(ALL ITEMS LISTED MUST BE TYPED)

ABSTRACT

The Illinois Junior Academy of Science

CATEGORY Electronics STATE REGION # 3

SCHOOL Lane Tech College Prep IJAS SCHOOL # 3001

CITY/ZIP Chicago / 60618 SCHOOL PHONE 7735345400

SPONSOR Mr. Daniel Law

CHECK ONE: ☐ EXPERIMENTAL INVESTIGATION ☑ DESIGN INVESTIGATION
(Choice will determine rubric used for assessment)

NAME OF EXHIBITOR * Bianca Verdin GRADE 10

NAME OF EXHIBITOR ______ GRADE ______

* If this project is awarded a monetary prize, the check will be written in this scientist's name and it will be his/her responsibility to distribute the prize money equally among all participating exhibitors.

PROJECT TITLE Design of an Energy-Efficient Walking Robot

a) Purpose - The purpose of this design investigation was to create a walking quadruped robot that was energy-efficient. If walking robots were more energy efficient, they would be used for more exploration, search and rescue, and inspections.

b) Procedure - The body of the robot was created using a 1 cm thick PVC board. After constructing the body, all the electronic components were screwed into the body. Then, using the code for last year, by implementing it to all the motors, the servos were then programmed to move in a specific gait. The robot's energy intake and distance traveled were used to calculate the Cost of Transportation (CoT) of the robot.

c) Conclusion - While Design A may be more energy efficient, Design B is much more reliable and traveled longer distances than Design A. Design B was relatively energy efficient with a median cost of transportation of .14.

1. Limit Abstract to 3 paragraphs (250 words or less). Include: a) Purpose– what you set out to investigate; b) Procedure – how you did it; c) Conclusion – based on your results. Label each paragraph.
2. Must be typed, single-spaced, on the front side of this form. DO NOT write on back side of this form.
3. Three (3) copies of your COMPLETE paper are required at the State Science Project Exposition. Four (4) copies of your COMPLETE paper are required for the State Paper Session Competition.

The above form must be duplicated. (Student-generated forms must be in essentially the same format.)
*This form **MUST** be displayed on the front of the exhibitor's display board. It may be reduced to fit on a half sheet of paper. (Print at 75% reduction) Displayed abstract cannot be smaller than 8.5 inches (vertical) x 5.5 inches (horizontal).*

SAVE PRINT

SAFETY SHEET

The Illinois Junior Academy of Science

Directions: The student is asked to read this introduction carefully, fill out the bottom of this sheet. The science teacher and/or advisor must sign in the indicated space. By signing this sheet, the sponsor assumes all responsibilities related to this project.

Safety and the Student: Experimentation or design may involve an element of risk or injury to the student, test subjects and to others. Recognition of such hazards and provision for adequate control measures are joint responsibilities of the student and the sponsor. Some of the more common risks encountered in research are those of electrical shock, infection from pathogenic organisms, uncontrolled reactions of incompatible chemicals, eye injury from materials or procedures, and fire in apparatus or work area. Countering these hazards and others with suitable controls is an integral part of good scientific research. In the **chart** below, list the principal hazards associated with your project, if any, and what specific precautions you have used as safeguards. Be sure to read the entire section in the *Policy and Procedure Manual of the Illinois Junior Academy of Science* entitled "Safety Guidelines for Experimentation" before completing this form.

Possible hazards	Precautions taken to deal with each hazard
1. Choking and hair loss are possible from motors or power tools snagging on loose articles or hair. 2. Overheating components could cause burns or fire. 3. Electrocution from an improper connection of wires. 4. Cuts and scratches from the pins, wires, and power tools. 5. Pedestrians and animals may hit the robot during outside testing.	1. Hair was tied back in a ponytail; no loose clothing, necklaces, or lanyards were worn, and all items with a hazard of getting caught were moved away from the motor. 2. Motors were tested in short trials no more than an hour and if the components got hot testing was immediately stopped. 3. All bent, broken, or uncovered wires were thrown away and not used to connect the motors. 4. Power tools were handled by adults only and any cuts and scratches sustained were immediately sanitized and treated. 5. Testing was immediately stopped when pedestrians or animals were spotted on the sidewalk

Please check off any other possible endorsements needed. Include these documents in your paper and on your board.

