# Design and Control of Soft Quadruped Robot for Search-and-Rescue Applications in Unstructured Spatial Terrain

Kwasi Debrah-Pinamang
Department of Robotics and
Mechatronics Engineering
Kennesaw State University
Marietta, GA, USA
kdebrahp@students.kennesaw.edu

***Abstract*—Planetary exploration is one of the key areas of space robotics, with many novel robots being proposed to optimize the exploration and data collection in planetary environments. However, as humans are deployed on other planets, there is always the need for safety and the potential chance of the need to facilitate an emergency search and rescue. This paper proposes a novel design for a soft quadruped robot for search-and-rescue applications on spatial terrain.**

**Keywords—robotics, soft robotics, bio-inspired robots, space robotics, autonomous exploration**

## I. Introduction

Over the past few decades, space robots have continued to evolve to support the growing need for various tasks in spatial environments. Many different robots have been deployed for various purposes, ranging from planetary exploration to collection of soil samples. As studies of space continue to advance, the demand for robust, unique robots to conquer the challenges that come with spatial environments has increased.

The development of space robots is a challenging problem due to the various challenges that come with the operation and deployment of technologies in space. The first major challenge is the differing gravitational field of other planets. Namely, the Moon and Mars have gravitational constants significantly less than that of Earth. This causes the control of robots to be much more difficult, as the motion exhibited by robots because of the gravitational field can complicate the tuning and testing of control algorithms. Another challenge provided by spatial environments is the extreme temperatures that robots will have to endure. For example, extreme cold generally will increase the rate of failure of onboard electronics. In environments where extreme cold is an obstacle, a form of insulation to retain heat will be used. The opposite, cooling systems, can be deployed in environments with extreme heat. Putting aside the danger posed to electronics, the material selected also must be capable of standing up to extreme temperatures, as some material that may work well on Earth can falter quickly upon exposure to unforgiving conditions in space [1].

High-energy particles and radiation also pose a problem in the design and deployment of space robots. Planetary environments tend to offer less protection from radiation than Earth, making deployed robots more susceptible to radiation damage. Like with temperature conditions, robots designed for space applications must possess some material or method of resisting radiation. One final condition that many space robots deal with is the terrain. Planetary terrain can often be characterized as unstructured and unstable, making terrain traversal different for ground vehicles. Planetary rovers, a common choice for surface exploration, often feature innovative wheel designs and drive systems to deal with the terrain. However, these drive systems can be complex and heavy on power consumption [2]. Thus, other robot systems have been explored for spatial environment traversal. One such system is the quadruped robot.

Quadruped robots, like the name implies, are mobile robots with four legs. They tend to be designed to possess a similar appearance to quadruped animals, namely dogs and cheetahs. Quadrupeds are often deployed in place of wheeled vehicles in applications that require high levels of maneuverability, traversability, and dynamic motion. In addition, they are capable of being equipped with sensors such as cameras and LiDARs. This makes them a candidate in areas such as space exploration, industrial servicing, and military applications. However, quadruped robots suffer in terms of complexity, controllability, and cost. Despite these shortcomings, quadruped robots remain a robust and effective solution in various engineering applications [3].

As mentioned above, the control of quadruped robots provides a difficult challenge due to the complexity of quadruped robot systems. Control systems developed for quadrupeds must be able to handle the unique actuation system. The actuation system of these robots usually consists of three actuators at the base of the leg: an ab/ad actuator, a knee actuator, and a hip actuator. These three actuators, all stationed next to each other, all actuate the leg in a different direction, providing it with three degrees of freedom. The leg itself consists of two links connected to the knee joint. The control of the quadruped robot can generally be divided into multiple modules: motion planning, balance and force control, swing leg control, and joint control [4]. Each individual module plays a role in the stable operation of the quadruped robot.

Soft robotics is a term that refers to robots constructed using soft materials as opposed to rigid materials. In many cases, this allows for robots with increased mobility and flexibility. In addition, due to their soft nature, soft robots are much safer for use in cooperation with humans [5, 6]. Some common instances of soft robots include bio-inspired robots and medical robots. Bio-inspired robots are robots designed to mimic characteristics akin to existing organisms. Various organisms possess unique methods of movement, and the goal of bio-inspired robots is to translate the actuation method of animals into a controllable robot to achieve a certain degree of motion [7, 8]. This effectively translates to observing how an animal moves to conquer its environment and attempting to create a robot to move in a similar manner to traverse the same type of environment. For example, worms are known for their intricate movement method in fine environments like soft dirt. Taking inspiration from the movement of worms and snakes, scientists and engineers at NASA JPL designed a snake robot for traversal of snowy terrain for exploration of the icy surface of Enceladus, one of Saturn's moons [9].

