Design of a Walking Cave Research Robot

Electronics

Design Investigation

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Signature of Sponsoring Teacher

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Definition of Need

NASA has been exploring the possibility of using both bipedal and quadruped walking robots to explore and map out martian caves. However, here on Earth, the percentage of caves that we have explored is estimated to be only 10% (Kambesis, 2007), but some researchers claim it could be even less. Most exploration robots are drones, but drones only work when a cave has a large space without bends. A drone couldn't fly in a cramped tunnel with bends and turns. One way that robots map out areas is by taking a 3D scan of an area. An important factor to consider is the energy-efficiency of the robot. When a robot goes on a cave mission, whether here on Earth or on Mars, the battery life must last for a long time. However, walking robots are not as energy efficient as wheeled robots or drones are (Xiao & Whittaker, 2014). Ultimately, a small, energy efficient, quadruped walking robot would be well suited for cave exploration. This design will use the code created for last year's robot to create a robot that researchers can control remotely. The robot will collect data using an ultrasonic sensor to calculate the distance of walls and obstacles. It will then send both a live feed of the cave from the camera and the calculated distance of the cave walls from the robot to the operator. Not only does this allow for caves to be viewed and surveyed without a human in the cave, but it also allows for easy maneuvering for the robot. The website would be very user-friendly, allowing for little to no training to control the robot, which has the added benefits of saving precious resources that could be delegated everywhere in research.

Background Research

In the book *Basic Electronics: Theory and Practice*, Westcott defines electronics as devices that control the flow of electrons (2020). Electrical and electronics engineering as a whole studies both the storage of electrical energy and how electrical energy can be manipulated by devices to create efficient solutions to problems society currently faces. Batteries, solar panels, computers, and robots are all examples of devices that couldn't have been made without electrical and electronics engineers.

Electrical engineers have been working on ways to create ways to navigate uneven terrain. However, these innovations are often made with the intentions of the technology being used for researching celestial bodies, such as NASA's collaboration with Boston Dynamics on the NeBula project. However, back down here on Earth, most of the cave systems on Earth are unexplored . The conditions of caves on Earth are very different from caves and craters on Mars and the Moon, and therefore a robot designed to explore Martian caves wouldn't be suited for the damper Earth caves. Much of the current cave surveying technology on Earth are drones, but their propellers make it have to squeeze into channels the way a small walking robot could. Drones however, are much more energy efficient than current walking robots, due to their light-weight designs. This means longer battery life, which is very crucial in missions. So, the drone is seen as the better option currently for mapping caves on Earth.

Discussion

Walking Robots

"A walking robot is a robot with legged locomotion." Wong et al. (2021). Walking robots use limbs circulating through a pattern of movement instead of tracks or wheels to propel themselves forwards. This unique way of moving allows the robot to traverse all types of terrain, both smooth and uneven. However, walking robots are more susceptible to tipping over, especially if the gait of the robot does not match its current environment. However, adding sensors to the robot and having the gait adjust to the environment, although difficult to do, is a solution that many researchers are working on currently (Ortiz & Vinjamuri, 2021). A gait is the relationship of the position of limbs at any given moment.The gait is a repeating pattern which ultimately propels the robot forward. Ultimately, the gait affects the speed and the stability of the robot. Static gaits have a wider area of support, but are slower than dynamic gaits (Gong et al., 2018).