_____Human as Test Subjects –for any projects involving humans-even surveys.
_____Microorganism-for any projects involving bacteria, viruses, yeasts, fungi or protozoa
_____Non-Human Vertebrates -for any projects involving fish, amphibians, reptiles, birds or mammals
_____Tissue Culture-for any projects involving growing eukaryotic tissues or cell cultures
_____Recombinant DNA-must be conducted in a registered research laboratory under professional supervision
_____Use of Firearms – including all required documents
_____Letter from institution where research was done or IJAS SRC-if an exception to the IJAS rules has been granted.

SIGNED [signature]
Student Exhibitor(s)

SIGNED [signature]
Sponsor *

*As a sponsor, I assume all responsibilities related to this project.

This Sheet Must Be Typed and this form **must** be displayed on the front of the exhibitor's display board. Displayed Safety Sheet can not be smaller than 8.5 inches (vertical) X 5.5 inches (horizontal). Print at 75% reduction.

SAVE **PRINT**

Design of an Energy-Efficient Walking Robot

Electronics

Design Investigation

____

Signature of Sponsoring Teacher

____

Signature of School Science Fair Coordinator

Bianca Verdin
Lane Tech College Prep High School
Chicago, IL 60618
Grade 10

Table of Contents

Acknowledgments

I would like to thank Mr. Law for agreeing to sponsor this project. I know it must've been difficult because of the robotics club starting during this project and my understanding of only the bare basics of robotics. My father, Salvador Verdin, helped me code and create the robot, and he also handled the power tools. He sacrificed a lot of time to help me, and I appreciate that. Thank you to Charles Petajan, my mentor, for helping me with my Background Research. Thank you to my mom, Griselda Verdin, for helping me test the robot, as well as order the materials. I would like to thank Leila Miljkovic from the Lane Tech Writing Center for looking over my rough draft. Thank you to Divinefavour Osuji, for also looking at my draft and providing design-specific advice. Thank you to Ms. Young for pushing me to complete this robot.

Definition of Need

Robots are now being used for search and rescue missions, mining, worksite inspections, agriculture, and much more. The robots must deal with obstacles, such as steps, doors, or irregular terrain (Bellicoso et al.). However, legged robots are less energy efficient than robots with wheels. According to Xiao and Whittaker (2014), walking takes up 29% of a robot's total energy usage. That is not factoring in the energy needed for the robot's computers, controllers, and means of communication to move the motors. This means that a walking robot has to dedicate 71% of its energy to walking, an energy that would normally go towards computing, like sensing its surroundings. It would need more energy to move as long of a distance as a robot with wheels. This makes sense because walking robots need more motors than wheeled robots. The energy consumption of the robot only gets worse as it walks, meaning that they are often not seen as reliable enough to do certain tasks like, for example, space exploration, even though it could improve certain aspects of how we explore other planets. During last year's project, energy consumption was a tremendous problem. The power source was not enough to power both the microcontroller and multiple motors, however, the improvements of the code did slightly help to lower how much energy each motor needed. Using the improvement to the code from last year, all the motors will be connected to the Arduino and a strong enough power supply and create a body for the prototype of the complete robot. The robot will be tested outside on the sidewalk. Then using the formula for specific resistance, the cost of transportation will be calculated. The goal is for the robot to have an average cost of transportation less than .15.

Background Research

Westcott (2020) said that electronics is "the study of devices that control the flow of electricity." This subject covers concepts spanning from robotics to electrical engineering. The purpose of electrical engineering is to research problems affecting current society and to design devices that improve on past inventions. Smartphones, computers, and robots are all products of electrical engineering.

