Simscape Analysis on Omnidirectional Quadruped Solidworks Model

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Abstract

This project is inspired by swarm robotics, which mimics the collective behavior observed in natural swarms (1). Swarm robotics has potential applications in environmental monitoring, search and rescue, and agricultural automation (2). The project aims to implement quadrupeds (four-legged robotic agents) in swarm robotics. Typically, swarm robots are compact and perform tasks on a smaller scale collectively, while quadrupeds are generally larger and built for heavier, more complex tasks (3, 4). This report investigates whether quadrupeds can be designed to operate collaboratively in a swarm, potentially being scaled down to the size of the average swarm robot and effectively localized. This investigation will utilize SolidWorks and Simscape software to build and analyze quadruped models as small, compact machines. Although the results of this research are incomplete, they will provide insights into the challenges faced in this area of study.

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Review

Research into miniaturizing quadrupeds for swarm applications is ongoing but presents significant engineering challenges due to factors like power requirements, mechanical complexity, and control algorithms (5, 6). The concept of making quadrupedal robots small enough to operate as typical swarm robots is still largely theoretical and experimental (5, 6).

Application

Quadruped, such as Spot developed by Boston Dynamics, is increasingly used in construction, security, monitoring, and law enforcement [8, 9, 10]. Trimble is one of the many companies that use Spot for navigating rough and uneven terrains with ease, making it ideal for surveying construction sites and hazardous areas [9]. In construction, Spot is employed to survey terrains, create 3D maps of sites, and conduct analyses to expedite project completion [8, 9]. These capabilities enable construction teams to monitor progress, detect potential issues early, and ensure that projects stay on schedule. The ability to create detailed 3D maps helps in planning and executing construction tasks with higher precision and efficiency [8, 9].

Spot has been utilized by NB Power for site documentation and construction monitoring [10]. By automating the documentation process, Spot can provide real-time updates and visual records of construction progress, reducing the need for human inspectors to navigate potentially dangerous areas. This not only improves safety but also increases the accuracy and consistency of site inspections. Spot's ability to access confined or hazardous spaces ensures that inspections are thorough and comprehensive, further enhancing the safety and efficiency of construction operations [10].

Furthermore, Boston Dynamics collaborated with Innovation Labs to modify Spot for inspecting remote or hazardous areas to ensure safety and operational efficiency [8, 10]. In security and monitoring roles, Spot can patrol areas, detect unauthorized intrusions, and monitor environmental conditions. The robot is equipped with advanced sensors and cameras that allow it to detect objects and substances that may go unnoticed by humans, such as hazardous gases and concealed items [8, 10]. This capability is particularly valuable in environments where human presence is risky, such as chemical plants, nuclear facilities, or disaster-stricken areas.

Despite their usefulness, the high manufacturing cost of these robots has limited their widespread availability [8, 9, 10]. The sophisticated technology and components required to build a quadruped robot like Spot contribute to its high price, making it a significant investment for most organizations. Additionally, there are ongoing concerns about ensuring their safe operation in public spaces [8, 9, 10]. The deployment of autonomous robots in public areas raises questions about reliability, the potential for malfunction, and the need for regulatory frameworks to govern their use. Ensuring that these robots operate safely and effectively in dynamic and unpredictable environments is an ongoing challenge that requires continuous development and refinement of their systems and protocols.

Modeling

Quadruped robots have made significant advancements in robotic technology by utilizing the principles of quadrupedal locomotion, enhancing mobility, versatility, and autonomy [11, 12, 13]. The development of quadruped robots can be traced back to experimental models in the late 20th century, such as the "Phony Pony" and Marc Raibert's one-leg hopper [11, 12]. However, early designs like the "Phony Pony" had limitations such as basic functionality and high energy consumption [11]. The large-scale industrial quadruped "Big Muskie" faced challenges with slow walking speeds and cumbersome operation, leading to its eventual dismantling in 1990 [13]. More recent advancements by Boston Dynamics, including "BigDog" and "Spot," have revolutionized applications in construction, security, and exploration due to their agility and robustness [8, 14]. Nevertheless, modern quadrupeds encounter challenges such as high manufacturing costs, limited battery life, and regulatory hurdles [15, 16]. Despite these challenges, ongoing advancements in materials, sensors, and artificial intelligence (AI) continue to drive quadruped robots towards greater efficiency, reliability, and versatility, promising significant impacts across various fields of robotics and beyond [15, 16].

Design Concept

Every concept design in this report is first assembled in SolidWorks as CAD models. These assemblies are then imported into Simscape Multibody, where the mechanisms are translated into Simscape models. By interfacing these models with Simulink, a wide range of analysis and design tasks can be performed, including actuator control, manipulation algorithms, gear mechanism design, PID controller tuning, and visualizing the behavior of the mechanisms.

Prototypes

Each prototype presented in this report features a Zeee 2S Lipo Battery, specifically a 7.4V 5200mAh 50C hard case battery with Deans T Plug, weighing approximately 250g and measuring 138mm in length, 47mm in width, and 25mm in height [15]. This type of battery is highly regarded and commonly used in high-powered RC vehicles due to its performance with multiple actuators. Additionally, each prototype incorporates four SG90 Micro Servo motors, each weighing 9g and measuring 22.2mm in length, 11.8mm in width, and 31mm in height [16]. Known for their reliability, these servos are widely used across various applications. An Arduino Nano serves as the microcontroller because of its compact size and user-friendly interface [17]. Further components will be integrated between Prototype One and Prototype Two, with the following iterations focusing on improving the design.