Biped vs. Quadruped Robots

Legged robots come in different types, including bipedal and quadrupedal. Biped robots walk on two legs, like humans and birds. The higher center of mass and the smaller base of support means that bipedal robots are incredibly unstable. Quadruped robots have twice the amount of legs than bipedal robots. There are two different styles of quadrupeds: sprawling-type and mammal-type (Kitano et al., 2016). For mammal-type quadrupeds, their designs are inspired by quadruped vertebrate mammals, such as dogs or cats. The robot's joints are located beneath its body, with its limbs spaced shoulder-width apart. This type of robot is common due to its cost-efficiency and appealing, familiar design to audiences. Sprawling-type quadrupeds are more similar to spiders or insects, but with fewer legs. The legs come up from the body and then down towards the floor, and the distance between the limbs and the body is wider. This makes both the robot's center of mass lower and a wider base of support, which provides more stability than the mammal-type quadrupeds (Kitano et al., 2016). There are other types of walking robots with more legs, such as hexapods, but they are too costly and less energy-efficient for the added support to be worth it. There is an even rarer type of walking robot, one-legged walking robots, which works like a pogo stick. They are too unstable, and not much research has been done on one-legged walking robots because of this. Gong et al., (2018) found that quadrupedal robots are more stable and capable of carrying heavier loads compared to one-legged and biped robots.

Current Innovations in Quadruped Robots

Walking robots have a surprisingly long history. Frank and McGhee's "phony pony" was the first autonomous walking quadruped robot, and it was created back in 1966, although there is evidence for walking legged robots existing as far as the 1800's. The Original Cheetah, designed by Boston Dynamics back in 2013, holds the record for the fastest walking robot. Then in 2021, with MIT, they redesigned and created a new mini cheetah which could do impressive feats, such as a backflip (Zewe, 2021). The robot's flexibility and speed are useful, but it is also able to leap, which is very difficult for a walking robot. The mini cheetah has two controllers; one controller is used to control the robot while the other one takes in the robot's surroundings and "learns" and "adapts". The robot then gets both benefits of blind robots (robots with no cameras or sensors) and robots that sense and process, all while improving on robots that would need a map of the area first (Zewe, 2021). The new smallest walking robot is an insect-like robot that could fit on the side of a penny (Morris, 2022). Its small build can be very helpful in biology, especially in studying small ecosystems and insects. Debatably, the way the robot is powered is more impressive than its microscopic size. Instead of using electricity, Rogers and his team made a robot using an alloy which bends when heated. Repeated rapid heating causes the robot's walking motion. Glass pieces on the legs help the alloy return to its original shape after being deformed (Morris, 2022). TITAN XIII, the latest in the quadruped series, is a battery-powered, sprawling robot that walks efficiently at 1.38 m/s (Biswal & Mohanty, 2020). Walking robots are already being used in complex and potentially hazardous situations. The ANYmal could navigate through an oil site and measure different gauges, and the position of valve handles (Bellicoso et al., 2018). These inspections boost both safety and efficiency on the worksite, leading to increased productivity.

Energy Efficiency

One measurement of energy-efficiency is the Cost of Transportation. It's calculated by dividing the energy used in joules by the gravitational potential energy of the robot if lifted the distance it walked (E/Mgd). Another way to calculate the Cost of Transportation is by using the power in watts and dividing that by the product of the mass, velocity, and gravitational field strength (P/Mgv). Another term for Cost of Transportation is Specific Resistance (Kajita & Espianu, 2018). The formula takes into account variables such as the mass, gravity, distance, and surface friction to calculate the ratio of energy used for movement (Xiao & Whittaker, 2014). There have been numerous designs to lower the energy consumption of walking robots. One creative solution designed by Wong et al., utilized springs up and down the robot's legs to absorb the shock of stepping. However, the robot is still not as efficient as living beings. Cornell's Walkman, the most energy-efficient walking robot, consumes 368 W, which means it has a SR of 1.35. That SR is seven times higher than the average person walking. (Kashmiri et al., 2018.)

Speleology

Speleology is the study of cave systems. A cave is a natural cavity in the Earth, which allows water to flow from input points to output points (Gillieson, 2021). Speleology is considered a very physical science and is often called a "sporting science" because speleologists have to explore the caves that they are researching (Muffato et al., 2022). Of course, that means that speleology is still hindered by human capabilities, because despite the creation of surveying technology, still much of the research has to be done by humans, especially for collecting cave samples. Caves are, however, a very dangerous environment since they're dark, damp, enclosed and sometimes don't contain enough oxygen.

