Final Report

Mobile Tensegrity Robot with Reaction Wheel for Enhanced Impact Resistance

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Abstract

This project aims to develop a robot capable of self-balancing and moving via an integrated gyroscope as well as resistant to high forces due to the tensegrity limbs. The work includes designing the structure of the flywheel and robot carcass, selecting metal and elastic component materials. The robot's structure is fabricated with lightweight aluminum, polylactic acid plastic (PLA), silicone rubber. Its actuation system consists of brushless DC electric motor (BLDC), smart actuators, and a Control Moment Gyroscope (CMG) for real-time position and orientation control. Validation includes physical testing of locomotion and design simulations. The novelty of this work is the combination of elastic tensegrity structures with the gyroscope for increased durability and flexibility. This research advances the development of a robust, agile mobile robot capable of adaptive orientation and navigation in complex environments. Theoretically, it introduces a novel design enabling the robot to withstand falls from up to 1 meter by dynamically reorienting during descent to land on its legs without damage—a capability unattainable by robots with conventional mechanical structures. Practically, despite current hardware limitations, the prototype employs a control moment gyroscope to achieve rotational and translational movement without actuating the wheels on its legs, demonstrating potential applications in exploration, disaster response, and autonomous systems.

Chapter 1: **Acknowledgments**

We would like to express our deepest gratitude to the Institute of Smart Systems and Artificial Intelligence (ISSAI) for providing access to valuable resources and a collaborative research environment throughout the course of this project. We are especially thankful to our research adviser, Dr. Atakan Varol, for his continuous guidance, insightful feedback, and unwavering support, which were instrumental in shaping the direction of our work. We also extend our sincere appreciation to Professor Michele Folgheraiter for his help in acquiring critical hardware resources. Their mentorship has significantly contributed to the completion of our Capstone project.

Chapter 2: **Introduction**

In the autonomous industry, mobile robots are regarded as the essential tool thanks to their mobility, multifunctionality and ability to adapt to unpredictable environments through the usage of sensors and controller. The current trend also includes the implementation of artificial intelligence on top of advanced sensor systems that further improve the productivity of such machines compared to the human workforce, especially in unsafe areas such as the execution of hazardous tasks and emergency situations. In terms of types of mobility, there is generally a high variety of options that involve wheels, artificial legs, and hybrid systems [1]. For this project, legged robots are highly relevant as they possess the necessary characteristics required for navigation in the complex and erratic terrains.

Research Problem

Despite the advantages legged robots offer, they face significant challenges that limit their operational effectiveness, particularly their vulnerability to falls and the resulting structural damage [2]. As noted by Wensing et al. [3], key issues include motion planning, force estimation, and control strategies that maintain balance during movement. These problems are especially pronounced on uneven or steep terrain, where the risk of instability increases. Falls in such environments can cause major mechanical failure, requiring costly repairs and jeopardizing mission objectives [4, 2]. One of the possible solutions to mitigate these challenges is to integrate tensegrity structures in the robot design.

Tensegrity structures consist of compressive elements interconnected by tensioned cables [5]. These systems are lightweight, reducing impact forces, and can incorporate elastic components to absorb and dissipate impact energy [6]. Tensegrity robots offer a promising alternative due to their lightweight, compliant, and damage-tolerant structures. However, they face their own challenges, including underactuation, complex nonlinear dynamics, and difficulty in achieving accurate control and efficient locomotion [7]. Gyroscopic systems, on the other hand, can improve balance and orientation by leveraging angular momentum. Yet they often suffer from high power demands, control complexity, and sensitivity to external disturbances [8, 9].

These limitations highlight the need for a new approach that combines the structural resilience of tensegrity with the active stabilization capabilities of gyroscopic actuation. This integration offers the potential to overcome the control and stability challenges seen in current robotic systems, especially in dynamic or unpredictable environments.

Current robotic designs do not adequately address the need for impact resistance, particularly in dynamic environments where falls are a real risk. For instance, existing robots typically rely on rigid structures that can crack or deform upon impact, rendering them ineffective in high-stakes scenarios where reliability is essential. This research addresses the gap in existing studies regarding the incorporation of tensegrity structures into legged robots to enhance their impact resistance. By doing so, the aim is to develop a system that can withstand falls without incurring damage, thus increasing the overall longevity and effectiveness of these robots.

Research Motivation

The motivation for this research is driven by the pressing need to improve the robustness and adaptability of legged robots in dynamic and unpredictable environments. As robotics technology continues to advance, the demand for reliable autonomous systems that can operate in hazardous situations has increased significantly. The ability to endure falls without sustaining damage is crucial for applications that demand high mobility and resilience.

1. **Critical Needs in Emergency Situations:** In disaster response scenarios, legged robots must be capable of traversing challenging terrains to perform search and rescue

missions. The ability to navigate rubble and obstacles while withstanding falls enhances their operational effectiveness. Liu et al.[10] demonstrate a serpentine tensegrity robot designed to navigate and survive in collapsed environments, underscoring its potential in search and rescue missions.

2. **Economic Efficiency:** In industrial settings, damaged robots can lead to costly repairs and operational downtime. However, robots with tensegrity structures display enhanced impact resistance traits[11], which not only reduces maintenance costs, but also ensures continuous operational capacity, thus increasing productivity. The motivation to create cost-effective solutions aligns with broader industry goals to enhance efficiency.

3. **Expanding Application Domains:** As technology evolves, the scope of legged robots continues to expand into areas such as space exploration, where adaptability and resilience are paramount [10]. The motivation to explore and validate these new application domains drives the research to enhance the capabilities of legged robots through innovative designs.

Research Objectives and Questions

Research Objectives

1. To design a robot structure utilizing a Control Moment Gyroscope (CMG) for stabilization and locomotion.

2. Develop and validate a control system using Raspberry Pi and Dynamixel smart actuators to enable precise joystick-controlled translational and rotational movements.

3. Evaluate the robot's stability and locomotion performance through physical experiments on controlled surfaces.

Research Questions

1. What is the impact of changes in the orientation of the gyroscopic flywheel on the robot's ability to perform translational and rotational movements under joystick control?

2. How accurately can the Raspberry Pi-based control system, integrated with Dynamixel smart actuators, execute joystick commands for locomotion, and what are the key limitations in motor response?

3. What does physical experimentation on controlled surfaces reveal about the robot's stability and locomotion performance?

Applications of Research

This research has far-reaching implications in various domains where legged robots are deployed, particularly in scenarios that require resilience and adaptability.

1. **Inspection and Rescue Missions:** Liu et al. [10] discussed role of tensegrity in disaster-stricken areas. Because tensegrity structures are lightweight and versatile, they could carry a bigger range of sensors necessary for inspection and rescue operations. Additionally, since these robots can withstand high impact collisions, they could be dropped into emergency zones by a drone or a land-based mobile robot to inspect the inside environment, for example. One such application would be a wheeled tensegrity robot that demonstrates increased robustness, and flexibility, and mobility without compromise[11].

