Developing a Low-Cost Research-Grade Quadruped Robot
A Thesis Proposal

Gabrielle Conard

Advisor: Professor Alexander Brown
Committee: Professor Brent Utter and Professor Luis Schettino

Abstract

As robots have become more integrated into factories and homes, they have been tasked to operate in increasingly complex environments. Researchers have turned to legged robots, such as quadrupeds, to meet the need to traverse unexpected obstacles and uneven terrain, both indoors and outdoors. While progress has been made in developing state-of-the-art robotic platforms that can accomplish this goal, little has been done to develop a low-cost quadruped robot, which is crucial to making these robots more accessible to researchers and robotics students alike. We propose to develop a low-cost, research-grade quadruped robot based on the MicroDog platform that uses active compliance to absorb falls, navigate uneven terrain, and climb steps.

Section I. Introduction

Robots are becoming increasingly woven into the fabric of everyday life. From Roombas that zip around our living room floors to robotic arms that assemble our cars in manufacturing plants, they are shaping how our society operates. However, these robots have been mostly limited to the flat, predictable realms of the lab, factory, or home. Venturing outside has proved much more challenging, but is necessary if robots are to be used in applications such as search and rescue [1], planetary exploration [2], and construction site inspections [3]. While wheeled robots are advantageous in certain applications, biologically-inspired legged robots have proved to be superior in traversing uneven terrain. However, since animal locomotion is complex, developing legged robots is no simple task [4]. As a result, legged robots, and especially quadruped robots, have been the subject of extensive research.

One challenge is developing a robot that can respond to external stimuli, such as unexpected obstacles presented by rough terrain or falls. A number of state-of-the-art quadruped robots, such as Boston Dynamics' commercially available Spot [5], use advanced vision systems to map the terrain and identify potential footholds. In addition, it is also useful to sense the excess force acting on the legs and creating active compliance in the joints of the robot. Compliance, or the "flexibility" of the joints, is crucial for mitigating impacts from unexpected obstacles that could damage the robot. While a number of quadrupeds use the motors themselves to detect and respond to impacts, such as the MIT Cheetah 3 [6] and Ghost Robotics' Minitaur [7], other robots use force sensors. In the case of quadrupeds, these are often installed in the feet, allowing the robot to detect when a foot is in contact with the ground. For example, Biodog uses force sensing resistors to compare the signals produced by the Central Pattern Generator (CPG) to the actual motion of the legs in order to better control Biodog's gait pattern as well as characterize the surface friction [8]. On the other hand, a quadruped robot developed by the

National University of Defense Technology in China uses force control to achieve compliance by evaluating the desired force distribution and changing its behavior when the actual force exceeds the desired force [1].

However, developing active compliance and rough terrain navigation in small scale robots, such as those using hobby servo motors, has been largely overlooked. While rapid-prototyped robots are not as powerful as their larger companions, these are important for miniaturizing and reducing the cost of quadruped technology. The complexity and cost of developing quadruped robots can be prohibitive to researchers entering the field [9]. In order to promote progress in this field, it is imperative that quadruped technology becomes more accessible.

Recently, some progress has been made to meet this need. Low-cost quadruped robots ranging from over $1000 to as little as $200 have been developed, many of them open-source to encourage others to push the designs even further. However, as reviewed in Section II, the vision for the majority of them was to implement gait patterns such as walking and trotting and to navigate their environments by avoiding obstacles, rather than overcoming them. Only one low-cost quadruped robot, which is lacking documentation other than a YouTube video, has successfully developed active compliance [10]; another is still in development [11].

To address the lack of low-cost research-grade quadrupeds, we propose to develop a robot that is capable of both avoiding and maneuvering over obstacles autonomously, absorbing the impact from a fall, navigating uneven terrain, and climbing a step using active compliance. We will continue to improve the compliant MicroDog platform we developed in the spring and summer of 2020, while maintaining a maximum cost of $200.

This proposal is arranged as follows: a detailed review of the other low-cost quadruped robots as well as their more expensive counterparts is laid out in Section II. In Section III, we discuss the methodology with which we will approach each goal. The design component is explained in Section IV, while Sections V and VI present the project's timeline and budget, respectively. Finally, we give some closing remarks in Section VII.