A challenge within electrical engineering is creating a robot that more naturally moves through irregular terrain. Most robots use wheels to move around, limiting where the robot can go. However, walking robots use legs to move, instead of wheels or tracks. Their legs provide easy mobility through irregular terrain. Currently, Boston Dynamics has created LittleDog and Spot, two quadruped robots designed after dogs. It is important for there to be walking robots because they can help with natural disasters, such as pulling people out of the rubble, and they can complete tasks that are too dangerous for humans, like exploring the terrain of Mars. People that might use a walking robot are researchers and first responders, as the robots are able to go into smaller crevasses and can survive risky situations.While they can be very helpful, they are often not practical in their consumption of power. According to Kashiri et al. (2018), Big Dog has a Specific Resistance of 15 and so Big Dog can only run for 30 minutes in one full 15-liter tank of fuel. However, mammals have a power density of 0.041 W/g, meaning that robots still have a long way to go when it comes to efficiency, especially compared to living things.

Discussion

Walking Robots

According to Wong et al. (2021), “a walking robot is a robot with legged locomotion." (2) This means that instead of using wheels or tracks to move around, it uses legs controlled by several servo motors to move around. This comes with multiple advantages which include the ability to move across difficult terrain. Legs are less likely to get stuck in mud, dirt, grass, or any terrain where a wheel digs itself in; legs also do less damage to the ground than tracks or wheels (Todd, 2013). However, walking robots are very unstable. Teaching a robot to see and overcome obstacles is also difficult. For example, if a walking robot has to climb steps, the robot must see the step and raise its legs to accommodate (Ortiz &

Vinjamuri, 2021). The robot will have one static gait because the stability of the robot is more important than the speed of the robot. A gait is the relationship of animal limbs at a certain time and place. It includes the regularly repeating pattern of when the limbs hit the floor and how the animal moves its limbs. Quadruped robots have two groups of gaits, static and dynamic gait. Static gait means that the center of the mass of the robot is always being held up by a triangle. It is very stable, however, it is also very slow (Gong et al., 2018). Many gaits make the robot more or less stable. A creeping gait is when the robot only lifts one leg at a time (Kajita & Espianu, 2008). Because it only raises one leg at a time, it is always supported by that triangle, but is not the most efficient way to move. An understanding of gaits is needed to code the motors in a way that not only allows the robot to walk stably. It also prevents the robot from browning out (brownout is when the components of the robot take too much power from the batteries at the same time and causes the robot to fail).

Biped vs. Quadruped Robots

There are multiple types of legged robots, such as bipedal and quadrupedal robots. Biped robots have two legs and are usually humanoid. The center of mass is a lot higher than the center of mass of most quadruped walking robots, which makes them more unstable. However, due to there being fewer legs, depending on the robot, it can be more energy efficient than a quadruped robot. Quadruped robots use four legs. There are two different quadrupeds: sprawling and mammal-type. The mammal type quadruped is biologically inspired by mammals, for example, dogs or cats. The joints are underneath the body of the robot and their limbs are shoulder-width apart. This type of robot is popular because of its cost-efficiency. Sprawling-type quadrupeds are like spiders, 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 the robot's center of mass lower, which gives the added benefit of the robot being more stable (Kitano et al., 2016). There are other types of walking robots with more legs, such as hexapods, but they are costly and less energy efficient. To sum it up, Gong et al., (2018) state that one-legged and biped robots are not as stable and cannot carry the same amount as quadrupedal robots, and the experts and other multi-legged robots structurally have an unnecessary amount of legs, which take up energy and add mass. This investigation influenced the design of the robot, as the pros and cons of each type of robot were evaluated and the robot was made to be a mammal-like quadruped.

Current Innovations with Quadruped Robots.