Current Innovations in Cave Surveying

While the earliest speleologists may have drawn maps of caves freehandedly, modern innovations have made mapping out cave systems much easier and more accurate. The ability to map out caves in 3D, for example, can help not only map caves more accurately but also contribute towards research about the origins of caves (Idrees & Pradhan). Mobile mapping systems are one of the more recent technologies in speleology designed to aid in making 3D maps of caves (Stefano et al.). Often, mobile mapping systems are drones. Drones work well as a mobile mapping system since manufacturers already design drones to be small and lightweight with a camera function. To scan out areas in a cave, the drones use small lasers to calculate the distance between objects and the drone. Those scans must overlap for the scans to be stitched together properly to create a full scan of the entire cave. However, larger caves are still an issue for LIDAR scans to recreate (Richard & Zupan, 2020).

Ultrasonic Sensors

Ultrasonic sensors use a sound that is at a higher frequency than what people can hear. It transmits that noise and, similar to how a bat uses echolocation, the ultrasonic sensor receives the sound when it bounces off an object. Then, using the time it took from the sound being transmitted to the time that the sensor received the sound back, it can calculate the distance of the object from the sensor (Latha, Murthy, & Kumar, 2016). One benefit is that ultrasonic sensors can work through multiple materials and states of matter, as long as the different speeds of sound of each material is considered (Koval, Vaňuš, & Bilík, 2016, p. 153). This is very different to LIDAR, where a material's refraction of light can skew the calculated distance of the object.

Another pro about ultrasonic sensors is that they are able to work no matter how much light is in an area or how much heat. However, the ultrasonic sensor depends on the angle at which the sound bounces off an object, and overall has a hard time detecting smaller objects (Zhmud et al. 2018). So while ultrasonic sensors may not be perfect for a fully detailed 3D image of a cave system, its ability to work in dark and damp environments makes it beneficial for overall measurements.

Related Studies

NASA's Jet Propulsion Lab has been working with Boston Dynamics to create a series of both quadruped and bipedal robots meant to explore Martian caves. The Collaborative SubTerranean Autonomous Robots (CoSTAR) team at NASA has developed an autonomous robot meant to traverse and map cave systems. Using the DARPA Subterranean Challenge, they hope to develop this technology with their NeBula Project to create robots that will be able to find caves that can be used as sanctuary by future astronauts on Mars (Bourman et al., 2020).

Another project that heavily inspired this cave research robot is a cave drone designed by Zhang and his team in 2017. The SmartCave drone was meant to work alongside humans to map out caves. The SmartCave drone is capable of creating detailed 3D maps. However, the drone must have the proper lighting to do so, since it uses RGB-D data (Zhang et al., 2017)

Conclusion

During this investigation, there became a sharp distinction of how walking robots were being used to map out caves on Mars versus our current cave surveying tools. NASA focuses its NeBula project on autonomous robots, which makes sense for exploration of a planet that we cannot send people to yet. However, in speleology, people perform the research, observation, and measurements. While there has been a recent development of robots for cave surveying, they are seen as only a tool, the same way rope and a helmet are tools for speleologists. According to Zhang et al. (2017), the data gathered is useless without a person there to see the cave for themself and interpret the measurements. There should be, however, more research on a device that isn't fully autonomous but also does not need a human in the cave with it. Remote technology could allow a speleologist to collect data on dangerous caves while also getting the full picture of inside the cave.

Materials

- 8 Tiankong Rc MG90S micro servo motors with servo horns
- 1 ESP32 WROOM with 38 pins
- 1 ESP32 breakout board
- 1 JSN-SR04T waterproof ultrasonic sensor
- 1 switch
- 2 9V batteries
- 1 3D Printer with PLA Filament
- 22 gauge wire
- 1 laptop
- 1 Micro USB cable
- 1 #0 Phillip screwdriver
- 16 #0-80 x ¾ in. Panhead Phillip screws
- 8 #0-80 x 1/8 in. Panhead Phillip screws
- 1 soldering iron
- 1 roll of solder
- 2 25-pin circuit boards
- 1 capacitor
- 1 roll of electrical tape
- 1 roll of masking tape
- 1 scale
- 1 multimeter
- 1 stopwatch
- 1 ammeter