2. **Industrial Inspections:** In environments such as factories, power plants, or chemical facilities, legged robots can autonomously inspect infrastructure for wear and tear or

compliance with safety regulations. The hybrid design enables these robots to handle the rigors of their environment—encountering machinery, uneven floors, or sudden drops—without sustaining damage, thus maintaining continuous operational capability. For instance, a serpentine tensegrity robot can be deployed to in the oil and gas industry in order to monitor pipelines[12].

3. **Space Exploration:** In extraterrestrial missions, such as those planned for Mars or the Moon, legged robots must navigate challenging terrains that may include rocky landscapes and steep slopes. The combination of tensegrity elements and gyroscopic stabilization allows these robots to adjust their orientation during falls, ensuring safe landings and reducing the risk of damage. For example, NASA is investigating the use of tensegrity robots for space exploration due to their distinctive structural design, which offers notable benefits for navigating uneven and unpredictable surfaces [13].

In summary, the proposed research on incorporating tensegrity structures into legged robots addresses disadvantages of the current models and offers multiple applications.

Chapter 3: **Literature Review**

Various studies have explored tensegrity structures and their applications in robotics, particularly focusing on dynamics, locomotion, and control strategies.

The role of gyroscopes in stabilizing flywheel torque is exemplified by two distinct approaches to self-balancing two-wheeled robots, as demonstrated by Chen et al. [14] and Çetin and Ünker [15]. Chen et al. [14] utilize a reaction wheel to generate a restoring torque for maintaining equilibrium at a fixed point, particularly on slopes, with Lagrangian dynamics modeling the torque's contribution to pendulum stability. Their adaptive double fuzzy anti-integral saturation PID control enhances the reaction wheel's torque modulation, achieving robust stability under external impacts and continuous loads (e.g., 30 g weight), outperforming traditional dual-loop PID control.

In contrast, Çetin and Ünker [15] employ a control moment gyroscope (CMG) with double flywheels to stabilize a two-wheeled robot under recoil forces (up to 3000 N) during high-speed maneuvers, using Lagrangian-derived equations and a linear-quadratic regulator (LQR) controller to manage gimbal torque. Their LQR-controlled CMG eliminates oscillatory motions, achieving steady-state head angle (φ) and gimbal angle (θ) displacements of 0.106 rad and −0.146 rad within 1.4 s under a 120 N constant recoil force, compared to uncontrolled CMGs' stable but oscillatory behavior (0.10 rad and 0.14 rad amplitudes).

While Chen et al.'s [14] reaction wheel excels in static balance with adaptive control, Çetin and Ünker's [15] CMG offers superior torque output for dynamic stability under impulsive loads, highlighting the versatility of gyroscopic flywheel systems. These results underscore the synergy between gyroscopic torque and advanced control strategies, with Chen et al.'s [14] fuzzy PID optimizing load adaptability and Çetin and Ünker's [15] LQR ensuring robustness against high-magnitude disturbances.

Filimonov et al.[16] present a hybrid legged-wheeled robot with tensegrity structures, enhancing impact resistance for rugged terrains and emergency scenarios. The 16.11 kg robot uses aluminum bars, viscoelastic silicone sheets, and steel cables in its legs and shoulder-body connections, enduring 0.5–0.7 m drops without damage. Drop tests show the shoulder, buffered by tensegrity links, experiences minimal peak acceleration, validated by simulations (stiffness: 1500–6000 N/m, damping: 20–400 Ns/m). Legged mode navigates uneven surfaces, while wheeled mode offers efficiency on flat terrain, suiting industrial inspections or search-and-rescue in debris-filled zones. Unlike Chen et al.'s [14] reaction wheel or Çetin and Ünker's [15] control moment gyroscope, which rely on active control, this passive tensegrity design mitigates fall impacts structurally, offering robustness for high-risk applications[16, 14, 15].

Rovira et al. [17] derived the dynamic equations of motion for tensegrity structures using the Euler-Lagrange method, applying quaternions to overcome problems with the inversion of the inertia matrix. Their work focused on ensuring that tensegrity structures could accurately follow desired trajectory paths through controlled actuation, primarily using simulations.

Similarly, Sabelhaus et al. [7] employed simulations to develop tensegrity-based spine-like robots with flexible movement. However, while Rovira et al. [17] concentrated on trajectory tracking, Sabelhaus et al. [7] focused on the mechanical design and adaptive movement of robotic spines. Both studies relied heavily on simulations for validation, but Sabelhaus et al. [7] went further by proposing mechanisms to address specific design challenges such as multi-gear-ratio actuators and compliance systems, which were not addressed by Rovira et al. [17].

Schorr et al. [18] took a different approach by investigating uniaxial bidirectional motion driven by vibrations, leveraging the unique properties of multistable tensegrity structures. Their study introduced a modal analysis of nonlinear motion dynamics, contrasting with the purely kinematic and control-based focus of Rovira et al. [17] and Sabelhaus et al. [7]. While Schorr et al. [18] also utilized tensegrity structures, they were more concerned with adjusting motion characteristics for mobile robotic applications through vibration-driven mechanisms, offering a unique solution not explored in the other works.

Kaufhold et al. [19] also explored locomotion in tensegrity robots, focusing on rolling motion. Their untethered tensegrity-based robot demonstrated capabilities for planar uphill and downhill movement, a form of locomotion distinct from the trajectory tracking and vibration-driven motion seen in previous studies. The emphasis on terrain locomotion in Kaufhold et al. [19] sets it apart, particularly their focus on future work involving uneven terrain and energy recovery, aspects less explored by other authors.

On the other hand, Kim et al. [20] introduced a rolling locomotion system for soft spherical tensegrity robots, which used cable-driven actuation. Like Kaufhold et al. [19], they focused on rolling motion but applied it to soft robots, bringing a different design perspective by leveraging compliant materials. Both studies share the theme of rolling locomotion but differ in their focus on soft versus rigid tensegrity structures and the corresponding control strategies for deformation and movement.

In the realm of multi-locomotion systems, Spiegel et al. [21] introduced a shape-shifting tensegrity robot capable of switching between locomotion strategies like wheeling and jumping. This multi-modal approach highlights a different path from the single-mode locomotion systems discussed by Rovira et al. [17], Sabelhaus et al. [7], and Kaufhold et al. [19], providing greater adaptability in complex terrains. Yang et al. [22] similarly emphasized adaptability, demonstrating small-scale tensegrity robots with high versatility in diverse terrains, but they focused more on experimental validation than theoretical modeling highlighted by Ma et al. [23].