The first design showcased in Appendix A is a spherical mobile robot with sphere wheels that allow the machine to rotate in the Z axis and translate in the Z and Y axes. If assisted by a wall, it could potentially rotate in the X axis. The driving motor is the Mini DC Motors 3V 6V low torque 16500 rpm max, which, despite being only slightly larger than a servo motor, possesses sufficient power to propel a small vehicle [18]. However, the design's limitations have the machine experience rough motion rather than smooth operation. This prototype drew inspiration from Midoritamidori's Omni-Directional Mobile Robot, which also utilizes sphere wheels to achieve this feat [14]. Alternatively, Prototype One explores the performance of spherical wheels when positioned at varying angles to assess their effectiveness.

The second prototype in Appendix B is more complex as it has four degrees of freedom, translating on the X, Y, and Z axes and rotating on the Z axis. There is also the potential for rotation on the X axis if assisted by a wall, although this capability is theoretical. This concept utilizes one gearbox in each leg, each containing a 5mm bevel gear with a 1.5mm bore [19]. This prototype replaces the mini DC motor with the micro-coreless motor 3.7v with 35,000rpm as the driving force [20], while also incorporating a mini DC motor in the knee joint of each leg [18]. This machine displays a more conventional take on the Quadruped design, resembling most concepts except for the tire wheels that are attached to it.

The final result is a quadruped with only three differences from the second prototype. In Appendix C, the wheels, the base of the machine, and the leg have been redesigned to accommodate the sphere wheels taken from the first prototype [14]. This quadruped is capable of five to six degrees of freedom, translating on all axes, rotating on the Z and Y axes, and potentially rotating on the X axis.

Development

Prototype One served as a solid foundation for building subsequent prototypes, though it had several notable flaws. It included a significant amount of unused space, resulting in unnecessary weight. Additionally, the machine's bulky design meant the wheels were larger than necessary, and the paired DC130 motor required more voltage to drive these heavy wheels [18]. The wheels themselves, being perfect spheres, only drove smoothly on flat surfaces, which restricted the machine's weight capacity and terrain adaptability (See Appendix A).

Building upon the general idea from the first prototype, Prototype Two features a flat foundation with servo motors attached to the sides of the Lipo battery, facing downward (See Appendix B). The mount for the DC130 motor in Prototype One was replaced with a rotating mount to provide the quadruped with greater freedom of movement. These modifications introduced more variety and better weight distribution, easing the burden on the legs. However, Prototype Two still faced new issues: only some necessary space was utilized, the Lipo battery was not securely fastened to the foundation, and if the machine fell, the battery would detach. In a physical prototype, wiring would also pose a problem due to the difficult positioning of the mini DC motors [20]. Furthermore, the machine could not move sideways.

To address these issues, Prototype Three drew inspiration from the sphere wheel of the first prototype (See Appendix C). Unlike the tire design, this iteration referenced an omnidirectional sphere for the tracks [21]. While this robot does not rely on traditional wheels, the overall design concept remained useful. Consequently, in Prototype Three, the wheels were made spherical but with tracks and grooves at the bottom to enhance stability during walking. The foundation was redesigned as a case to securely hold the Lipo battery, fully utilizing the previously unused space. This approach resolved the stability and space issues, making the machine more robust and versatile across various terrains.

Material

When researching materials for the wheels, several options were considered, including natural rubber, BUTYL, Nitrile NBR, and Silicon. Each of these materials has distinct properties that make them suitable for specific applications:

1. Natural Rubber:
    1.1. Properties: Natural rubber is known for its high elasticity, resilience, and excellent tensile strength. Has good abrasion resistance, making it ideal for applications that require a material to maintain its integrity under stress [22, 25].

    1.2. Advantages: Its flexibility and shock-absorbing properties make it an excellent choice for wheels that will traverse different terrains. Natural rubber can handle rough and uneven surfaces better than some synthetic rubbers, providing a smoother ride and better traction [22, 24].

    1.3. Common Use: Natural rubber is widely used in the automotive industry for tires and other components that require durability and flexibility. Its ability to perform well under varying conditions makes it suitable for the wheel application in the prototypes [23].

2. BUTYL Rubber:
    2.1. Properties: BUTYL rubber is known for its impermeability to gases, chemical resistance, and weathering resistance. However, it is less flexible than natural rubber [26].

    2.2. Advantages: Its resilience makes it ideal for applications like inner tubes and liners where air retention is crucial.

    2.3. Disadvantages: Due to its lower flexibility compared to natural rubber, it may not provide the same level of performance on varied terrains [26].

3. Nitrile NBR Rubber:
    3.1. Properties: Nitrile NBR rubber offers impressive resistance to oils, fuels, and chemicals. It also has good tensile strength and elasticity [28].

    3.2. Advantages: It is widely used in the automotive and aeronautical industries where exposure to oils and fuels is common.

    3.3. Disadvantages: While it has good mechanical properties, it may not offer the same level of flexibility and shock absorption as natural rubber for terrain navigation [27].

4. Silicon Rubber:
    4.1. Properties: Silicon rubber is known for its excellent heat resistance and flexibility over a wide temperature range. It also has good electrical insulation properties [27, 29].

    4.2. Advantages: Ideal for applications that require exposure to high temperatures and electrical insulation.

    4.3. Disadvantages: It is typically more expensive and less wear-resistant compared to natural rubber, making it less suitable for wheel applications that require frequent interaction with rough surfaces [23, 24, 30].

Based on these considerations, natural rubber was chosen for the wheels due to its flexibility and performance on various terrains [31].

For the body of the prototypes, wood was selected for its affordability and availability. The specific type of wood considered was Pine:

1. Pine:
   1.1. Properties: Pine is a softwood known for its workability, lightweight, and relative strength. It has a good strength-to-weight ratio, making it suitable for structures that need to be both strong and easy to handle [32].