Section II. Literature Review

Several other robots have been developed in an attempt to fill this gap. In the realm of research, a simple insect quadruped robot called robot-K was designed to be more accessible to students [12], and another group developed an amphibious open source robot with the goal of providing a platform for other researchers that would be simple to operate and modify [9]. Neither of these provide the total cost of their robots, but from the materials described, both likely cost under $200. However, these two examples have few, if any, sensors to observe the environment around them and do not include force sensors on the limbs, making it difficult to navigate uneven terrain. The robot-K has no sensors [12], which may be one of the reasons why the robot is limited to walking over gaps less than 2 cm deep and on an incline of no more than 5 degrees. The amphibious robot does have an ultrasonic sensor [9], but this still does not provide adequate information about the surface terrain.

MUTT, a $600 quadruped robot developed by students at WPI, also attempts to meet the need for low-cost quadrupeds by relying primarily on rapid-prototyping and off-the-shelf parts for constructing the robot [13]. In order to overcome rough terrain, the robot walks around obstacles using a camera and mapping software instead of walking over them, which is not practical when encountering stairs or regions where obstacles are unavoidable. Similarly, another team designed the arachnid-like quadruped, Charlotte, to make research-grade quadruped robots more accessible to researchers with smaller budgets [14]. However, the goal of this $540 robot was to map and navigate its environment using LIDAR, and it does not appear that the group addressed the issue of rough terrain.

One of the fastest trotting low-cost robots developed is the Cheetah-cub quadruped robot [15]. This 1.1 kg robot can travel up to 6.9 body lengths per second and traverse a step-down perturbation without external sensors. However, it does this by using passive compliance, a method of creating soft joints by using physical springs or elastic components, rather than in software like active compliance. Passive compliance can be useful for meeting a single goal. However, since changing the stiffness of the joint involves replacing the spring or changing the design, it is not as useful if one needs different spring constants for different applications, such as a robot that both trots and jumps. In addition, [15] notes that to trot in rough terrain, future designs of the robot will need to use feedback from sensors to operate.

Outside of academia, it appears more progress has been made, perhaps due to the smaller budgets of hobbyists. A quick survey of products from RobotShop shows that most quadruped kits range from $65 to over $900, aimed for introducing students in elementary school up through undergraduate studies to robotics [16]. However, they are not quite as cost effective as they might appear. For example, while the motion-tracking Adeept DarkPaw Quadruped Spider Robot Kit is sold at a reasonable price of $115, it does not come with the Raspberry Pi that it needs to operate and it is difficult to add sensors or make other modifications to the chassis or electronics [17]. As a result, it is not the most practical platform to use for research. On the other hand, the Lynxmotion Phoenix 3DOF Hexapod platform includes only the chassis and legs for about $250 [18], which costs more than a number of the fully-equipped robots investigated in this review.

Several alternatives to the products of RobotShop and similar robotics stores exist, however. For example, the Stanford Robotics club has developed several quadruped robots, their most recent one being the Stanford Pupper [19]. This open-source small robot can walk, creep, and jump for a total cost of $700 to $1250, depending on whether builders buy a kit or buy the parts themselves. While Pupper is designed to be "hackable," it does not currently attempt to traverse uneven terrain. Another hackable robot, a kitten-inspired quadruped called OpenCat Nybble, has been developed by Petoi LLC [20], and the company is currently fundraising to put out a second quadruped, Bittle [21]. While they are not actively compliant, both are equipped with springs to achieve passive compliance, which again has its disadvantages compared to active compliance. The kits for both of these partially open-source robots are being sold for $225 [21], [22].

A community of electrical, computer, and robotics engineers have been developing the SpotMicro, an open-source, low-cost version of the Boston Dynamic's Spot [23]. One of the most recent versions can walk and trot untethered both forwards, backwards, and sideways and is remotely controlled via a laptop [24]. From the parts listed on this version's GitHub page, it has an estimated cost of $250 [25]; however, this price will likely increase as sensors are added to meet the goal of autonomous navigation and obstacle avoidance. To aid in traversing rough terrain, they are training the robot in simulation using augmented random search [23]. While this is useful in that it allows the robot to learn how to react appropriately to what its sensors detect, this strategy is only useful in navigating the changes in terrain that the sensors can see, which can be fairly limited if one is using inexpensive IR sensors or cameras.