Design Plan

A robot designed for cave exploration should be made for the damp, cramp, and rocky environment. The walking robot must be waterproof, with a lid to protect wires from contacting water. This also means that no wires can be outside of the shell. The robot needs to be lightweight and compact, because not only does it allow the robot to move through tunnels, but it also lengthens the battery life of the robot. Speaking of battery life, the robot should be as energy-efficient as possible, since long missions inside the cave will prevent the robot from being able to come back to be recharged frequently.

Table 1.1

Design Criteria	What Makes Up This Design Criteria	Importance on a Scale of 1-5
Functionality of the Robot/Code	• The robot is able to walk for at least 10 seconds. • The robot walks in the direction dictated by the website. • Camera sends a video feed in real time to the website. • Ultrasonic Distance Sensor sends distance from walls to website	5
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise.	3

Table 1.1 shows the design criteria of the walking quadruped robot.

Part A: Assembling the Robot

Figure 1.1

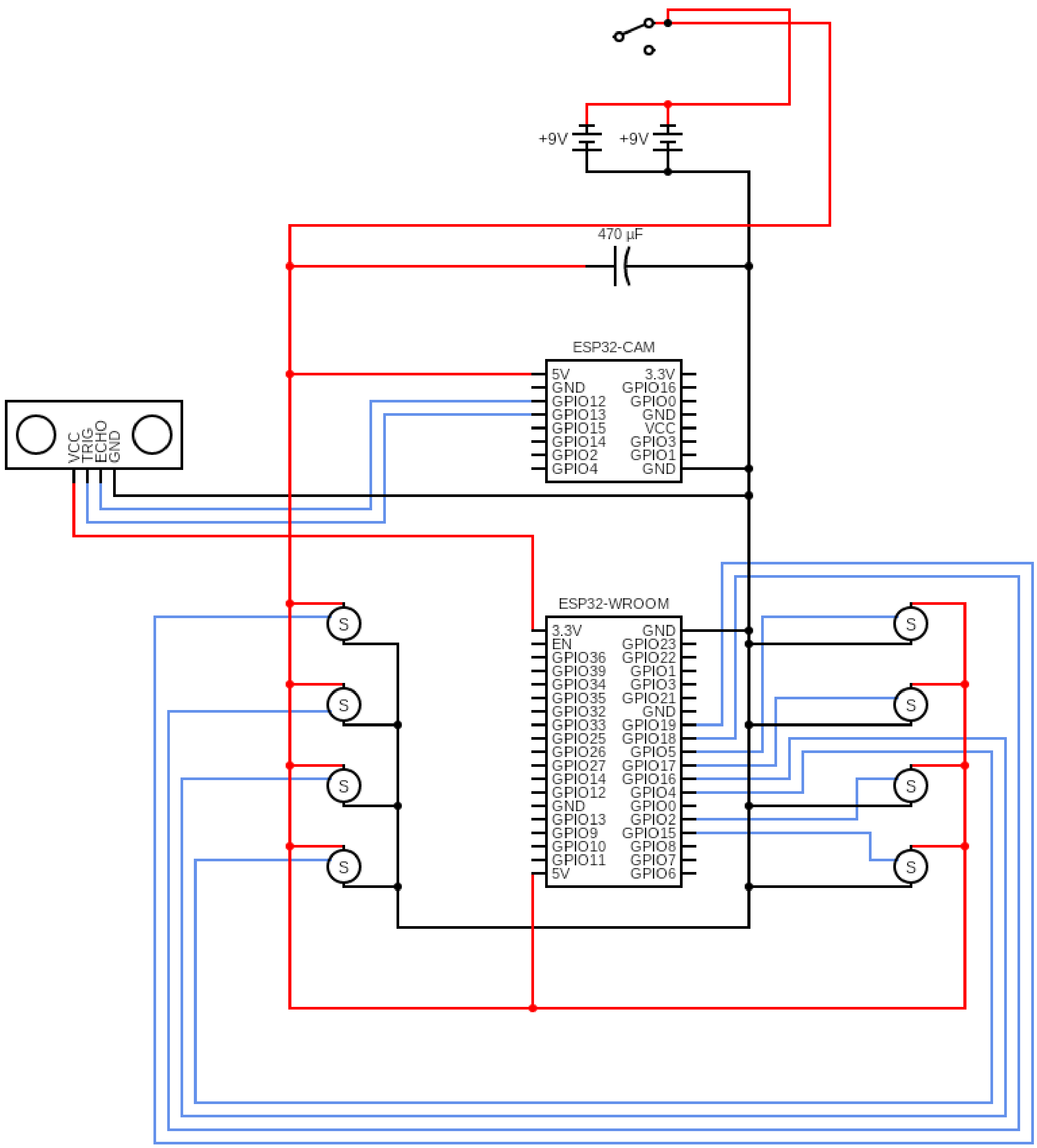

Figure 1.1 is a circuit schematic of the walking robot. Red is power, black is ground, and blue is signal.

1. Access the 3D model of the main shell

   https://www.tinkercad.com/things/0yAdChAAoom-terra-main-shell?sharecode=F4I1eA-63z9FFSmZ8h-bRmI4C01MFFqGjmB5kObS6os

2. Access the 3D model of the shell of the legs https://www.tinkercad.com/things/10peqRiguQp-terra-legs?sharecode=lffXcsSoBly_YptRjgjOkWizd_iZEr9wF6Lc9RfUFkY
3. Export the files and upload the files to the 3D printer.
4. Print out the models one at a time.
5. Remove supports and sand down the pieces.
6. Screw down the ESP32-WROOM.
7. Attach the ESP32-CAM to the hole in the front.
8. Follow Figure 1.1 on how to complete the circuit.
9. Attach the switch to the switch hole.