In sensor accuracy and control, Rudyk et al. [9] and Hong et al. [8] analyzed noise and error compensation in MEMS gyroscopes, which play a crucial role in mobile robot navigation. Both studies proposed methods to improve measurement accuracy, with Rudyk et al. [9] focusing on random error analysis and Allan variance, and Hong et al. [8] focusing on filtering techniques for yaw angle estimation. These studies provide crucial insights for improving the control of tensegrity robots in dynamic environments.

In summary, various studies have advanced tensegrity robotics and gyroscopic stabilization, yet projects integrating both remain scarce. Tensegrity structures have been employed for their passive compliance and adaptability—such as in trajectory tracking via Euler-Lagrange dynamics [17], vibration-driven locomotion [18], and rolling or hybrid motion systems [19, 20, 21]. Filimonov et al. [16] demonstrated tensegrity's structural impact resistance without active control, while Sabelhaus et al. [7] and Yang et al. [22] explored mechanical adaptability in dynamic environments. Meanwhile, gyroscope-based actuation has shown strong potential in balance and stabilization, as seen in Chen et al.'s [14] reaction-wheel-controlled robot and Çetin and Ünker's [15] LQR-driven control moment gyroscope system, both capable of counteracting external disturbances and loads with high precision. Complementary efforts to improve MEMS gyroscope accuracy [9, 8] further support the viability of such sensors in mobile robotics. However, no existing study fully combines the structural advantages of tensegrity with the active torque control of gyroscopic mechanisms. This gap suggests untapped potential for robots that require both environmental adaptability and dynamic stabilization in rugged or unpredictable terrains.

Chapter 4: **Methodology**

Research Approach

This research focused on the design, simulation, control systems development, and physical prototyping of a 4-legged robot propelled by a gyroscope, utilizing a tensegrity structure for mobility and stability. The project followed a multidisciplinary methodology combining robotics and control theory. The process involves iterative design, simulation, physical prototyping, and testing to optimize the robot's structure and function.

Optimization Criteria

The primary criteria for optimization were:

- Minimizing overall weight to maintain energy efficiency during locomotion.
- Balancing tension and compression elements for flexibility in motion while ensuring robustness under impact.
- Maximizing structural stiffness to facilitate the movement of the robot actuated by the gyroscope.

Theoretical Basis for CMG Dynamics in the Simulation Methodology

To enhance the accuracy and effectiveness of the physical implementation of the 4-legged robot propelled by a control moment gyroscope (CMG), it is crucial to incorporate the theoretical equations that govern CMG dynamics. These equations serve as the foundation for understanding how the CMG influences the robot's stability, locomotion, and torque generation. By applying these principles to the physical system, it becomes possible to predict and control the robot's response to gyroscopic forces, motor actuation, and external disturbances.

The angular momentum H of the CMG disk, which represents the rotational energy stored in the system, is given by:

$$H = I \cdot \omega \tag{4.1}$$

where I is the moment of inertia and ω is the angular velocity of the disk [24].

The torque τ resulting from changes in angular momentum is defined by:

$$\tau = \frac{dH}{dt} = I \cdot \frac{d\omega}{dt} + \omega \times H \tag{4.2}$$

Here, the first term represents the torque needed to change the spin rate, and the second term accounts for gyroscopic torque due to orientation changes [24].

The torque generated by the motor driving the CMG is modeled by:

$$\tau_m = K_t \cdot I_m - B \cdot \omega_m \tag{4.3}$$

where K_t is the motor torque constant, I_m is the current, B is the viscous friction coefficient, and ω_m is the motor angular velocity [25].

The precession rate Ω, which describes the rotation of the angular momentum vector due to external torques, is approximated by:

$$\Omega = \frac{\tau_{ext}}{H} \tag{4.4}$$

where τ_{ext} is the external torque acting on the system [26].

These equations were used during implementation of the CMG focused robotic system.

Hardware Development and Prototyping

The hardware development process followed the simulation and optimization phases. Initial prototypes were created using 3D printing for rapid design iterations, allowing quick tests of different structural configurations. Essential components, such as gyroscopes, actuators, and sensors, were integrated based on the refined designs.

Materials and Fabrication

The robot's frame was constructed using lightweight 4mm aluminum sheet (needed form was fabricated on laser cutter BODOR P3015), PLA and polyethylene terephthalate glycol (PETG) plastics. Tensegrity links were made from 2mm thick silicone rubber sheets with 40 shore A hardness. This combination ensured flexibility and impact resistance while maintaining lightweight characteristics essential for mobility. The flywheel was made from a 1-kg break disk. The mechanical design was developed in Autodesk Fusion 360 computer-aided design (CAD) software. Lastly, fabrication was facilitated through Ultimaker S5 and Bambu Lab X1 Carbon 3D printers to produce complex geometries rapidly. The robot legs were designed and assembled in accordance with design and materials of the legs in research by Filimonov et al. [16].

After the fabrication, the robot underwent impact and load bearing tests to verify that its materials and design can withstand the expected forces exerted by the gyroscope while maintaining its structural integrity.

Control Systems Integration

The robot's control systems was programmed in Python using the Raspberry Pi's Thonny IDE. A Control Moment Gyroscope (CMG) system was integrated to assist in orientation control and facilitate locomotion through controlled internal actuation.

Testing and Validation

The validation phase consisted of evaluating the robot's ability to achieve locomotion using its internal actuators and inertia created by CMG. Testing was conducted in controlled environments. The key evaluation criteria were assessing the robot's capability for locomotion, meaning that it is capable of moving forward and turning while maintaining the stable orientation on the surface.

The tests were conducted in both simulated and physical environments to validate the robot's locomotion capabilities. The objectives were to verify translational and rotational movement using joystick inputs, to evaluate system responsiveness, stable motion, and finally to measure control accuracy by comparing command signals with real-time motor feedback.

Experimental Setup

The methodology consisted of experimental validation of the robot's motion control system using both manual input and motion capture. A two-axis joystick was used to send control commands to a gimbal-actuated flywheel system, allowing the user to manipulate the robot's movement.

Two primary tests, translational and rotational maneuvers, were conducted to evaluate the robot's response accuracy and control performance. During these tests, OptiTrack motion capture was used to record real-time positional data. The joystick-generated goal positions and the actual motor responses were captured simultaneously to compare the input-output correlation.

The translational motion test evaluated the robot's linear back-and-forth movements, while the rotational motion test analyzed the robot's turning behavior. Position data from the Dynamixel motors were analyzed to assess system stability, responsiveness, and lag.

Data Collection and Analysis

We collected data from physical experiments carried out through Motion Capture system **Optitrack** on flat surfaces under 120 frames per second (FPS) data capturing, which yielded information regarding the position of markers that were placed on the robot's legs and CMG. In other words, we performed the dynamic behavior analysis of simulated and actual joint trajectories.

Ethical Considerations

The study adheres to strict ethical standards in engineering research. No human or animal subjects were involved. All simulations and tests focused solely on mechanical systems. All references and code sources were properly credited, and design files are shared transparently.