It appears that only one low-cost quadruped, other than the one we developed during an independent study in the spring of 2020 [26], has the capability of sensing force and reacting compliantly [10]. Released in July 2020 by Martin Triendl, there is no other documentation other than the linked YouTube video, making it difficult to know how he approached this problem. However, there is another quadruped robot being developed with the goal of incorporating force sensors to respond to its environment [11]. At present, this approximately $400 robot is roughly 6 inches tall and 10 inches long, and its capabilities include walking in all directions and recovering from an impact from the side using its onboard IMU.

As demonstrated, work on compliant low-cost quadrupeds is just beginning, and there is much to be done to meet the need for inexpensive robots that can cross uneven terrain like they would face outside the laboratory. However, it is important to note that a number of larger, more expensive quadrupeds have accomplished this feat. While not everything can be exactly replicated, investigating how they approached this problem can inspire solutions that can be applied to low-cost robots. For example, using inexpensive hobby servos could help reduce the cost and complexity of the robot, a strategy employed by several of the examples above. However, unlike other electric motors, hobby servos cannot be controlled by simply regulating current and are instead controlled by sending position commands. This makes it difficult to use current to sense motor torque, from which the external forces can be estimated, and respond appropriately. As a result, using direct drive to detect and respond to impacts, as it was used for controlling the MIT Cheetah 3 [6] and the Ghost Robotics' Minitaur [7], cannot be used in this application; some sort of force sensor is necessary to take in external stimuli. In addition, unlike [27], which aimed to mitigate the impact experience by a one-legged parachuting robot while landing by using servo gain to control the stiffness of the joint [28], one is not able to control gain directly on inexpensive hobby servos. To overcome this challenge, we developed a virtual spring over the course of the independent study by measuring the applied force using a hall effect sensor in each foot, calculating the distance the foot should lift up to compensate, and sending position commands to the servos to achieve that foot position [26].

While it is difficult to pull directly from larger-scale robots to develop compliance in our model, the literature does offer more guidance on navigating difficult terrain that could be applied to a small robot. As mentioned before, training the robot in simulation like developers have been doing with SpotMicro can aid the robot in learning how to react to obstacles [23]. Another philosophy is to treat everything as an unmodeled disturbance, an approach that Agility Robotics has used for its bipedal robots, ATRIAS [29] and Cassie [30]. Neither robot has external sensors and are effective blind to the world around them. Instead, they use passive dynamics and software control to respond to obstacles [30]. While this method does not require sensors, using sensors in combination with this approach can reduce the complexity of the dynamic control. For example, The MIT Cheetah 3 quadruped also operates under the assumption that the terrain is flat and unobstructed, but uses torque control to detect excess torque created by an unseen obstacle and make appropriate adjustments [6]. Employing such an approach can improve the robustness of our robot's response to uneven terrain.

Section III. Methodology

In order to meet the need for low-cost, research-grade quadruped robots, we will continue to use and improve the MicroDog platform developed in the spring and summer of 2020. Since active compliance has been implemented using hall effect force sensors in the feet of the robot, the focus of this thesis will be to evaluate the effectiveness of these sensors and develop applications of active compliance. The major capabilities we plan to develop are:

- Autonomy (obstacle avoidance)
- Impact absorbance from a fall of 5 inches
- Ability to navigate uneven terrain and gait disturbances of 1 inch in height or depth
- Ability to climb a step of 2 inches

Before progress can be made towards these features, however, several improvements must be made to the current platform and software. The walk gait is still under development; completing this is crucial to meet the goals. In addition, it is important to know the workspace of each leg, or the three-dimensional region each foot can reach. Our current mathematical model must be validated on the physical robot, which can be done using image tracking.

While autonomously wandering around a room does not require a compliant robot, developing collision avoidance will help the robot to avoid obstacles that it cannot climb over, such as a wall. To develop obstacle avoidance, it is necessary to characterize the distance sensors on the robot. The MicroDog is currently equipped with infrared detectors on the front and rear of the chassis and an ultrasonic sensor on the front. Testing these sensors to determine the maximum distance at which they can detect an obstacle and what kinds of obstacles they can see will allow us to decide whether other sensors, such as a camera for better vision or an optical flow sensor for determining the robot's velocity, are necessary to navigate a room without colliding with any objects. We can then develop the robot's ability to determine if an object is something it can climb over or something it should avoid.