10. Screw the servo motors into place.
11. Screw the small rod to the top servo motors and top leg (the hollowed out piece) to the bottom servo motor.
12. Attach the long rod from the small rod to the foot piece (the weird curved shape) and the foot piece to the top leg using screws.

Part B: Coding the Robot and Website

1. Access this github link: https://github.com/bsverdin/Walking-Robot.
2. Click on the folder titled “Walking Robot Code”.
3. Click on the folder titled “Model TERRA”.
4. Inside that folder, there are two folders, with the names of the folders corresponding to the board that the code will be uploaded to. Click on the folder titled “ESP32-CAM”.
5. Open the file called “Terra_cam”.
6. Upload the code to the ESP32-CAM.

7. Click on the folder titled "ESP32-WROOM".
8. Open the file called "Terra_wroom".
9. Upload the code to the ESP32-WROOM

Part C: Testing the Robot

1. Mass the robot in kilograms.
2. Fully charge the batteries.
3. Put some masking tape on the floor at the beginning of the hallway
4. Turn on the robot and place it on the floor behind the masking tape.
5. Let the robot run in a straight line until failure.
6. Record the seconds between when it starts and when it fails/falls over.
7. Measure the distance that the robot traveled.
8. Calculate the Cost of Transport using the P/Mgv equation, with g being equal to 9.8 m/s^2.
9. Repeat for five trials for every design.

Design Results

Table 1.2

Design Criteria	What Makes Up This Design Criteria	Completion on a Scale of 1-5
Functionality of the Robot/Code	• The robot is able to walk for at least 10 seconds. • The robot walks in the direction dictated by the website. • Camera sends a video feed in real time to the website. • Ultrasonic Distance Sensor sends distance from walls to website	3
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise.	3

Table 1.3 shows the completion of the design criteria for the first design.