Soft actuators, as their name implies, are actuators for soft robots, enabling the movement of robots constructed of compliant materials. They can generally be divided into two categories: physical actuators and chemical actuators. Physical actuators use a physical quantity to produce mechanical energy and motion. Common quantities used include electricity, temperature, and pressure of a controlled fluid. On the contrary, chemical actuators produce mechanical energy via chemical reactions. One such method would be combustion of butane and oxygen to power a robot. While chemical actuation has the potential to provide a greater overall force, physical actuation methods tend to be cheaper to implement, be more sustainable, and be more efficient [10, 11].

## II. Related work

The proposed design for this robot is inspired by a similar project in [12]. In this paper, a soft quadruped robot was designed with the purpose of traversability across varying terrain, with the robot being capable of climbing slopes, walking across a rocky road, and even swimming in small bodies of water. The robot utilizes precharged pneumatic actuators for the actuation of the joints in addition to servo motors to control a tendon to guide the motion of the legs. The soft legs, constructed fully out of silicone rubber, are actuated at pressure values ranging from 60 kPa to 100 kPa for contraction and extension. The main body of the robot dog is 3D-printed with PLA and contains the necessary electronics for operation of the robot: a 7.4V battery, motor controller board, and receiver for the external controller. In addition, a camera is embedded at the front of the main body of the robot to record the actuation system while the robot is in motion.

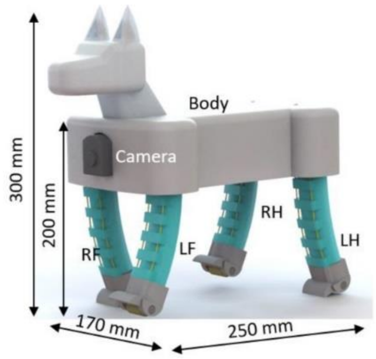


**Fig. 1.** Model of Soft Quadruped Robot [12]

## III. Method

The design proposed is a soft quadruped robot containing a camera and LiDAR for obstacle avoidance and detection. The main body of the robot is constructed out of thermoplastic polyurethane (TPU). TPU is chosen due to its durability, abrasion resistance, elasticity, and resistance to low temperatures. The onboard electronics for robot control will be encased in the TPU shell of the main body. The electronics encased in the robot include a motor controller board, servo motors for control of the actuation system, and an onboard computer for computing of perception and planning algorithms. The feet of the quadruped, like the main body, will also be constructed from TPU. However, the feet will likely be constructed of a softer TPU material compared to the quadruped's main body. The use of soft TPU material for the feet will allow for high flexibility and durability, allowing the quadruped to remain in contact with the Martian surface for long missions.

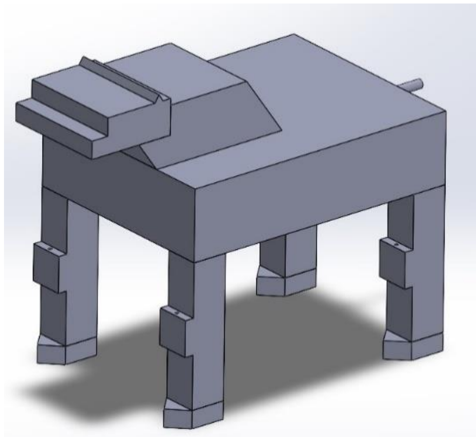

**Fig. 2.** Preliminary CAD Model of Soft Quadruped Robot

The legs of the quadruped are constructed from silicone rubber and are actuated using pre-charged pneumatic (PCP) actuators. PCP actuators are one of the methods of soft actuation, falling under the category of fluid actuation. A tube, usually constructed from silicone rubber, possesses an internal cavity that is set to a pressure value. An air tube attached to the internal cavity can change the pressure at will, allowing the pressure to be set to above or below its set value. When the tube is set to a pressure greater than its set value, the silicone rubber expands. Likewise, when the pressure is set to a value below the set value, the structure contracts [13]. This phenomenon can be used to actuate the legs of the quadruped robot, as the process of expansion and contraction of a joint is akin to the motion of legs of organisms. In the quadruped design, cables are used to guide the legs, allowing them to swing forwards and backwards while expanding and contracting.

Silicone rubber, the standard material choice for PCP actuators, can experience issues when operating in low temperatures like the environment of Mars. The material may deteriorate more quickly due to use or even experience cracking after becoming brittle due to the cold. To mitigate this, the quadruped legs will possess an outer layer of aerogel. Aerogel, a plastic-like material, is commonly used in low-temperature environments due to its high thermal conductivity. The addition of the aerogel layer will help shelter the silicone rubber legs from the extreme cold, enabling the quadruped to perform strongly throughout long missions [14].

The robot electronics are encased in the quadruped robot's body for protection against the elements. The main sensors onboard are the camera and radar. These two devices are responsible for collecting information on the environment and identifying missing landmarks or individuals. A camera is used for two purposes in this application: object avoidance and target detection. The camera will assist the radar sensor in the avoidance of obstacles in the process of navigation as well as identifying the target of the search-and-rescue algorithm. The type of camera used can be modified to suit the application, but for general use, an RGB-D camera can be utilized. The radar sensors will be wrapped around the robot and mainly used for obstacle avoidance. Radar is chosen over other distance sensors like LiDAR due to its more consistent performance in poor visibility conditions. As dust storms are not uncommon on Mars, ensuring that the sensing system is not impacted by poor weather conditions is imperative for a successful application.