Since we plan to use active compliance to meet the other goals, the next step will be to characterize the force sensors. The sensors on the current MicroDog platform consist of a hall effect sensor and a magnet embedded in the top and bottom of each foot, respectively. As the foot is compressed, the hall effect sensor detects the increasing proximity of the magnet and outputs a higher reading. While we were able to obtain an estimation of the relationship between the applied force and the sensor reading last spring, it is necessary to get a more accurate relationship between these values over the course of a step cycle as well as when force is applied at different angles. This will be especially helpful in developing methods to traverse rough terrain. One method of testing this is to mount a leg or the robot on a stand, such as [31] used, and measure both the hall effect sensor reading and the applied force using a standard load cell. The load cell can also be adjusted to press against the foot at different angles. Another approach is to have the robot walk across a force plate as used to test the Cheetah-cub [15], which would allow us to analyze the forces occurring throughout the walking gait. These tests will allow us to determine if the current force sensor design is suitable for complex tasks, or if modifications or other designs must be considered, such as the 3D-printed force sensors developed by Rachel Sloan as a part of her thesis last year [32].

Another way that [31] used their test stand was to perform drop tests, which can be useful for us to develop fall recovery. Currently, the MicroDog does respond slightly compliantly to a short fall, but we would like to improve this capability for higher drops of at least 5 inches (or approximately one body height). As described in Section II, a benefit of using active compliance instead of passive compliance is that we can easily adjust the stiffness of the joints in software without having to change the physical design, such as replacing a spring. We can simply tune the virtual spring, allowing the joints to bend more to absorb powerful impacts. In addition, we can experiment with using different stiffnesses in different modes. For example, while the robot is walking, a higher stiffness is necessary to maintain control of the robot. However, if the robot senses that it is in the air (i.e. all force sensors are registering no ground force), it will adopt a low stiffness to absorb the imminent impact. Although we are focusing on developing active compliance, elasticity is present in the foot and other leg components, and this may need to be taken into account to develop an accurate impact absorbance model [33]. Another feature that will likely need to be developed is damping to suppress oscillatory behavior [31], [33].

The next step is to develop the ability to traverse rough terrain, with a goal of overcoming obstacles at least 1 inch tall or valleys 1 inch deep. Many quadrupeds, including LittleDog [34], [35], overcome uneven terrain using expensive motion capture systems to scan the terrain and create a foot placement plan. Even though our cost constraint prevents us from using such systems, it is worth investigating the approaches these researchers took. For example, [34] paid careful attention to the placement of the feet to determine the trajectory of LittleDog's center of gravity (COG). Keeping the COG within the support polygon, or the region in which the COG must be located for the robot to balance on three legs, is crucial to maintaining the robot's balance. We can use the force sensor measurements and the locations of the feet to determine what adjustments to the stance are needed to keep the COG in the support polygon. In addition, the sensors can prevent the legs from forcing their way to the planned position if there is an obstacle in the way [35].

However, we still need to develop methods to appropriately respond to these unexpected obstacles since we cannot use a high-quality camera. As noted in Section II, one approach is to use augmented random search to train the robot in simulation, like developers have been doing with SpotMicro [23]. This allows the robot to learn how to respond to the obstacles it can sense. Again, it is also possible to supplement our sensors by using passive dynamics to develop robust gait adaptation like ATRIAS [29] and Cassie [30], or to modify MIT Cheetah 3's controller to use feedback from the force sensors [6]. To test our algorithm, we will first present the robot with a single obstacle or valley. As the quadruped robot becomes more skilled at overcoming this challenge, we will increase the height or depth of the obstacle. Finally, the robot will be tested on a 1-foot long course with a series of elevation changes.

While a climbing a stair is similar to overcoming rough terrain, the greater height means that the robot has to maneuver its legs differently in order to climb over it. As [36] points out, while traditionally quadruped robots aim to keep the COG within the support polygon to maintain balance, this is not necessarily the case for climbing stairs since the robot is tilted relative to the earth. In addition, it was discovered in [37] that employing a parallelogram polygon between the feet rather than a rectangular polygon was helpful in maintaining balance as well. As mentioned previously, experimentation with the IR and ultrasonic sensors will be performed while developing autonomy to develop a method of differentiating between a small obstacle, a stair, and a wall. Once we can identify a stair, we can adjust the algorithms we developed to traverse rough terrain to accommodate for the new challenges to maintaining balance using the methods discussed in [36] and [37]. Testing with several single stair heights will be performed, with the goal of climbing a 2 inch stair, or about 35% of the leg length.