Redesign Plan

The small custom horns created for the “elbows” and “knees” of the robot were printed in a manner that was too small for the 3D printer and PLA filament. The shafts themselves, when compared to the shafts of the servo motor horns that came with the servo motors, were also taller. This resulted in defective pieces not connecting to the servo motors properly, unless screwed in with M2.5 x 8 screws instead of the M2.5 x 5. However, as the servo motors moved, two things happened. One, the lack of detail on the inside of the printed shift meant the grooves for the teeth were not printed correctly, and slowly worn away until it could move freely, unless the shaft was screwed on tighter. Two, as the screws applied pressure to the top of the shaft, and as the servo motor rotates, the defects in the printing would ultimately cause the shaft to be torn apart. This was an issue even when the spare parts that were printed were printed with a higher density. Using a different material or fabrication method could have prevented the shafts coming apart. 4 AA batteries replaced the two 9v batteries, as the camera was drawing up to 7v when it should only draw about 5v. This prototype’s smaller, more curved feet have less friction with the floor.

Figure 1.2

Figure 1.2 shows the type of defects that the custom 3D printed horns suffered from

Part D: Redesign

1. Melt off the broken shafts with the tip of a hot glue gun, careful not to remove any length from the rod attached to the shaft.
2. Taking a servo motor horn, glue the remaining rod from the 3D printed horn on top of the servo motor horn. Remove length from the servo motor horn as needed for the long rod to move the complete degrees of motion.
3. Instead of connecting the long rod to the small shaft with the long rod on top, connect with the long rod behind the small shaft.
4. Place small, even strips of hot glue on the bottom of the feet for added friction

Redesign Results

Table 1.3

The Effect of Power (W) and Average Velocity (m/s) on the Cost of Transport						
	Distance (m)	Time (s)	Velocity(m/s)	Voltage(V)	Power(W)	CoT
Trial 1	0.42	36.96	0.0114	5.5	0.0495	0.87
Trial 2	0.29	19.79	0.0147	5.4	0.0486	0.66
Trial 3	0.06	9.36	0.0064	4.5	0.0405	1.26
Trial 4	0.04	12.47	0.0032	4.9	0.0441	2.75
Trial 5	0.14	14.59	0.0096	4.8	0.0432	0.90
Mean	0.19	18.634	0.0090	5.02	0.0452	1.29
SD	0.162	10.926	0.0044	0.4207	0.0038	0.8446
SE	0.032	2.185	0.0009	0.0841	0.0008	0.1689

Table 1.3 shows the average velocity, power, and cost of transportation of the redesign.