   1.2. Advantages: Pine is cheaper than many hardwoods and is readily available in many regions. It is easy to cut, shape, and join, making it ideal for prototype construction where modifications might be frequent.

   1.3. Common Uses: Pine is commonly used in furniture making, construction, and general woodworking due to its versatility and cost-effectiveness [32, 33].

   1.4. Comparison with MDF and Plywood: MDF (Medium-Density Fiberboard) is cheaper and easier to machine but lacks the strength and durability of solid wood. Plywood is strong and durable but can be more expensive and heavier than Pine. Pine offers a middle ground with sufficient strength, ease of use, and cost-effectiveness [33].

By choosing natural rubber for the wheels and Pine for the body, the prototypes leverage the best properties of each material to ensure functionality, durability, and cost-effectiveness. The goal is to have the prototypes tested on different terrains, with natural rubber providing the necessary flexibility and Pine offering a reliable and affordable structural base.

Summary

Quadruped robots, like Boston Dynamics' Spot, are increasingly used in construction, security, monitoring, and law enforcement due to their agility and robustness. Despite challenges such as high manufacturing costs and operational safety concerns, technological advancements have made significant progress but are limited to specific fields [8], [10]. Early prototypes have evolved from basic walking machines to sophisticated designs [12]. The quadruped prototypes discussed in this report include components such as Zeee 2S Lipo Batteries [15], SG90 Micro Servos [16], Arduino Nanos [17], and various motors [18]. The final design of the quadruped features spherical wheels inspired by omnidirectional tires, allowing for multiple degrees of freedom [21]. Material choices for the prototypes include natural rubber for the wheels, providing flexibility and durability, and pine wood for the body, offering an affordable, strong, and lightweight option [22], [32].

Analysis

To start working in Simscape, the first step is to import the SolidWorks prototypes into the Simscape environment. This process will automatically generate corresponding blocks and joints that accurately represent each part of the SolidWorks model, preserving the physical and mechanical characteristics of the design [34]. After the initial import, any additional blocks necessary to facilitate the maneuvering of the machine will be added. These blocks may include actuators, sensors, and controllers, enabling the simulation of the robot's movement and interactions with its environment [34, 36]. Once the setup is complete, simulations are run to compare the performance and behavior of the different prototypes. This comparison will help identify the strengths and weaknesses of each design, providing valuable insights for further improvements and optimizations. Simulating and analyzing these prototypes in a virtual environment is crucial for refining the designs before proceeding to physical testing, ultimately saving time and resources in the development process [34, 35].

Contact Forces

Understanding gravity in Simscape proved challenging initially. However, tutorials and documentation were very useful in understanding what to do [34]. It became clear that there are multiple approaches to implement gravity, often tailored to specific projects. For this project, the contact forces were focused around the wheels and other components that interacted with the ground.

One significant issue was connecting the Spatial Contact Force to the Solid Brick. As shown in Appendix D, the Simulink (.slx) files were organized into subsystems for better visibility and management. A rolling ball project by Janne Salomäki provided essential guidance on linking contact forces to solid bricks [35]. This project utilized a 6-DOF Joint block, allowing three translational and three rotational degrees of freedom. According to the Matlab documentation, applying this block to the main component enables the entire machine to move freely in any direction rather than remaining fixed in place.

The base frame was then connected to the World Reference to apply gravity to the entire project. The Spatial Contact Force requires a reference and a ground object, which in this context refers to the specific shape or wheel of the robot.

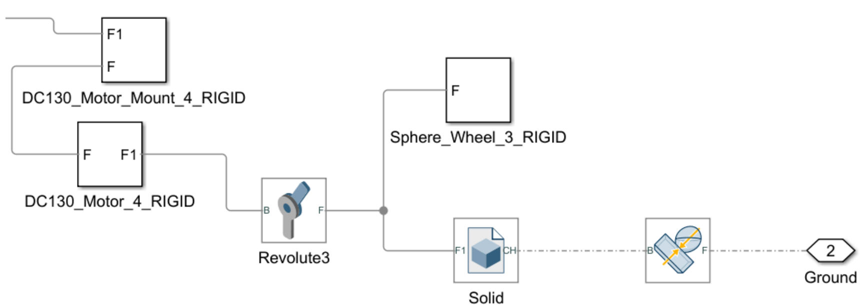

Figure 1: Prototype One's Leg Simscape

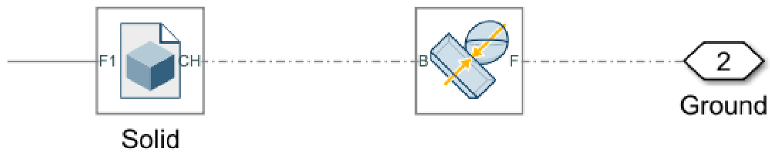

Figure 2: The Contact Force

The "Solid" block replicates the robot's wheel. A custom frame of reference was created, "F1," to correct the wheel's orientation issues, that occurred when using the original reference. Those issues resulted in the wheel having sideways and misaligned placements. Additionally, applying the Convex Hull ("CH") ensures that the "Solid" block can serve as a stable base for Contact Forces. These adjustments to the prototypes can be found in Appendices D and E.

Driven

The Revolute Joint connected to the torque is driven by the DC130 Motor, which powers the wheel. The small black arrow represents a Simulink-PS Converter, converting a constant value into a physical signal for the joint to interpret and execute [39, 48]. The only modification made to the motor was enabling torque adjustments, allowing any constant value to be applied as the wheel's voltage [18].