Section IV. Design Component

Unlike some quadruped research that has been done purely in simulation, these developments will be applied to a physical quadruped robot that we have been developing since the early spring of 2020. This approximately 6-inch tall platform consists of a custom printed circuit board that acts as the chassis with an onboard battery mounted beneath and four 3 DOF legs, each equipped with three micro servos and a hall effect force sensor. The ATmega34U4 microcontroller acts as the low-level controller and the Raspberry Pi Zero W will be used for high-level control. This process has involved several iterations to increase the range of motion in the joints, fix a number of electronics issues, simplify the design, and decrease material and parts cost. We expect to produce at least one more robot, with modifications to the PCB to improve the user interface, such as including buttons and indicator LEDs, and to protect the servos from high battery voltage.

As described in Section III, numerous experiments will need to be designed in order to test and refine both the mechanical and software design. A test stand will be developed to characterize the force sensors and collect data from drop tests. In addition, uneven terrain courses and steps will be developed to test the robot's ability to traverse them. Video tracking and measurements from various sensors (force sensors, IR detectors, etc.) will be used in tandem to observe the behavior of the robot during these experiments.

Section V. Timeline

Table 1 summarizes the milestones laid out in Section III and provides an approximate timeline for the entire project.

Table 1: Timeline

Month	Goals
September	▪ Improve walking with active compliance ▪ Add transitions between rest, stand, and walk ▪ Release robot as open-source on GitHub, YouTube, and potentially readthedocs
October	▪ Develop autonomous navigation (obstacle avoidance) ▪ Validate limb workspace model ▪ Begin characterization of hall effect force sensors o Design experiments ▪ Update documentation
November	▪ Perform characterization experiments o Determine if improvements or alternative designs must be considered

	▪ Perform drop tests. Improve compliance if necessary ▪ Update documentation ▪ Prepare for Midyear Presentation
Winter Break (December-January)	
January/February	▪ Investigate methods of navigating uneven terrain ▪ Begin development of uneven terrain navigation ○ ½" valley/step tests ▪ Update documentation

March	▪ Develop uneven terrain/gait disturbance navigation
	  ○ 1" valley/step tests
	  ○ 1-2 feet long uneven course test
	▪ Begin developing stair navigation
	▪ Update documentation

April	▪ Finish development of stair navigation ○ 2" stair test ▪ Update documentation
May	▪ Finalize thesis paper ▪ Prepare for thesis presentation

Section VI. Budget

Table 2 below outlines the funds we will need to complete this thesis.

Table 2: Estimate Budget

Category	Item	Unit Cost	Quantity	Total
Robot Platform	Next Platform Prototype [1]	$150	2	$300
	Final Platform Prototype [2]	$150	2	$300
Experimental Equipment and Materials	3D Printer PLA Filament	N/A	N/A	$25.00
	Test Stand with load cell(s) [3]	~$75.00	1	~$75.00
Tools	Creality Ender 3 Pro 3D Printer [2]	$250.00	1	$250.00
			Total	$950

1. Based on previous platform's bill of materials: https://docs.google.com/spreadsheets/d/1R35zKp76xegpvEchprQsLss8zgrh7O8lWaY5e2ZEcXM/edit?usp=sharing
2. If funds allow
3. More research must be done to determine what equipment is needed and approximate cost.

Section VII. Conclusion

To address the need for low-cost, research-grade quadruped robots, we plan to continue to build upon our compliant quadruped platform. While keeping the cost under $200, we will develop obstacle avoidance, impact absorbance, uneven terrain navigation, and step maneuvering. In doing so, we hope to open the door for future researchers and robotics students to the exciting world of quadruped robotics.

Section VIII. References

[1] J. Xu, L. Lang, H. Ma, and Q. Wei, "Contact force based compliance control for a trotting quadruped robot," in *The 27th Chinese Control and Decision Conference (2015 CCDC)*, May 2015, pp. 5144–5149, doi: 10.1109/CCDC.2015.7162790.

[2] H. Zhuang, H. Gao, Z. Deng, L. Ding, and Z. Liu, "A review of heavy-duty legged robots," *Sci. China Technol. Sci.*, vol. 57, no. 2, pp. 298–314, Feb. 2014, doi: 10.1007/s11431-013-5443-7.