Figure 1.3

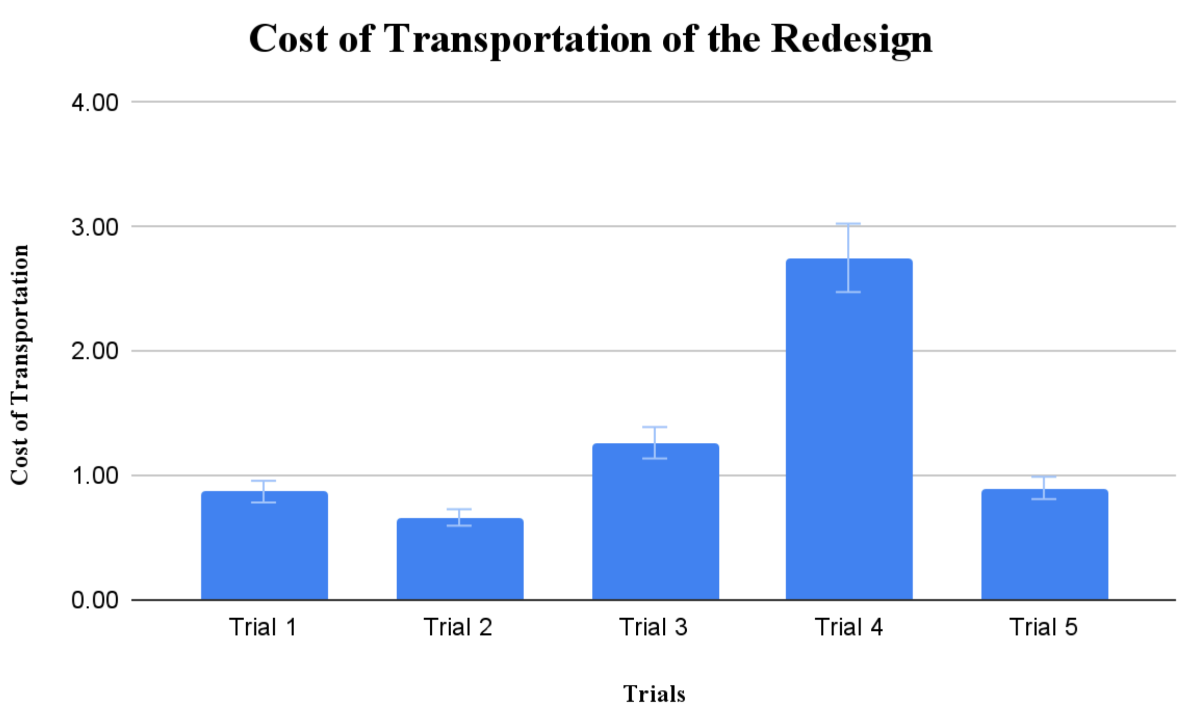

Figure 1.3 shows the Cost of Transportation of the redesign between the 5 trials.

Table 1.4

Design Criteria	What Makes Up This Design Criteria	Completion on a Scale of 1-5
Functionality of the Robot/Code	• The robot is able to walk for at least 10 seconds. • The robot walks in the direction dictated by the website. • Camera sends a video feed in real time to the website. • Ultrasonic Distance Sensor sends distance from walls to website	4
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise.	4

Table 1.4 shows the completion of the design criteria for the redesign.

Conclusion

After redesigning the robot, its Cost of Transportation was similar to other walking robots, and potentially more energy-efficient than current walking robots. For example, the prototype had an average Cost of Transportation of 1.29. Walkman, the world's most energy-efficient walking robot so far, has a Cost of Transportation of 1.36. As trials went on, the Cost of Transportation increased, likely because of the batteries running out. Between trials 4 and 5, the batteries were recharged. Another reason for the larger Cost of Transportation is that digital ammeter. The digital ammeter adds unnecessary weight to the robot, which will impact the Cost of Transportation. Also, the current given by the ammeter through all trials was 0.00A. Of course, this would be impossible, as without any current, nothing would be powered. This wasn't a wiring error, either, as other sources using the same digital ammeter yielded similar results of 0.00A to 0.01A. To be conservative, the current was estimated to be 0.009A of power. If the current was lower, then the power was calculated to be too high. Both more weight and more power will negatively impact the Cost of Transportation. However, the redesign was an overall success for creating an energy-efficient walking robot, even despite these circumstances.

Ultimately, while the redesign walked significantly better than the initial design, both struggled with problems caused by the fabrication of the legs. The legs were designed to minimize the amount of torque acting on the shaft of the servo motor. However, without the wider legs and larger feet, the base of support was much smaller than the previous prototypes, causing it to fall more often than its predecessors. While the 3D printer printed the larger pieces fairly well, the small servo horn for the "elbows" and "knees" were printed with defects such as gaps along the walls of the shaft, which greatly compromised the integrity of the robot. These defects were still there after the density of the pieces were increased as well. Perhaps making the robot bigger or finding an alternative method for creating the body of the robot would solve most of these issues.

The purpose of this prototype was to aid speleologists in examining cave systems. In the future, more can be done with this prototype to improve this device for cave systems. For one, deeper walls on the robot to allow wires to fit more easily in the body.While keeping most of the design of the legs from this year’s project, making the legs wider and altering the foot to be similar to previous prototypes. These changes would affect the weight, which could negatively affect the Cost of Transportation. Another design change that could be made is simply adding a photoresistor so that the ESP32-CAM light would turn on and allow for viewing in the dark.