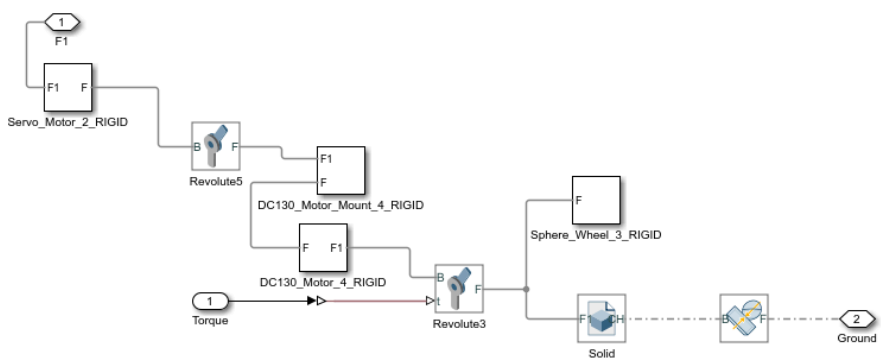

Figure 3: Prototype One's Leg Simscape with added Torque

In each design, except for Prototype One, the quadruped falls through the floor supported only by the wheels, as they are the only parts with contact forces [36]. To address this, each leg is temporarily fixed in position to proceed with the Driven analysis. This involves assigning positions to the knee joints. Adjustments to the joint settings include adding a damping coefficient, providing resistance for later testing [40, 41]. Additionally, a time constant is set for the converter to determine how quickly the robot processes signals [48].

See Appendix F for the updated version of Prototype One. It drives stably without shaking, but it unexpectedly turns. Initially, it was thought that rapid movement caused it to lift off the ground, but that was not the case. The quadruped's fast movement resulted in it spinning out. This method will be applied to the other prototypes as well.

Solver Solution

MathWorks is experiencing significant lag and won't load the simulations, putting testing on hold [36]. The computer was reset and background software was closed, suspecting that the Wi-Fi might be the issue. During the testing of Prototypes Two and Three, it was discovered the problem was not the computer but the solver solution [38]. With more parts in both assemblies, the software has more to process, causing the simulation rate for Prototype One to be incompatible with the other models [40].

The solver solution is one aspect that remains challenging. The solver solution window in Simscape, and according to tutorials, there should be a tab for Zero Crossing to speed up the simulation [37]. However, the simulation needs to finish to access that tab. The simulation runs extremely slowly, particularly when the contact force is used. The simulation was left running for a day, but it crashed at approximately 5% completion. To see the Simscape blocks final results for Prototype Two and Three, see Appendix G.

Self-Balancing

The objective of this phase was to evaluate how each prototype maintains body stability under various conditions [36]. The methodology was inspired by the previously referenced ball-rolling project [35]. The platform was designed to rotate and flip in random directions, requiring the robot to adjust automatically.

To implement the self-balancing mechanism, the platform was made interchangeable. Initial adjustments involved resizing the platform to be reasonably larger than the robot. However, the machine was not centered on the platform, so three new reference frames were added before the foundational rigid frame [47]. These reference frames allowed the platform to have a universal joint connected to two signals, acting like voltage inputs to move the platform in various directions for specified intervals. See Appendix H.

The primary goal was to design a Proportional-Integral-Derivative (PID) controller that would sense changes in the quadruped's position in each XYZ direction and move all four legs appropriately to maintain the machine's stability. Lacking knowledge of PID controllers, I referred to multiple videos, tutorials, and university notes, which provided the foundational knowledge needed to build and tune the PID [44].

The PID controller was tasked with maintaining the leg's starting position by adjusting the motor's torque to alternate around the desired goal until it reached it. The controller read the motor's current position as feedback to determine if adjustments were needed. Initially, only one leg was tested to gather data for further refinement.

During testing, the arm oscillated as expected by the PID but responded excessively to slight changes in the Y-axis, with its speed gradually accelerating instead of maintaining a constant rate. Two main issues were identified: the controller was referencing the zero position of the arm instead of the platform foundation, and the arm's movements were too extensive, causing instability [42].

A review of the notes revealed a tune function in Simscape, eliminating the need for manual adjustments [40]. After tuning, the arm's movement aligned with the desired goal, improving both speed and position control. However, the PID still did not account for the entire robot's position, only the connected arm. Testing with all legs equipped with PIDs showed that the machine could stand upright as all arm motors reached zero, indicating a lack of comprehensive position feedback.

Subsequent testing with the arm alone confirmed that the arm oscillated around zero, regardless of the starting position. This behavior indicated that the PID was correcting based on the arm's zero position rather than the foundation's. The fundamental issue was identified as the source of error feedback; the controller corrected the arm when it was not at zero but needed to be corrected based on the foundation's position. See Appendix I.

Conclusion

After conducting extensive research and experimentation as detailed in this report, it is clear that the development of quadruped robots for swarm applications presents both significant challenges and potential opportunities. This project was inspired by the principles of swarm robotics, which are designed on natural swarm behavior, and aimed to investigate whether quadrupeds, traditionally larger and more complex than typical swarm robots, can be scaled down and integrated into collective robotic systems effectively.

Swarm robotics offers diverse applications in environmental monitoring, search and rescue missions, and agricultural automation. The evolution of quadrupeds from industrial giants like "BigDog" to more versatile and agile platforms such as Boston Dynamics' "Spot" demonstrates great improvements in robotic mobility and autonomy. However, miniaturizing quadrupeds to operate on par with conventional swarm robots remains largely experimental and theoretical.

This research explored the use of SolidWorks and Simscape to model and simulate compact quadruped designs. Focusing on enhancing stability through PID controllers and mechanical refinements. The iterative design process, documented in Appendices A to C, emphasized the importance of addressing weight distribution, motor dynamics, and terrain adaptability in increasing quadruped performance.