Although there is more focus on the research of walking robots, they are not a new concept. The first walking robot was invented in the 1800s by a man named Chebyshev and the first autonomous quadruped robot was created in 1960 called the "phony pony" in California (Biswal & Mohanty, 2020). The fastest quadruped robot has been the Cheetah by Boston Dynamics in 2013. They made a new mini cheetah created by MIT in 2021, and it is the first to do a backflip (Zewe, 2021). This flexibility and speed can be very useful, but its ability to leap is more fascinating, as it would allow the robot to get over chasms or enormous obstacles it can't step over. Not only that, but it also uses a two-part controller; one controller controls the robot while the other one is a neutral controller that takes in the ground's view and "learns" from experience. The robot then gets both benefits of blind robots and improves on robots that would need a map of the area first (Zewe, 2021). The new smallest walking robot is a microscopic insect-like robot that has many gaits and can even jump (Morris, 2022). Its small build can be very helpful in biology, especially in studying small ecosystems and insects. The most interesting thing, however, is not its size, but the way it moves. It is not powered by any electricity or hardware. Instead, researchers created a metal-like material that keeps its shape that it was bent into when heated and used it to create the robot. Here, the researchers used a ray of light to quickly and repeatedly heat the robot, which made the metal move. The scientist put glass on the robot to help the alloy return to its shape (Morris, 2022). The TITAN series of robots have been a major source of inspiration for the robot. TITAN XIII, the newest quadruped of the series, is a battery-powered sprawling quadruped robot that can walk efficiently at 1.38 m/s speed (Biswal & Mohanty 2020). Walking robots have proven their ability to be used in situations such as inspections. The ANYmal was able to navigate through an oil site and measure different gauges, and the position of valve handles. These inspections greatly improve the health and safety of the worksite as well as improve efficiency and production (Bellicoso et al., 2018).

Energy Efficiency

Energy efficiency does not have a set definition or measurement, however, the usage of the word that best fits the design is the ratio of the amount of useful output of a process compared to the amount of energy input of the process (Patterson, 1996, p.377). Many experts view energy efficiency as being either first-law efficiency (ratio of useful output to input) or second-law efficiency (based on the quality of the output to the energy input) (Saunders et al., 2021). The issue becomes how to define the useful output and energy input. Several indicators can track change in energy efficiency; they fall into Thermodynamic (purely from thermodynamics), Physical-thermodynamic (energy input still measured in thermodynamic units, but the output is measured in physical units), Economic-thermodynamic (output measured in terms of market price), and Economic (purely market-based) (Patterson, 1996, p.377-378). For this robot, the main measurement will be physical-thermodynamic based. Specific resistance measures the energy efficiency of a robot. It is the ratio of the amount of energy over the gravitational potential energy that the robot would have if it was raised off the ground by the distance walked. (E/Mgd) This is equivalent to the Cost of Transportation (Kajita & Espianu, 2008). The reason for this formula is that the total energy used for moving varies on the mass, the gravity, the distance, and even the amount of friction on the surface walked (Xiao & Whittaker, 2014). The robot will be tested on the same floor over all trials, so friction of the floor is less of a problem. There have been many designs to lower the energy consumption of walking robots. Many robots take inspiration from real life. These are biologically inspired robots. One robot, made by Wong et al., uses springs up and down the robot's legs to replicate how live things absorb the shock of stepping. However, even robots biologically inspired are not as efficient as animals or people. The Walkman robot shows a maximum consumption of 368 W, having an SR of 1.35. The SR is seven times higher than a person walking. (Kashiri et al.)

Servo Motors

Servo motors are motors which can be controlled to move to specific angles. There are motors with 180 rotation and continuous rotation. Servos are controlled by pulses through the signal. "For a normal servo, sending a 1 ms 5v pulse turns the motor to 0 degrees, and sending a 2 ms 5v pulse turns the motor to 180 degrees." (Blum, 2019, 102) Servo motors differ from your average DC motor, as not only can you specifically position the motor, but the servo motor has three pins, one for ground (brown), one for power (red), and one for signal (yellow/orange). (Blum, 2019, 102) A problem that occurred in the initial design was the motors shaking uncontrollably and attaching multiple motors would cause the motors to rattle and stop. The reason this happened was that the Arduino Uno takes 5v and each servo motor takes 4.8v to 6v. Because all the motors were pulling power and the microcontroller, the cable that was providing the power could only supply enough voltage for the microcontroller. This can cause servos to "jitter". (Bräunl, 2013). Another way to avoid the "jitters" through the program is to add slight delays between the calls for each servo. This will increase servo torque. (Bräunl, 2013) This information is important, as this problem was prevalent in both previous year's work, and this year's work, and when it "jitters", it causes a surge in the amount of energy use, which must be prevented.