Risk Management

Development and testing of the given robotic structure involves certain risks such as structural failures, electronic system malfunctions, and testing delay. Due to such risks it is important to integrate risk management into the project. To mitigate these risks we performed tests on of smaller-scale prototypes. In addition, the integration of emergency stop buttons ensures safety of the prototype and electric equipment. Regular inspections and iterative debugging of the code ensured operational safety.

Chapter 5: **Implementation and Execution**

Mechanical Design and Fabrication

The robot features a symmetrical and rigid metal frame that supports a unique locomotion system based on a **Control Moment Gyroscope (CMG)**. The central structure houses the core actuation unit, a revolving disk (gyroscopic flywheel), responsible for generating both stabilization and movement through angular momentum transfer. The primary structure is constructed using a metal frame composed of lightweight aluminum alloy rods, which provide rigidity while minimizing mass and maintaining structural balance. The frame supports four articulated leg assemblies positioned at each corner as shown in Figure 5.3.

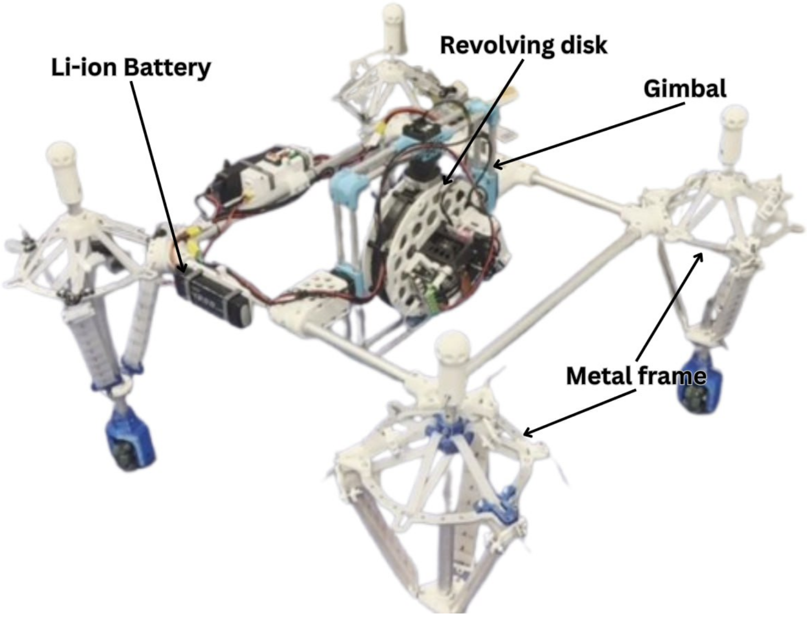


Figure 5.1: Structural layout of the robot

Key structural components include:

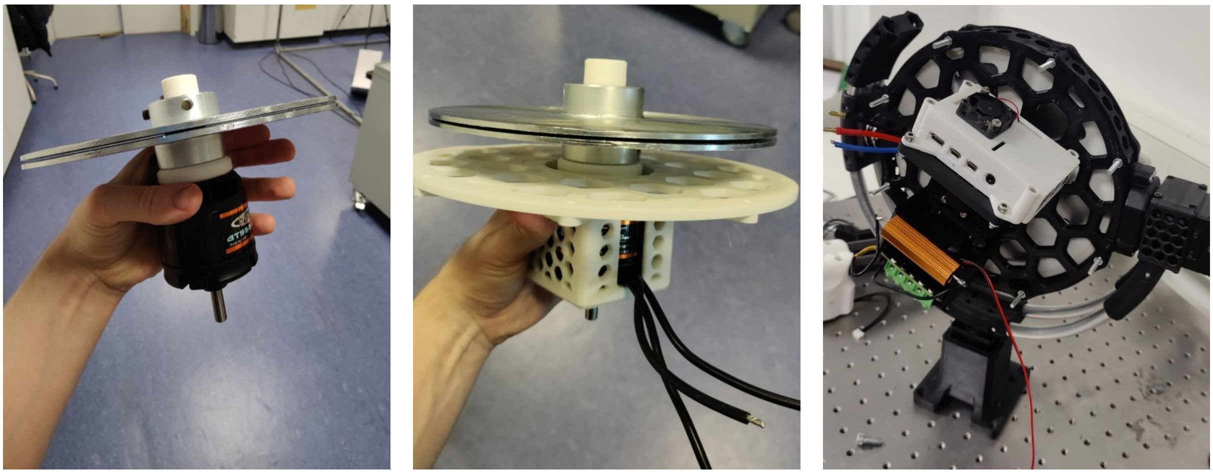
- **Revolving Disk:** Mounted at the center of the structure, this disk is driven by the high-speed EMAX GT5325/09 brushless motor and acts as the flywheel generating angular momentum. When its spin axis changes via the gimbal, the reactive gyroscopic torque causes the entire robot to roll, turn, or shift.
- **Gimbal Assembly:** A dual-axis gimbal encloses the flywheel and provides the degrees of freedom necessary to tilt its spin axis. This mechanism enables dynamic reorientation of the angular momentum vector, resulting in directed motion of the robot. The gimbal is actuated by two Dynamixel PH42-020-S300-R motors,
- **LiPo Battery:** A compact high-discharge lithium-polymer battery is mounted on the frame to supply power to both the gyro motor and control electronics, with placement optimized for balance.
- **Leg Modules:** Four compliant wheeled legs ensure surface contact for stability and terrain adaptability. The suspension system mitigates vibrations and shock during locomotion.

- **Switches and Cables:** Strategically routed power and signal cables and easily accessible switches ensure system reliability and safety with minimal electromagnetic interference.
- **LCD Screen:** An onboard display provides real-time feedback on operational parameters, aiding debugging and monitoring during development.

In this configuration, locomotion is achieved not by direct motorized propulsion of the wheels but through reaction forces generated by gyroscopic precession. The layout ensures minimal interference with the flywheel and allows future actuation upgrades.

Actuation System

This design utilizes the principles of angular momentum and gyroscopic precession to induce motion. When the flywheel spins at high speed, any change in its orientation results in reactive torques that propel the robot. The rotor is mounted within a dual-axis gimbal frame, allowing tilting along two perpendicular axes, as shown in Figure 5.2.



(a) A disk connected to motor

(b) The disk connected to an encased motor

(c) Dual-axis gimbal connected to Raspberry Pi 4 module

Figure 5.2: The gyroscope prototyping in stages

The gyroscope system comprises the following components:

- **Rotor:** The high-speed spinning element that generates angular momentum, powered by the EMAX GT5325/09 325 kV Brushless Motor.
- **Gimbal System:** A dual-axis mechanism that permits tilting of the rotor, thereby enabling changes in the angular momentum vector to induce movement.
- **Housing:** A protective, lightweight enclosure that minimizes environmental interference while preserving rotor performance.