Despite encountering challenges such as simulation lag and controller tuning, the insights gained from this study are crucial for moving forward in this concept. Future research would focus on fixing the solver solution issue to continue testing Prototypes Two and Three.

In conclusion, while the journey to integrate quadrupeds into swarm robotics presents technical hurdles, the strides made in this project lay a foundation for further innovation. The vision of localized, collaborative quadruped robots in diverse swarm applications may be theoretical and seem out of reach, but with more ideas and creativity it can become a reality.

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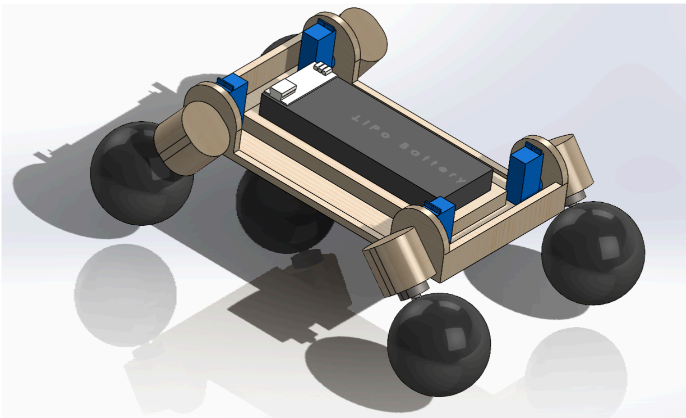
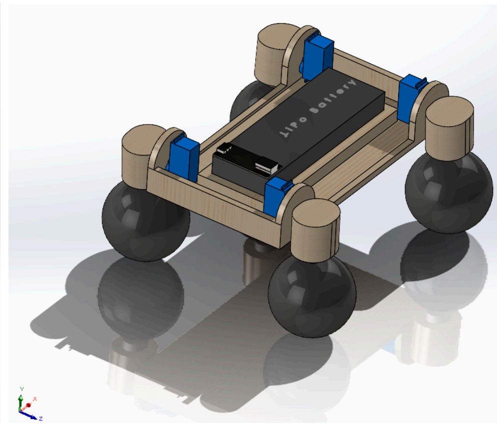
Appendix

APPENDIX A





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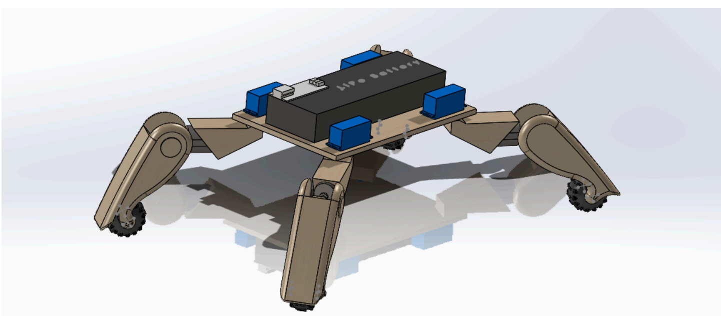

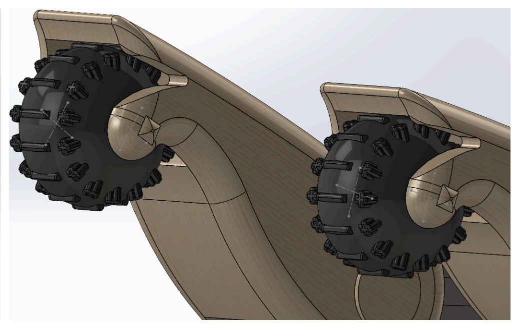

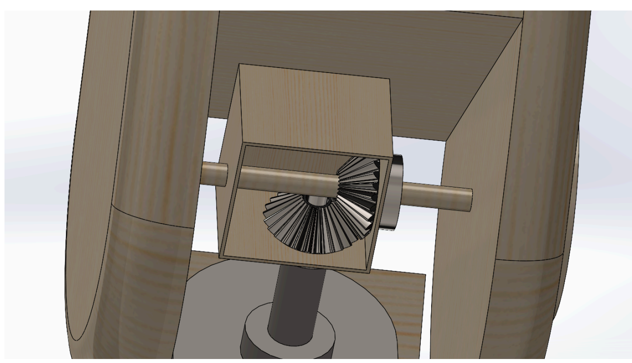

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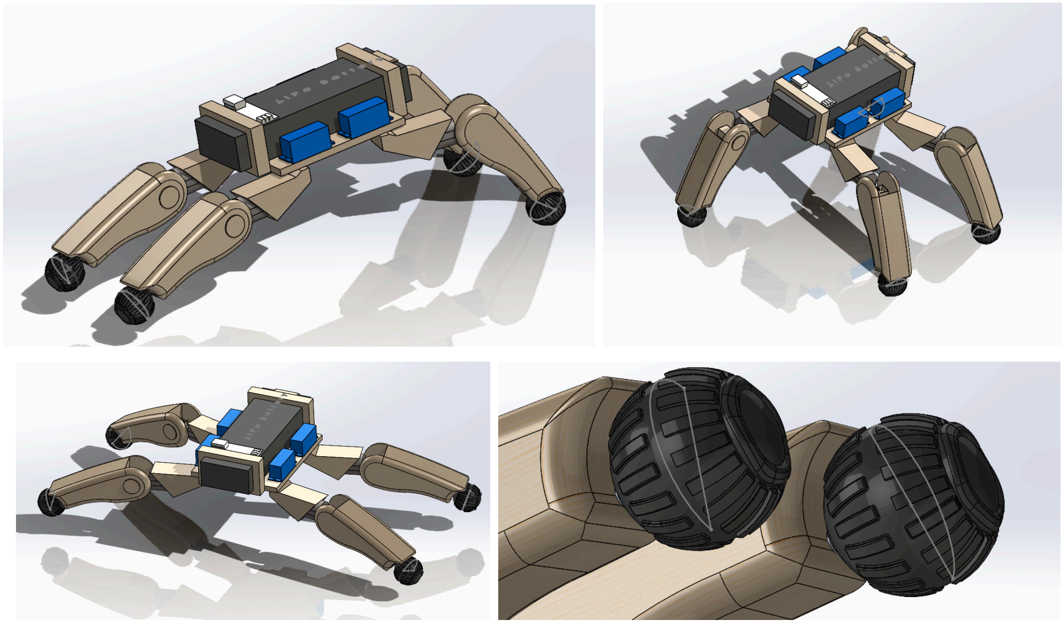