Reference List

Bouman et al. (2020) Nebula: Team costar's robotic autonomy solution that won phase II of darpa subterranean challenge. "Field robotics", March 2022, vol. 2, p. 1432-1506.10.55417

Gong, D. et al. (2018) Bionic quadruped robot dynamic gait control strategy based on twenty degrees of freedom. *IEEE/CAA Journal of Automatica Sinica,* 5(1), 382-388. 10.1109/JAS.2017.7510790

Idrees, M. O. & Pradhan, B. (2016) A decade of modern cave surveying with terrestrial laser scanning: A review of sensors, method and application development. *International Journal of Speleology*, 45, 1, p. 71 http://dx.doi.org/10.5038/1827-806X.45.1.1923

Javaid, M. et al. (2021) Sensors for daily life: A review. *Sensors International*, 2. https://doi.org/10.1016/j.sintl.2021.100121

Kajita, S. & Espiau, B. (2018) Legged Robots. Handbook of robotics. (361-389) Springer. 978-3-319-32552-1

Kambesis, P. (2007) The importance of cave exploration to scientific research. *Journal of Cave and Karst Studies*, 69(1), (46–58). https://www.caves.org/wp-content/uploads/Publications/JCKS/v69/cave-69-01-46.pdf

Kashiri, N. et al. (2018) An Overview on Principles for Energy Efficient Robot Locomotion. Advances in Mechatronics and Biomechanics towards Efficient Robot Actuation. https://doi.org/10.3389/frobt.2018.00129

Kitano, S., Hirose, S., Horigome, A. & Endo, G. (2016) Titan-XIII: Sprawling-type quadruped robot with ability of fast and energy-efficient walking. *ROBOMECH Journal*, 3(8). https://doi.org/10.1186/s40648-016-0047-1

Koval, L., Vaňuš, J., & Bilík, P. (2016) Distance measuring by ultrasonic sensor. *IFAC-PapersOnLine*, 49(25). https://doi.org/10.1016/j.ifacol.2016.12.026

Latha, N. A., Murthy, B. R., & Kumar, K. B. (2016) Distance sensing with ultrasonic sensor and arduino. *IJARIIT,* 2(5). ISSN: 2454-132X

Muffato, V. et al. (2022) The practice of speleology: What is its relationship with spatial abilities? *Cognitive Processing,* 23, 217-233. https://doi.org/10.1007/s10339-022-01075-4

Ortiz, J. H. & Vinjamuri R. (2021) Collaborative and humanoid robots. Intech Open. https://www.google.com/books/edition/_/GtJGEAAAQBAJ?hl=en&gbpv=0

Richard, W. & Zupan, N. (2020) 3D laser scanning of the natural caves: Example OFŠKOCJANSKE JAME. *Geodetski Vestnik*, 64(1), 89. 10.15292/geodetski-vestnik.2020.01.89-103

Wong, L. H., Sivanesan, S., M F A Faisol, Othman, W., Wahab, A. & Alhady, S. (2021) Development of quadruped walking robot with passive compliance legs using XL4005 buck converter. *Journal of Physics: Conference Series*, 1969(), 26-27.

Xiao, X. & Whittaker, W. L. (2014) Energy considerations for wheeled mobile robots operating on a single battery discharge. *Carnegie Mellon University*. https://www.ri.cmu.edu/pub_files/2014/8/TR-14-16.pdf

Zewe, A. (2021). One giant leap for the mini cheetah: A new control system, demonstrated using MIT's robotic mini cheetah, enables four-legged robots to jump across uneven terrain in real-time. *MIT News*. https://news.mit.edu/2021/one-giant-leap-mini-cheetah-1020

Zhang, G. et al. (2017) SmartCaveDrone: 3D cave mapping using UAVs as robotic co-archaeologists. *2017 International Conference on Unmanned Aircraft Systems*

(ICUAS).10.1109/ICUAS.2017.7991499