Electronics and Control

The robot is controlled via a **Raspberry Pi 4**, which executes pre-programmed sequences and integrates with peripheral components. The power distribution circuit was encased in a dedicated box with a master switch, and all cabling was securely fixed to the frame.

Motor Control Hardware

The robot employs two major actuation systems. First, **Dynamixel P-Series smart actuators** provide high-torque, high-precision control of key mechanical elements, using

RS485 communication at 1 Mbps. Second, the **gyroscopic flywheel** is driven by a 325 kV brushless DC motor connected to an ODESC V3 ODrive controller. The controller operates in sensorless mode and is tuned for safe high-speed operation.

Table 5.1 summarizes the main parameters of the actuation system. It shows that the smart actuators have a broad positional range (in raw encoder units), while the ODrive motor controller is set to a maximum current limit of +20A for safe flywheel spinup. These parameters were selected to balance torque requirements, thermal constraints, and system responsiveness.

Table 5.1: Actuation System Parameters

Parameter	**Value**	**Description**
Motor Type	Dynamixel P-Series	High-torque digital servo
Protocol	Protocol 2.0	RS485-based communication
Baud Rate	1,000,000 bps	Serial communication rate
Position Range	-303454 to 303464	Raw encoder units
Torque Enable	1 (Enable), 0 (Disable)	Torque control flag
Continuous Torque	5 Nm	Torque that motor can transfer continuously
Continuous Speed	29.2 rev/min	Maximum continuous speed the motor can transfer
Max Current (ODrive)	+20A / -1A	BLDC driver limits
Max Speed (BLDC)	3600 rev/min	Maximum possible speed with current hardware

Control Architecture

The control system follows a hierarchical design. A joystick provides real-time manual input for servo actuation. An emergency stop mechanism disables torque upon user interruption (e.g., `Ctrl+C`). The ODrive includes fault protection for overcurrent and undervoltage conditions, with limits set to 20A for safe operation.

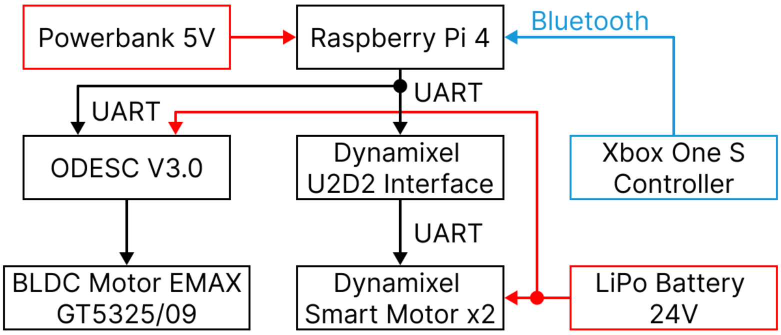


Figure 5.3: The control architecture of the robot

The proposed tensegrity robot integrates a modular control and power distribution architecture to enable robust operation and dynamic maneuverability, as depicted in Figure 5.3. The system is centered around a Raspberry Pi 4, which serves as the primary computational unit. The Raspberry Pi 4 interfaces with peripheral components via UART communication protocols, ensuring seamless data exchange for real-time control.

Power is supplied through two distinct sources: a 5V powerbank, which delivers stable voltage to the Raspberry Pi 4, and a 24V LiPo battery, which powers the motor subsystem. The LiPo battery directly drives two Dynamixel Smart Motors (U2D2 Interface) and a BLDC motor (EMAX GT5325/09), facilitating rotational and translational movements of the tensegrity structure. The Dynamixel motors are controlled through the U2D2 interface, which communicates with the Raspberry Pi 4 via UART, enabling precise actuation and feedback.

For motor control, an ODrive ESC (ODESC v3.0) is integrated between the BLDC motor and the Raspberry Pi 4, also utilizing UART for command transmission and motor feedback.

This setup ensures accurate speed and torque regulation, critical for maintaining stability during dynamic operations.

User interaction is facilitated through an Xbox One S controller, connected to the Raspberry Pi 4 via Bluetooth. This wireless interface allows for intuitive teleoperation, enabling the user to issue high-level commands for navigation and orientation adjustments in real time.

This architecture balances computational efficiency, power management, and control precision, making it well-suited for applications in exploration and disaster response, where lightweight and resilient robotic systems are essential.

Locomotion Strategy

Locomotion is achieved via gyroscopic precession and compliant leg interaction with terrain. The gyroscope is articulated by Dynamixel motors. The robot sequentially contracts and releases cables to induce tilting, which—combined with the central flywheel—produces a rolling gait.

The Dynamixel motor positions are controlled using sinusoidal functions to achieve periodic motion in the tensegrity robot. The position commands for the motors that create a translational movement are denoted as pos and pos_1, are defined as follows:

$$\text{pos} = A \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot \cos(\omega_{11} \cdot t) \tag{5.1}$$

$$\text{pos}_1 = -A \cdot 0.111 \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot \cos(\omega_{11} \cdot t) \tag{5.2}$$

where:

- A is the amplitude factor (`amp`),
- DXL_MAXIMUM_POSITION_VALUE is the maximum position limit of the Dynamixel motor,
- ω_{11} is the angular frequency (`w11`),
- t is the current time (`time_now`).

The negative sign and scaling factor of 0.111 in Equation (5.2) introduce a phase opposition and amplitude reduction for the second motor, ensuring coordinated motion within the tensegrity structure.

Similarly, sinusoidal motions for the gimbal axis were defined using following sinusoidal piecewise functions:

$$\text{For } t < \frac{t_1}{2}: \quad \text{pos} = 0.667 \cdot A \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot (\cos(\omega_1 \cdot t) + 0.5) \tag{5.3}$$

$$\text{pos}_2 = 0.5 \cdot A \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot (\cos(\omega_1 \cdot t) + 1) \tag{5.4}$$

$$\text{For } t > \frac{t_1}{2}: \quad \text{pos} = -0.667 \cdot A \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot \left(\cos(\omega_2 \cdot (t - \frac{t_1}{2})) - 0.5\right) \tag{5.5}$$

$$\text{pos}_2 = -0.5 \cdot A \cdot \text{DXL\_MAXIMUM\_POSITION\_VALUE} \cdot \left(\cos(\omega_2 \cdot (t - \frac{t_1}{2})) - 1\right) \tag{5.6}$$

where:

- A is the amplitude factor (`amp`),

- DXL_MAXIMUM_POSITION_VALUE is the maximum position limit of the Dynamixel motor,
- ω_1 and ω_2 are the angular frequencies (`w1` and `w2`),
- t is the current time (`time_now`),
- t_1 is the total time duration.

The conditional structure introduces a phase transition at $t = \frac{t_1}{2}$, reversing the sign and shifting the phase of the sinusoidal terms, which enables adaptive motion control tailored to different segments of the robot's operation cycle.