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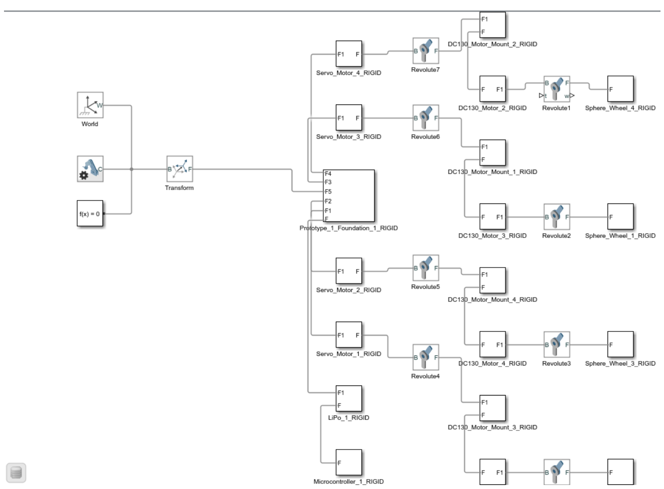

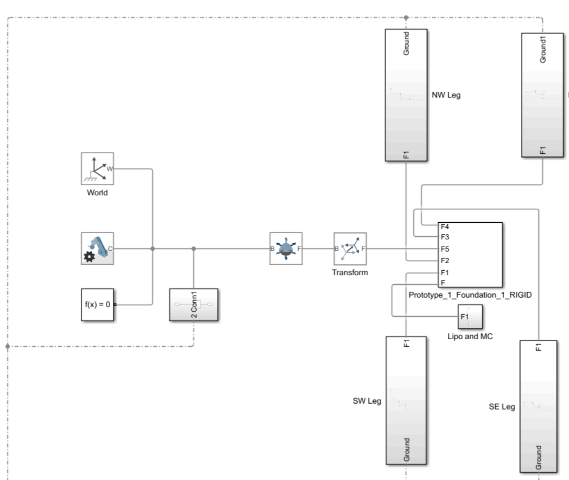

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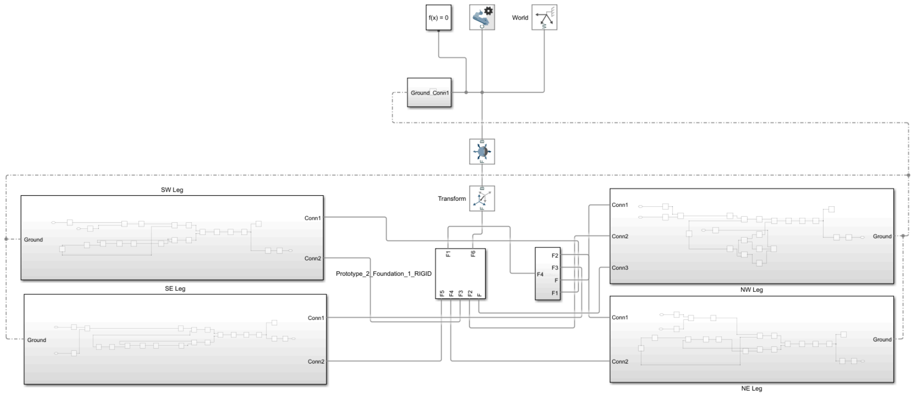