Powering the Robot

A battery is the best option to provide enough power for all the motors and microcontrollers. A battery is made of multiple cells in a series and comprises three parts: two electrodes (anode and cathode), and an electrolyte. (Beam et al., 2017) There are two types of batteries, rechargeable, and non-rechargeable. The rechargeable batteries can reverse the current to charge themselves. Non-rechargeable and rechargeable batteries both have their advantages. Non-rechargeable batteries have higher capacity, but once they run out of power, change the batteries, which will become more costly, especially if the batteries drain quickly. Rechargeable batteries don't have high capacities, but rechargeable batteries will save money later. Devices that quickly drain batteries often use rechargeable batteries, while low-drain devices use normal batteries. (Beam et al., 2017) With the batteries, there will also be a capacitor. A capacitor comprises two plates that can conduct electricity; sandwiched in between the plates is some sort of insulant. (Brindley, 2016, 58) The capacitor would store extra voltage from the battery. When the robot is consuming an outrageous amount of energy, the capacitor will release the stored energy to help there not be a shortage of power. This project uses an electrolytic capacitor, also known as a polarized capacitor. The electrolytic capacitor is named after the fact that it uses electrolysis to capacitate. This electrolytic action means that it is polarized, unlike most capacitors. (Brindley, 2016, 58)

The reason the capacitor is needed in the first place is because of Ohm's law. Westcott (2020) defines Ohm's law as, "Ohm's Law states that the current (I) between two points is directly proportional to the voltage (V) and inversely proportional to the resistance (R). As an equation, it is written I = V/R". (19) The current isn't proportional to the voltage or inversely proportional to the resistance, but the capacitor will reduce the resistance, making everything proportional. This investigation was critical to the design, as, before the understanding of Ohm's law and energy efficiency, the robot experienced a serious brownout and overheating, almost destroying the microcontroller.

Related Studies

One inspiration for the robot was Ranger. Bhounsule et al. (2012) made Ranger, which walked 40.5 miles completely on its own on a single charge, taking 30 hours, 49 minutes, and 2 seconds, setting a record for robot distance, and it walked at an average Cost Of Transportation of 0.19, which is less than any other legged robot at the time. Ranger has long legs, but does not have knees, instead, he has joints on his ankles, and his legs swing to walk. Its unique 4-legged biped design has it walk similar to a gorilla. The purpose of the study was to create an energy efficient robot that wouldn't fall down as often. The ankle joints were something from Ranger that was originally implemented to this design investigation. However, with the size and amount of energy that the motors took, it was not practical. Instead, I slightly implemented the foot shape of Ranger to create the rocking motion that the legs would need to walk.

Another important study of the development of the robot was the ANYmal. According to Hutter et al. 2016, the ANYmal is a quadrupedal robot that has a lot of range and mobility. The joint modules make the robotic dog's torque controllable and able to withstand the load on the motors during running or jumping. It was stable outdoors, easy to maintain, and user-friendly. ANYmal had different gaits and speeds that it could use and it can stand up or crawl up very steep stairs. The robot can run for 2 hours completely autonomously. Both of these studies are examples of very energy-efficient robots. Ranger and the ANYmal were both able to run long distances on a single charge. These robots set a standard of what should be expected from an energy-efficient robot. They also inspired many aspects of the design of the robot, such as the feet shape and the initial design of the legs.