To verify and fine-tune motion models, the OptiTrack motion capture system will be employed, enabling real-time tracking for closed-loop control development and experimental validation.

Chapter 6: **Testing and Results**

The preliminary tests involved controlling the gimbal system using a two-axis joystick. The user could manually adjust the flywheel's orientation, observing the resulting movements of the robot. These experiments validated the proof of concept, demonstrating that the robot could move in various directions depending on the gimbal adjustments. Moreover, a successful testing ensures the system responding accurately to user inputs and the stability maintained during motion. These requirements must confirm the effectiveness of the gyroscopic stabilization.

The robot's movement and its accuracy was evaluated by two sets of experiments: translational and rotational maneuvers. To collect data from the experiment, a motion capture system OptiTrack was used. The required position is sent to the motor via joystick, then the resulting motor position data is recorded in real-time comparison.

Translational Motion Test

In the translational motion test (Figure 6.1) the robot received commands from a joystick to induce back-and-forth linear movements. The goal and resulted motor positions are shown in the span of 4 seconds. Goal Position 0 and Goal Position 1 to the position command sent to each of the Dynamixel motors in the gimbal system, while Present Position 0 and Present Position 1 track the actual response of the motors. Figure 6.2 shows the snapshots of the translational motion that was executed for 40 seconds. As could be seen, the robot managed to travel a small, yet noticeable distance. Both motor 1 and motor 2 show the close accuracy between the goal position and the actual positions. This graph demonstrates robot's stable response to a translational motion command and validates the effective control loop of the system; however, there is a lag in the first motor.

Rotational Motion Test

The second test was rotational motion, in which a special command was sent to the robot. Similarly as in the translational motion test, the commands received from a joystick resulted in a sinusoidal position change in both motors. Both motor positions were recorded and put in the plot shown in Figure 6.3. Although goal positions and recorded positions presented

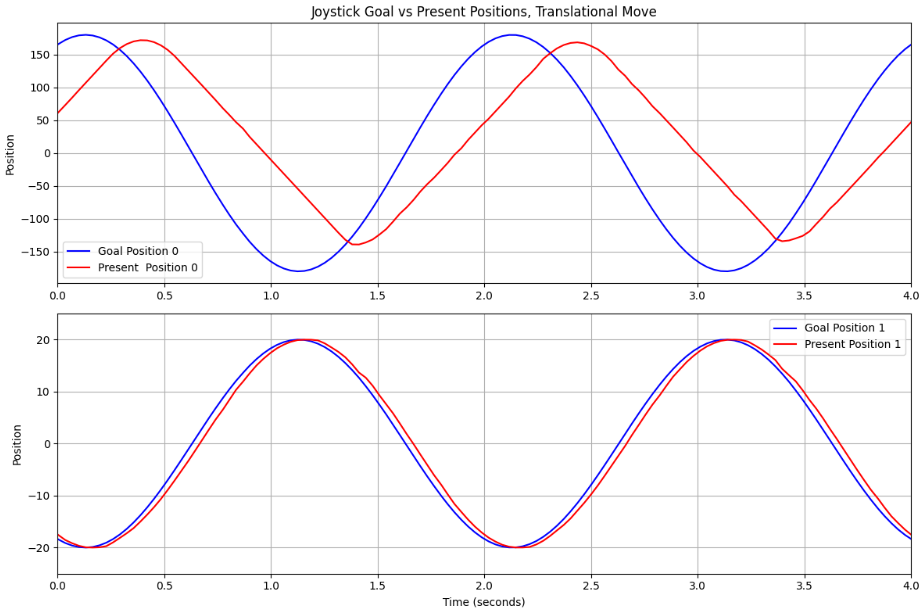


Figure 6.1: Joystick Goal vs Present Motor Positions during Translational Movement

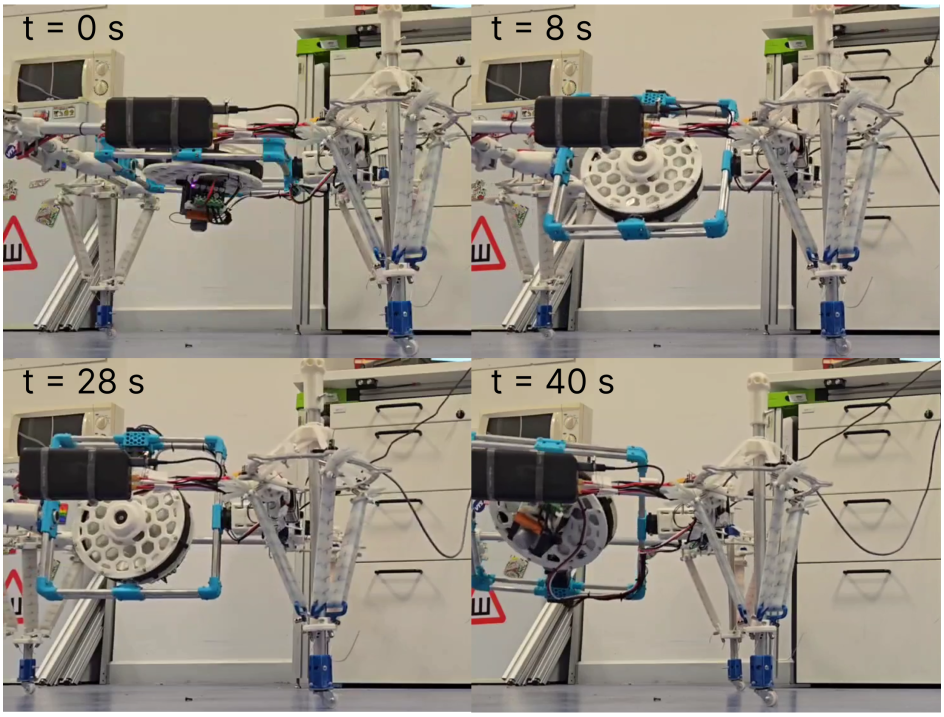


Figure 6.2: Translational Movement of the robot

similar shape of the waveform, there was a noticeable phase shift in the first motor, moreover, the amplitude of the Present Position 1 are depicted as smaller than that of a Goal Position. It can be inferred that rotational motion requires further tuning of the controller or smoothing of input signals for more precise performance. Though the issues with the motor response time are present, Figure 6.4 demonstrates a successful rotation of the robot over the same 40 seconds time.