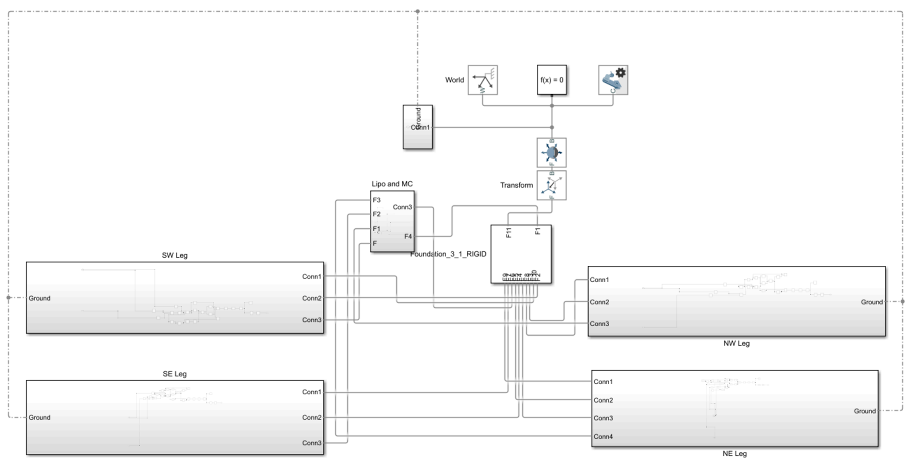

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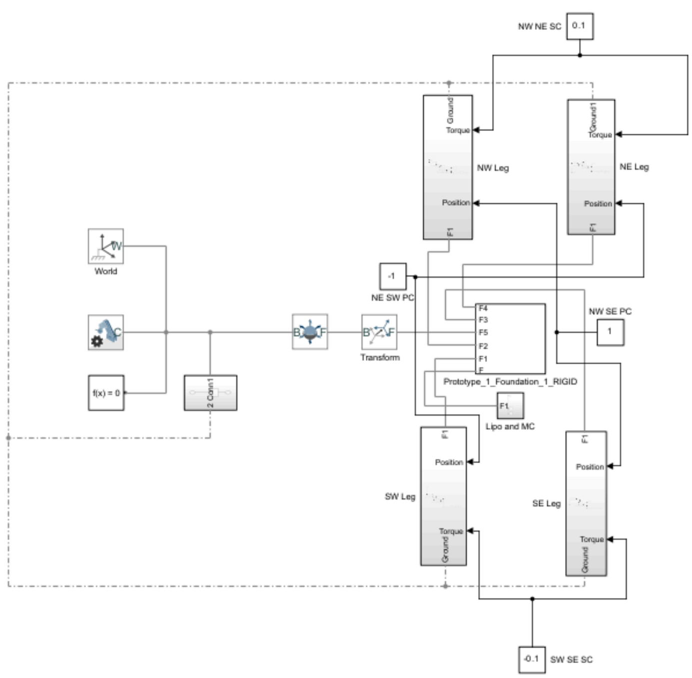

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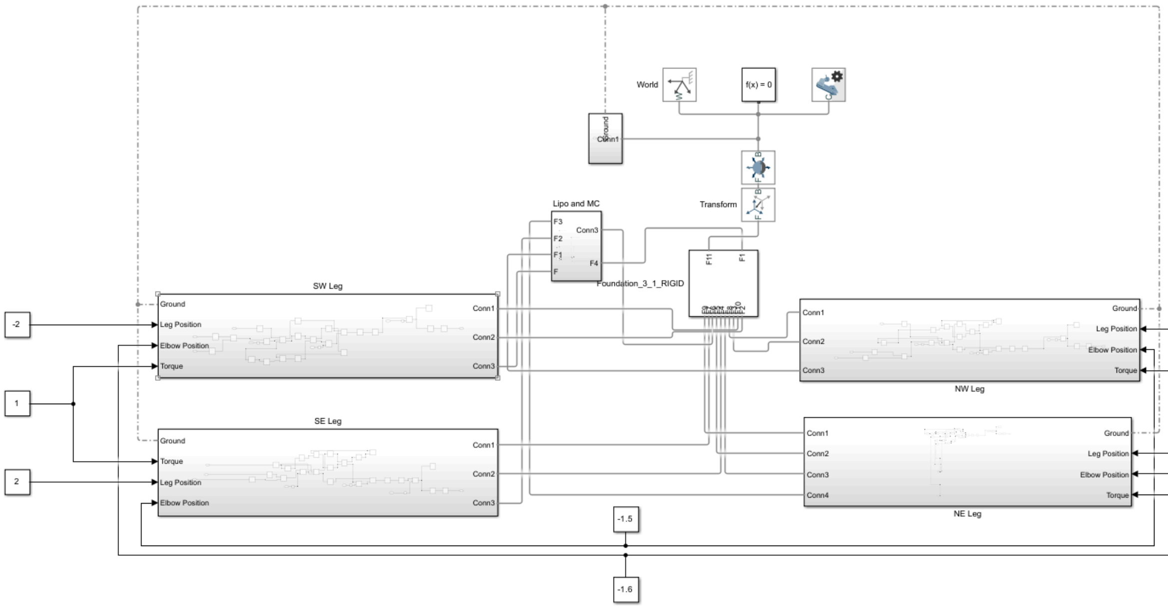