[3] M. Hutter *et al.*, "ANYmal - a highly mobile and dynamic quadrupedal robot," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2016, pp. 38–44, doi: 10.1109/IROS.2016.7758092.

[4] Y. Li, B. Li, J. Ruan, and X. Rong, "Research of mammal bionic quadruped robots: A review," in *2011 IEEE 5th International Conference on Robotics, Automation and Mechatronics (RAM)*, Sep. 2011, pp. 166–171, doi: 10.1109/RAMECH.2011.6070476.

[5] "Spot® | Boston Dynamics." https://www.bostondynamics.com/spot (accessed Sep. 07, 2020).

[6] Q. Nguyen, M. J. Powell, B. Katz, J. D. Carlo, and S. Kim, "Optimized Jumping on the MIT Cheetah 3 Robot," in *2019 International Conference on Robotics and Automation (ICRA)*, May 2019, pp. 7448–7454, doi: 10.1109/ICRA.2019.8794449.

[7] G. Kenneally, A. De, and D. E. Koditschek, "Design Principles for a Family of Direct-Drive Legged Robots," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 900–907, Jul. 2016, doi: 10.1109/LRA.2016.2528294.

[8] X. Li, W. Wang, and J. Yi, "Foot contact force of walk gait for a quadruped robot," in *2016 IEEE International Conference on Mechatronics and Automation*, Aug. 2016, pp. 659–664, doi: 10.1109/ICMA.2016.7558641.

[9] K. G. Karwa, S. Mondal, A. Kumar, and A. Thakur, "An open source low-cost alligator-inspired robotic research platform," in *2016 Sixth International Symposium on Embedded Computing and System Design (ISED)*, Dec. 2016, pp. 234–238, doi: 10.1109/ISED.2016.7977088.

[10] M. Triendl. "DIY quadruped robot (testing force feedback)," *YouTube*, July 03, 2020. [Video File]. Available: https://youtu.be/KRen4yexD4Y. (Accessed Sep. 02, 2020).

[11] M. Ayuso Parrilla, "DIY hobby servos quadruped robot." https://hackaday.io/project/171456-diy-hobby-servos-quadruped-robot (accessed Sep. 02, 2020).

[12] L.-C. Liao, K.-Y. Huang, and B.-C. Tseng, “Design and implementation of a quadruped robot insect,” in *2015 IEEE International Conference on Mechatronics and Automation (ICMA)*, Aug. 2015, pp. 269–273, doi: 10.1109/ICMA.2015.7237495.

[13] J. Graff, A. Martinez, K. Maynard and A. Bittle, "Low Cost Quadruped: MUTT", Worcester Polytechnic Institute, 2017.

[14] F. Garcia-Cardenas, N. Soberon, O. E. Ramos, and R. Canahuire, “Charlotte: Low-cost Open-source Semi-Autonomous Quadruped Robot,” in *2020 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, Ponta Delgada, Portugal, Apr. 2020, pp. 281–286, doi: 10.1109/ICARSC49921.2020.9096210.

[15] A. Spröwitz, A. Tuleu, M. Vespignani, M. Ajallooeian, E. Badri, and A. J. Ijspeert, “Towards dynamic trot gait locomotion: Design, control, and experiments with Cheetah-cub, a compliant quadruped robot,” *The International Journal of Robotics Research*, vol. 32, no. 8, pp. 932–950, Jul. 2013, doi: 10.1177/0278364913489205.

[16] “Quadruped Robots - RobotShop.” https://www.robotshop.com/en/quadrapod-development-platforms.html (accessed Sep. 07, 2020).

[17] “Adeept DarkPaw Quadruped Spider Robot Kit for Raspberry Pi.” https://www.robotshop.com/en/adeept-darkpaw-quadruped-spider-robot-kit-raspberry-pi.html (accessed Sep. 07, 2020).

[18] “Lynxmotion Phoenix 3DOF Hexapod - Black (No Servos / Electronics).” https://www.robotshop.com/en/lynxmotion-phoenix-3dof-hexapod---black-no-servos---electronics.html (accessed Sep. 07, 2020).

[19] “Stanford Pupper 2020 documentation.” https://pupper.readthedocs.io/en/latest/# (accessed Sep. 02, 2020).