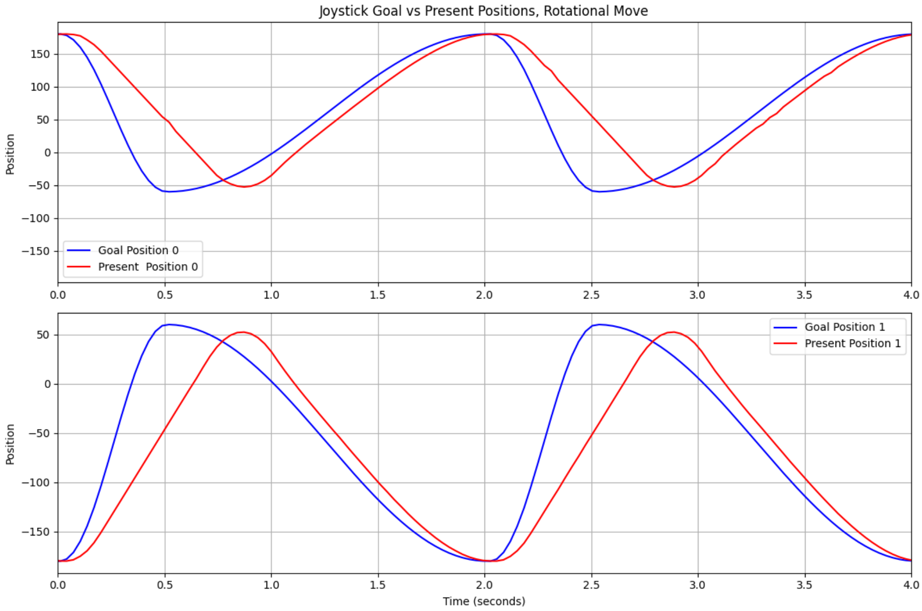


Figure 6.3: Joystick Goal vs Present Motor Positions during Rotational Movement

Validation Test

One more validation test, which involved both rotational and translational motions, was performed in the motion capture area to record precise data on the robot location. Figure 6.5

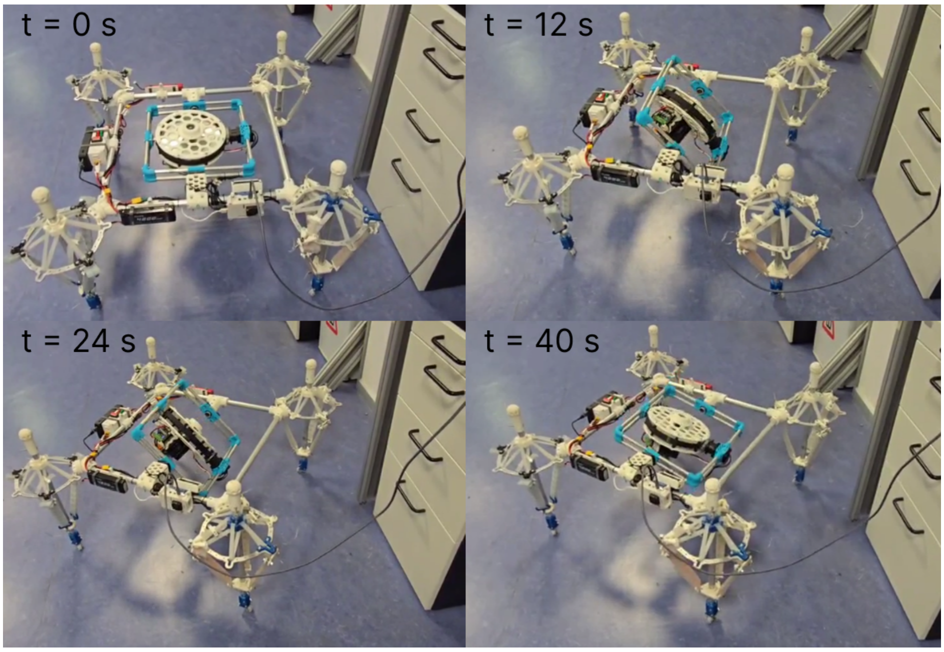


Figure 6.4: Rotational Movement of the robot

displays the results of the experiment, where it could be clearly seen that the robot has successfully performed a translational and then rototranslational motion. It is also important to mention that the CMG is creating oscillations due to its work, which is noticeable by the nature of the curve itself.

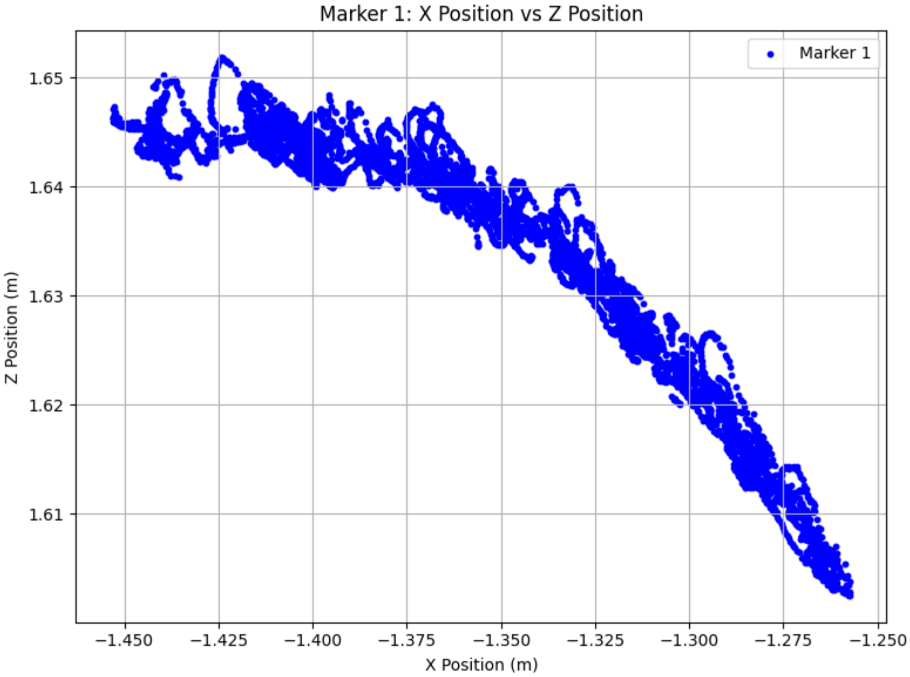


Figure 6.5: Robot Position, X-Z marker

Chapter 7: **Discussion**

The development and experimental testing of the 4-legged tensegrity robot with gyroscopic actuation provided significant information on its performance, aligning with the research objectives and answering the proposed research questions. This section evaluates the achievements against each objective and question, drawing comparisons with prior work from the literature to contextualize the findings and highlight the project's novel contributions.

Objective 1: Design a lightweight tensegrity robot structure integrated with a Control Moment Gyroscope (CMG) to achieve locomotion and stabilization through angular momentum manipulation. This objective was successfully achieved through the design and fabrication of a robot featuring a lightweight aluminum alloy frame, compliant wheeled legs, and a central CMG-driven flywheel. The structure, constructed using 3D-printed PLA plastic and steel cables for tensegrity links, balanced flexibility and robustness, enabling locomotion via gyroscopic precession. The flywheel, powered by an EMAX GT5325/09 brushless motor within a dual-axis gimbal, generated angular momentum for stabilization and movement, as demonstrated in physical tests. Unlike Sabelhaus et al. [7], who focused on compliant tensegrity spines without gyroscopic actuation, this design combines tensegrity's shock-absorbing properties with precise gyroscopic actuation, akin to Çetin and Ünker [15]. Hence, our project succeeds in addressing the literature's gap in hybrid actuation systems. Compared to Kaufhold et al. (2017), who focused on rolling tensegrity robots, this project's gyroscopic precession enables both translational and rotational movements, offering greater control versatility.