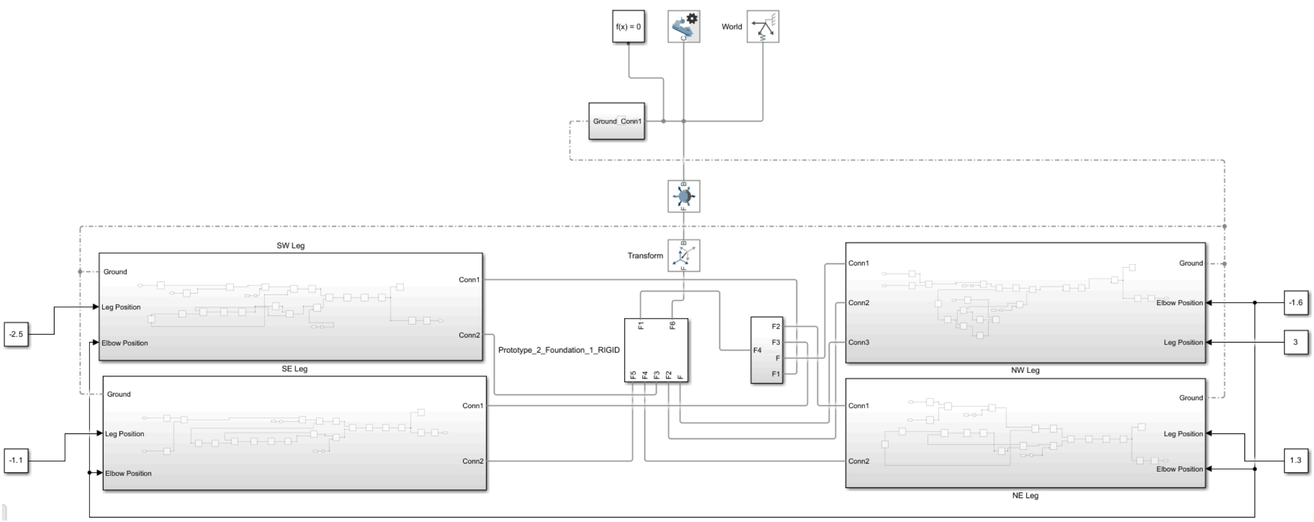

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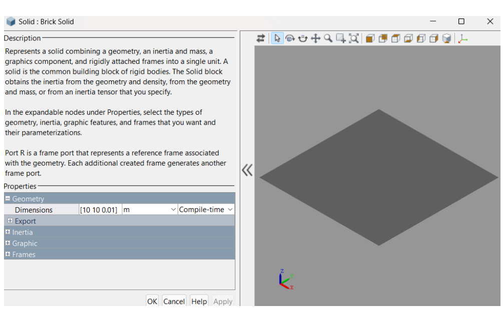
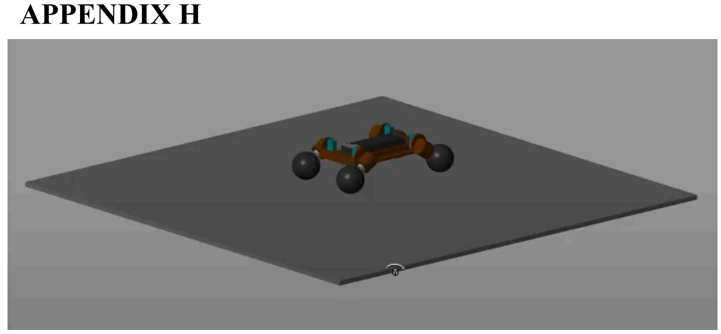
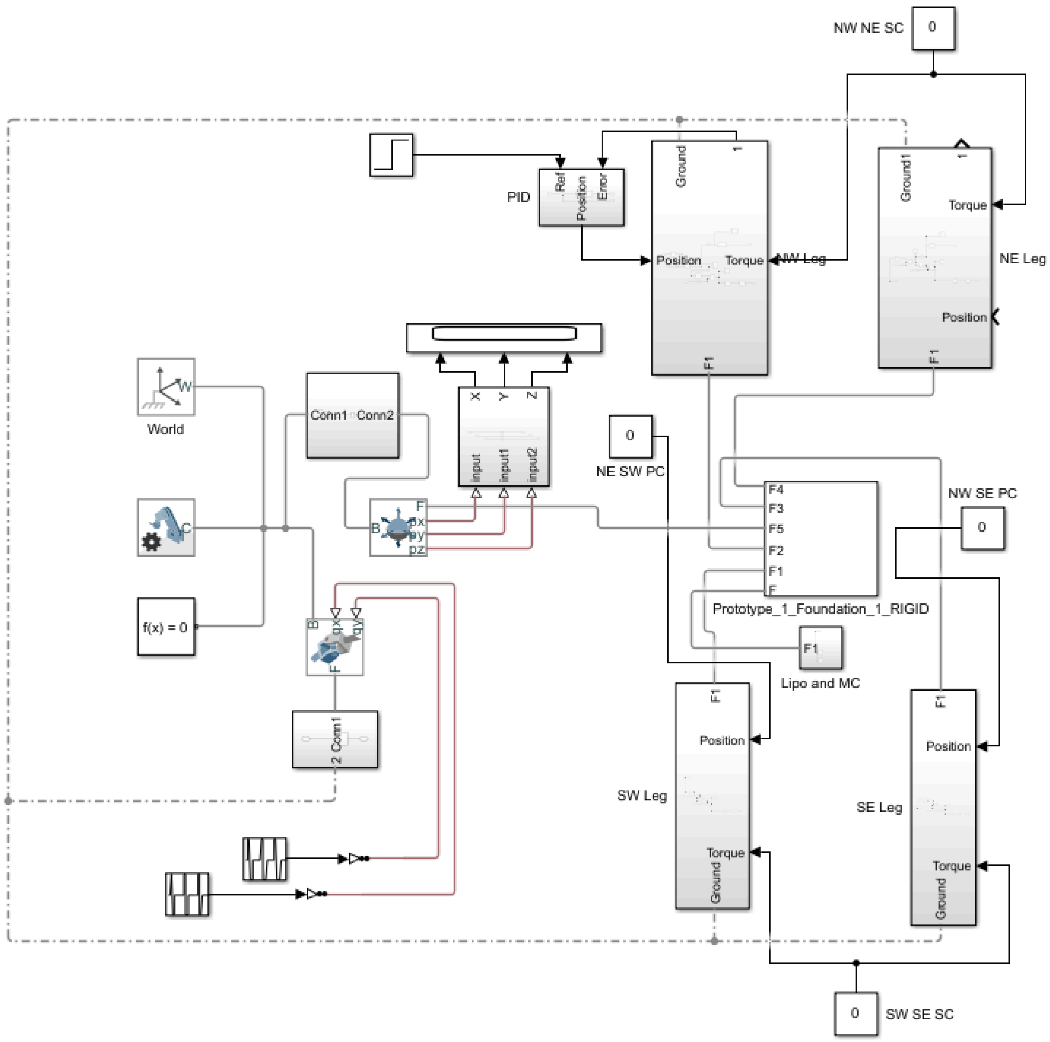




APPENDIX I



NW NE SC
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PID
Ref
Position
Error
Ground
1
Position
Torque
NW Leg
Ground1
Torque
NE Leg
Position
F1
World
W
C
f(x) = 0
Conn1
Conn2
X
Y
Z
input
input1
input2
B
F
px
py
pz
0
NE SW PC
F4
F3
F5
F2
F1
F
Prototype_1_Foundation_1_RIGID
F1
Lipo and MC
NW SE PC
0
2 Conn1
SW Leg
Position
Torque
Ground
SE Leg
Position
Torque
Ground
0
SW SE SC