[20] L. Rongzhong, “Petoi Nybble,” *Hackster.io*, Oct. 22, 2018. https://www.hackster.io/RzLi/petoi-nybble-944867 (accessed Sep. 02, 2020).

[21] “Petoi Bittle: A Palm-sized Robot Dog for STEM and Fun,” *Kickstarter*. https://www.kickstarter.com/projects/petoi/bittle (accessed Sep. 02, 2020).

[22] L. Rongzhong, “Nybble - World’s Cutest Open Source Robotic Kitten,” *Indiegogo*. https://www.indiegogo.com/projects/2421126 (accessed Sep. 02, 2020).

[23] “Home - SpotMicroAI.” https://spotmicroai.readthedocs.io/en/latest/ (accessed Sep. 02, 2020).

[24] SpartanIIMark6. “Raspberry Pi Spot Micro Quadruped Project,” *YouTube*, June 08, 2020. [Video File]. https://youtu.be/S-uzWG9Z-5E (accessed Sep. 02, 2020).

[25] mike4192, “Spot Micro Quadripeg [sic] Project,” *GitHub: mike4192/spotMicro*, Aug 14, 2020. https://github.com/mike4192/spotMicro (accessed Sep. 02, 2020).

[26] G. Conard and A. Brown, “Development of a Low-Cost Quadruped Robot,” Independent Study Report, Mechanical Engineering, Lafayette College, Easton, PA, USA, 2020.

[27] T. Tsujita, T. Kitahara, R. Tahara, S. Abiko, and A. Konno, “Drop test for evaluating effect of cushioning material and servo gain on parachute landing impact using a small one-legged robot,” in *2017*

IEEE International Conference on Robotics and Biomimetics (ROBIO), Dec. 2017, pp. 2474–2479, doi: 10.1109/ROBIO.2017.8324791.

[28] “Dynamixel MX–28AT,” *Robotis*, 2020. http://www.robotis.us/dynamixel-mx-28at/ (accessed Sep. 07, 2020).

[29] C. Hubicki *et al.*, “Walking and Running with Passive Compliance: Lessons from Engineering: A Live Demonstration of the ATRIAS Biped,” *IEEE Robotics Automation Magazine*, vol. 25, no. 3, pp. 23–39, Sep. 2018, doi: 10.1109/MRA.2017.2783922.

[30] Agility Robotics. “Cassie: Dynamic Planning on Stairs,” *YouTube*, Feb 20, 2019. [Video File.] https://youtu.be/qV-92Bq96Co (accessed Sep. 02, 2020).

[31] F. Grimminger *et al.*, “An Open Torque-Controlled Modular Robot Architecture for Legged Locomotion Research,” *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 3650–3657, Apr. 2020, doi: 10.1109/LRA.2020.2976639.

[32] R. Sloan, “Force Sensing 3D-Printed Composite Structures”, Thesis, Mechanical Engineering. Lafayette College, Easton, PA, USA, 2020.

[33] V. D. Yashunskiy and A. M. Romanov, “A Novel Approach to Touchdown Impact Damping for the Walking Robot Based on Low-Cost Geared Servo Drives,” in *2020 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, Jan. 2020, pp. 946–951, doi: 10.1109/EIConRus49466.2020.9039537.

[34] D. Pongas, M. Mistry, and S. Schaal, “A Robust Quadruped Walking Gait for Traversing Rough Terrain,” in *Proceedings 2007 IEEE International Conference on Robotics and Automation*, Apr. 2007, pp. 1474–1479, doi: 10.1109/ROBOT.2007.363192.

[35] J. Buchli, M. Kalakrishnan, M. Mistry, P. Pastor, and S. Schaal, “Compliant quadruped locomotion over rough terrain,” in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct. 2009, pp. 814–820, doi: 10.1109/IROS.2009.5354681.

[36] Y. H. Lee *et al.*, “Whole-Body Motion and Landing Force Control for Quadrupedal Stair Climbing,” in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Nov. 2019, pp. 4746–4751, doi: 10.1109/IROS40897.2019.8967527.

[37] Bo Huang, Lining Sun, and Yufeng Luo, “Statically balanced stair climbing gait research for a hybrid quadruped robot,” in *IEEE International Conference Mechatronics and Automation, 2005*, Jul. 2005, vol. 4, pp. 2067-2071 Vol. 4, doi: 10.1109/ICMA.2005.1626881.