Objective 2: Develop and validate a control system using Raspberry Pi and Dynamixel smart actuators to enable precise joystick-controlled translational and rotational movements. This objective was achieved by implementing a Raspberry Pi-based control system integrated with Dynamixel P-Series smart actuators and an ODrive controller for the flywheel. The system enabled joystick-controlled movements, validated through translational and rotational tests. Figure 6.1 and 6.3 illustrate motor responses, showing close alignment between goal and present positions, though with minor phase delays and amplitude discrepancies in translational tests. These results confirm the control system's functionality, with rotational control being particularly effective. In contrast to Rovira et al. [17], who used complex Euler-Lagrange modeling for tensegrity trajectory tracking, this project employs a simpler, joystick-driven control approach, making it more accessible for real-time operation. However, similar to Hong et al. [8], who addressed MEMS gyroscope control challenges, this work faced motor response limitations, suggesting the need for motors with greater speed and torque capabilities, as noted in the results.

Objective 3: Evaluate the robot's stability and locomotion performance through physical experiments on controlled surfaces. Physical tests on controlled surfaces, tracked via OptiTrack, confirmed the robot's translational and rotational locomotion capabilities, fulfilling Objective 3. The CMG's role in stabilizing the robot under joystick control aligns with Çetin and Ünker [15], whose LQR-controlled CMG minimized oscillations under dynamic loads. However, unlike their two-wheeled platform, the 4-legged tensegrity structure leverages passive impact absorption, similar to Filimonov et al. [16], enhancing stability on flat surfaces. The robot's leg structures closely resemble the design principles employed by Filimonov et al. [16], who utilized aluminum bars, viscoelastic silicone sheets, and steel cables to achieve robust impact resistance in their hybrid legged-wheeled robot. Their robot withstood drops from 0.5–0.7 m without damage, with simulations validating minimal peak acceleration at the shoulder (stiffness: 1500–6000 N/m, damping: 20–400 Ns/m). Given the structural similarities, particularly the use of tensegrity links to distribute forces and absorb shocks, the 4-legged robot is likely to exhibit comparable resilience to high-impact scenarios, such as drops or collisions.

Question 1: What is the impact of gyroscopic flywheel orientation changes on the robot's ability to perform translational and rotational movements under

joystick control? The experimental tests answered this question by demonstrating that flywheel orientation changes, controlled via the dual-axis gimbal, effectively induced translational and rotational movements. For examples, Figure 6.3 shows near-accurate motor responses for rotational commands. This aligns with Kim et al. [20], who explored actuation-driven tensegrity motion but used cable systems rather than gyroscopic control.

Question 2: How accurately can the Raspberry Pi-based control system, integrated with Dynamixel smart actuators, execute joystick commands for locomotion, and what are the key limitations in motor response? The testing results addressed this question, showing that the control system executed joystick commands with high accuracy for rotational movements but with noticeable delays and amplitude issues in translational movements. These findings are consistent with Rudyk et al. [9], who highlighted error compensation in gyroscopic control systems.

Question 3: What does physical experimentation on controlled surfaces reveal about the robot's stability and locomotion performance? Physical experiments revealed robust stability on controlled surfaces, with the tensegrity structure absorbing minor impacts and the CMG ensuring balance. This passive-active synergy distinguishes the robot from Chen et al. [14] and Çetin and Ünker [15], who relied solely on active control.

Limitations

There were several limitations observed during development. The gyroscope's rotor must spin at high speeds to generate sufficient angular momentum for effective balance control. However, increasing the rotor speed beyond a certain threshold introduced significant challenges. Specifically, the ODrive motor controller could not reliably support rotor speeds above a critical RPM, leading to instability and potential failure. Additionally, high-speed rotation introduced mechanical vibrations, often caused by rotor imbalance or misalignment. To mitigate these issues, future designs should incorporate precision bearings, balanced rotor assemblies, and vibration-damping materials. If high-frequency oscillations persist, counterweights and symmetrical design approaches may help minimize dynamic imbalance. Regular rotor calibration is also recommended to ensure consistent performance during high-speed operation.

With two axes of rotation, our robot can effectively control movements in the pitch and roll directions. This allows for forward/backward and side-to-side motion, which is sufficient for many applications. However, the absence of a third (yaw) axis means the robot cannot independently rotate around the vertical axis using the gimbal system alone.

Chapter 8: **Conclusion and Future Work**

This project presents the design and development of a novel gyroscopically actuated tensegrity robot capable of motion through the manipulation of angular momentum. The mechanical structure is lightweight and compliant, while the actuation system—based on a high-speed flywheel and gimbal-mounted smart actuators enables rolling locomotion without traditionally actuated wheels or legs. Electric control is centered around a Raspberry Pi and integrates ODrive and Dynamixel systems for distributed motion execution.

To enhance the robot's autonomy and control accuracy, several developments are planned. **Gyroscopic Control** will be improved by integrating a MEMS-based Inertial Measurement Unit (IMU), such as the Adafruit BNO055, to provide real-time orientation feedback. This sensor will enable the system to precisely calculate and monitor precession torques during movement, allowing more predictable and stable locomotion based on dynamic angular momentum shifts.

Additionally, **Active Gimbal Control** will be implemented using PID-based orientation control loops. These loops will operate on real-time feedback from the IMU and control the gimbal tilt angles through high-torque Dynamixel smart actuators. This advancement will allow fine-grained control over the flywheel orientation, enabling adaptive motion planning and terrain-aware locomotion. Together, these upgrades will transition the robot from open-loop motion to a fully feedback-driven system capable of closed-loop stabilization and semi-autonomous navigation.

A key focus was placed on modularity and future extensibility, which has been achieved through careful component integration and a flexible control architecture. Initial testing confirms the viability of this approach for generating motion via gyroscopic precession. Future work includes sensor integration and feedback-based control to enhance maneuverability and adaptivity. This lays the foundation for a new class of compact, compliant, and intelligent mobile robots capable of navigating diverse environments using unconventional actuation principles. Last, but not least, the contribution of this work creates a fundament that would be used to create a legged tensegrity robot with CMG, that would be capable to fall in arbitrary position and land on its legs thanks to the CMG.

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Chapter 9: **Appendix**

The repository containing the code:
https://github.com/Meneralllka/GyroBot
The link for the videos:
https://drive.google.com/drive/folders/1lF0kpsKUTRzXdeB4iHSQWekhZx97yRca