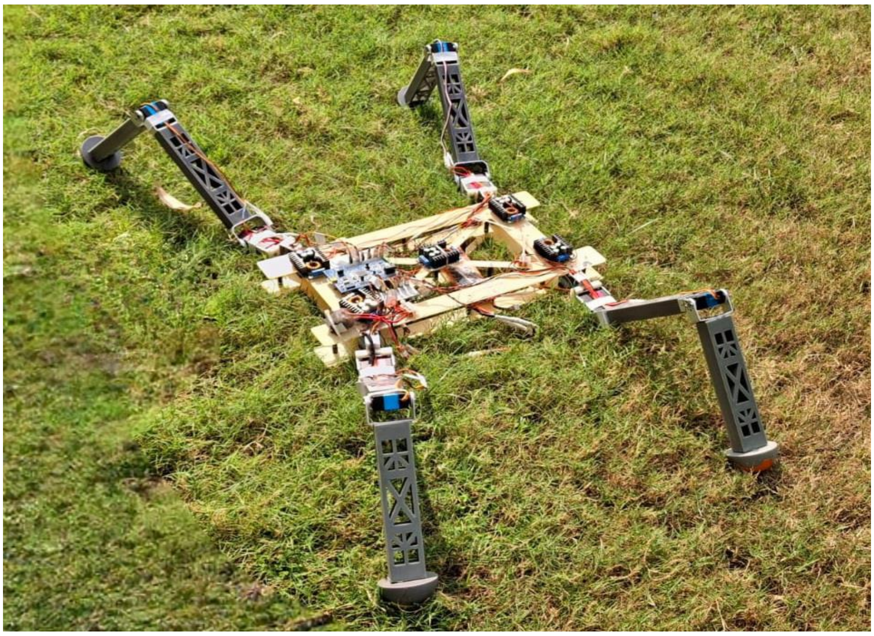


Figure 4.2.4 : Real Robot

Chapter 5 - Conclusion and Future Work

5.1 Summary

This project focuses on the design and development of a quadruped robot, addressing the limitations of wheeled robots in navigating unstructured and uneven terrains. Wheeled locomotion, while efficient on flat surfaces, lacks the adaptability required for complex environments. Inspired by quadrupedal animals, the project utilizes biological principles to enhance the robot's mobility through legged locomotion. This approach leverages independent footholds, allowing traversal over challenging terrains where wheels are impractical.

The electronics system, powered by an STM32 microcontroller, governs servo motor control via Pulse Width Modulation (PWM). This enables accurate leg positioning and dynamic gait adaptation. The system also integrates encoders, inertial measurement units (IMUs), and position feedback sensors to provide real-time data for balancing and terrain adaptation. The use of Direct Memory Access (DMA) in the microcontroller enhances efficiency by minimizing processing delays. Simulations tested the robot's response to varied conditions, ensuring its fault-tolerant design can withstand actuator and sensor failures.

The final prototype effectively demonstrates these capabilities, offering a reliable, energy-efficient solution for applications requiring mobility in rugged or hazardous environments. By combining advanced control systems, adaptive algorithms, and robust hardware, the quadruped robot showcases significant improvements over traditional mobility systems.

5.2 Conclusion

The project successfully achieves its objectives of designing and developing a quadruped robot capable of adaptive, fault-tolerant locomotion. Through mathematical modeling and dynamic simulations, the robot's locomotion system was synthesized and optimized for various terrains. The integration of rigid body dynamics and transient structural simulations ensured the robot's ability to handle real-world physical stresses while maintaining operational stability.

The electronics system, centered on the STM32 microcontroller, played a pivotal role in managing the precise movements of the servo motors and coordinating the adaptive gait cycles. The fault-tolerant algorithms enabled the robot to continue functioning despite failures in individual components, proving its reliability in demanding scenarios. The successful implementation of these features in the physical prototype demonstrated the practicality of the design and its adaptability to challenging terrains.

Overall, the project underscores the effectiveness of combining biologically inspired designs with advanced electronics and control systems. The developed quadruped robot offers a compelling solution for applications in search and rescue, hazardous environment exploration, and other fields requiring robust and adaptable mobility systems.

5.3 Future Work

1) Model Predictive Control (MPC)

Advanced control strategies, such as MPC, could be implemented to optimize trajectory planning and improve real-time decision-making. This would allow the robot to predict and adapt to terrain changes more effectively, ensuring smoother and more efficient locomotion.

2) Enhanced Estimation and Planning

Integrating advanced algorithms for environment sensing and planning can improve the robot's ability to predict obstacles and determine optimal paths. Techniques like simultaneous localization and mapping (SLAM) could be incorporated for navigation in unknown terrains.

3) Perception Systems and Machine Learning

Incorporating machine learning models and advanced perception systems will enable the robot to process complex environmental data, identify patterns, and make autonomous decisions. Sensors like LIDAR, stereo cameras, or ultrasonic sensors could further enhance obstacle detection and terrain analysis.

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