Aside from the sensors, the quadruped will also contain devices for communication, computation, and control. An onboard computer will be used to run search-and-rescue algorithms, process sensor data, and enable more robust control of the quadruped. The exact device used can vary, though the main criteria for the computer used are computational power, thermal capabilities, power draw, and radiation resistance. One computer that could possibly be deployed is the Raspberry Pi, though devices engineered specifically for space applications may provide more in terms of robustness and radiation resistance.

A motor control board will be utilized to control four servo motors. The board used must have the capabilities to integrate with the onboard computer so that the direction and gait of the quadruped can be controlled. The servos, which are controlled by the motor control board and attached to the legs, are responsible for controlling the quadruped actuation. A tendon cable will be pulled by the motor to pivot the leg and propel the robot forward.

The final component on the quadruped is an antenna, which will connect to the onboard computer and enable remote control and monitoring of the robot. More specifically, the antenna will allow operators to remote into the onboard computer, allowing for initialization of the search-and-rescue program and real-time monitoring of the robot while in operation. The specific frequency of the antenna can be modified depending on the application, with one common band in space robotics being the X-band, which is remote operation at 8-12 GHz. X-band allows for long-distance communication between a robot and a base station on Earth, making this band ideal for space robot applications. To avoid interference with the signal by the electronic housing material, the antenna will stick out the back of the quadruped, like the tail of a dog.

To improve the controllability and novelty of the proposed quadruped design, a closed-loop control system is proposed. The goal of this control system is to monitor the performance of the quadruped's actuation method and real-time correction for more precise movement. The control system, structured similarly to that of traditional quadrupeds, can be broken down into three categories: the low-level controller, the mid-level controller, and the high-level controller, with each controller being responsible for a different aspect of the quadruped's actuation system.

The low-level controller is simply responsible for the direct actuation of the joints, directly controlling the pressure sent into the cavity of the silicone rubber leg. A PID controller is used to control the pressure value signal fed into the cavity, while a pressure sensor within the cavity provides the controller with feedback to allow it to correct errors.

The mid-level controller is responsible for controlling the actuation system to achieve the desired trajectory and positions of the end-effector. In a standard manipulator system, the process of inverse kinematics would be done in this step. Inverse kinematics is a process in robotics of obtaining the joint angles necessary to achieve a certain position in a manipulator. In other words, it is used to enable the end-effector of a manipulator to reach a certain point in space to achieve a task. For the precharged pneumatic actuators, the goal is to perform a similar operation. When given the desired trajectory, the first step for the mid-level controller is to calculate the necessary bending angle of the manipulator needed for the end-effector to reach the desired position. Next, given the specific bending angle needed, the amount of pressure needed to achieve the needed bending angle is calculated. The calculated pressure is then used to calculate the expected position of the end-effector in addition to being sent to the low-level controller for the actuation system. Lastly, a position sensor is attached to the end-effector to provide feedback on the position and enable error correction in its positioning.

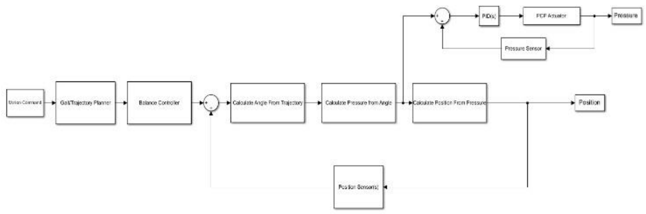


**Fig. 3.** Full Quadruped Controller Modeled in Simulink

The high-level controller is responsible for gait scheduling and utilizing a control algorithm to maintain body stability. Essentially, it can be considered the main controller, linking the robot command issued by the operator and the actuation system. The desired position in space is used to calculate the trajectory needed to reach that position, with the desired trajectory being fed into the mid-level controller. The first segment of the high-level controller is the gait scheduler. The gait scheduler aims to establish a walking gait pattern and plan a trajectory for each joint at every time step. The second segment, the body stabilizer, uses a PID controller to keep the roll, pitch, and yaw values of the robot as close to zero as possible. The goal is to minimize vibrations to maintain accuracy and consistency in sensor data collection. An Inertial Measurement Unit (IMU) is used to measure the roll, pitch, and yaw values in real time and correct the trajectory based on the expected RPY values at a given time. The corrected trajectories are then fed into the mid-level controller. The two segments of the high-level planner work to provide a trajectory for optimal motion of the actuation system.

## IV. CONCLUSION

This project proposes a novel design for a soft quadruped to efficiently traverse spatial terrain while being able to stand up to harsh conditions. The goal, search and rescue, has significance in the focus of human safety during space missions. Future work in this project will involve extensive simulation of the design for validation, as well as testing and development of the algorithm for efficient and accurate search and rescue.

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