Conclusion

For now, the energy efficiency of walking robots pales in comparison to wheeled robots or living things. Many designs for a more energy efficient robot have been made, in hopes that they will be used for research or rescue. There should be more research on ways to map out an area during an autonomous run. Designs like the Cheetah have attempted to resolve this issue, however, none have seemingly been able to quickly scan an area and react to it completely autonomously. This design benefited from the research on the cost of transportation and Ohm's law. Understanding the meaning behind the cost of transportation and how to measure it will help to compare to previous designs and if the design improved, both on the robot and other robots previously made by others. Research on Ohm's law was relevant as the high-draining motors would often pull too much power and cause a brownout. Using Ohm's law, improvements in the design, especially the connection of the capacitor and the type of battery used for the robot, significantly lowered the chances of the robot experiencing a brownout. In the future, more research on self-correcting autonomous robots will have to be made to correct the drift that the robot experiences.

Materials

- 9 Miuzei SG90 servo motors with servo horns
- 1 Arduino Uno
- 1 toggle switch
- 1 polarized capacitor 4700µF
- 4 1.5v keeppower rechargeable batteries
- 1 cm thick PVC board
- 22 gauge wire
- 1 laptop
- 1 A male to B male printer cable
- 6 x 3/4 in. flathead Phillip screws
- 1 #0 Phillip screwdriver
- 22 #0-80 x ¾ in. Panhead Phillip screws
- 9 #0-80 x 1/8 in. Panhead Phillip screws
- 1-2 Hot glue sticks
- 1 Hot glue gun
- 1 drill with a Philip drill bit
- 1 Circular saw
- 1 jigsaw
- 1 battery mount with 4 cells
- 2 25-pin circuit boards
- PVC glue
- 1 toothpick
- 1 roll of electrical tape
- 1 roll of masking tape
- 1 stopwatch
- 1 scale
- 1 multimeter

Design Plan

The robot can not take up over 4 1.5v batteries. It must remain relatively small and light, as the bulkiness and weight would add extra strain to the motors, which will cause them to pull more power from the battery to complete the step. The goal of the design is to run on the batteries for more than an hour.

Table 1.1

Design Criteria	What Makes Up this Design Criteria	Importance on a Scale of 1-5
Functionality	• The robot is able to walk for at least 10 secs • The robot walks in a straight line, unless the axis is changed from set position	5
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise	4

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

Part A: Assembling the Robot

Figure 1.1

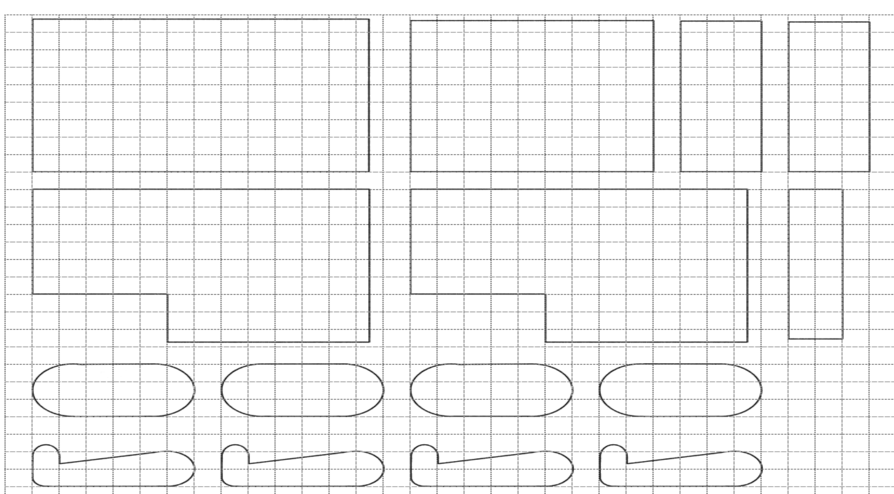

Figure 1.1 shows the pieces cut out of the 1cm thick PVC board, with each square being equal to $1cm^2$.

Figure 1.2

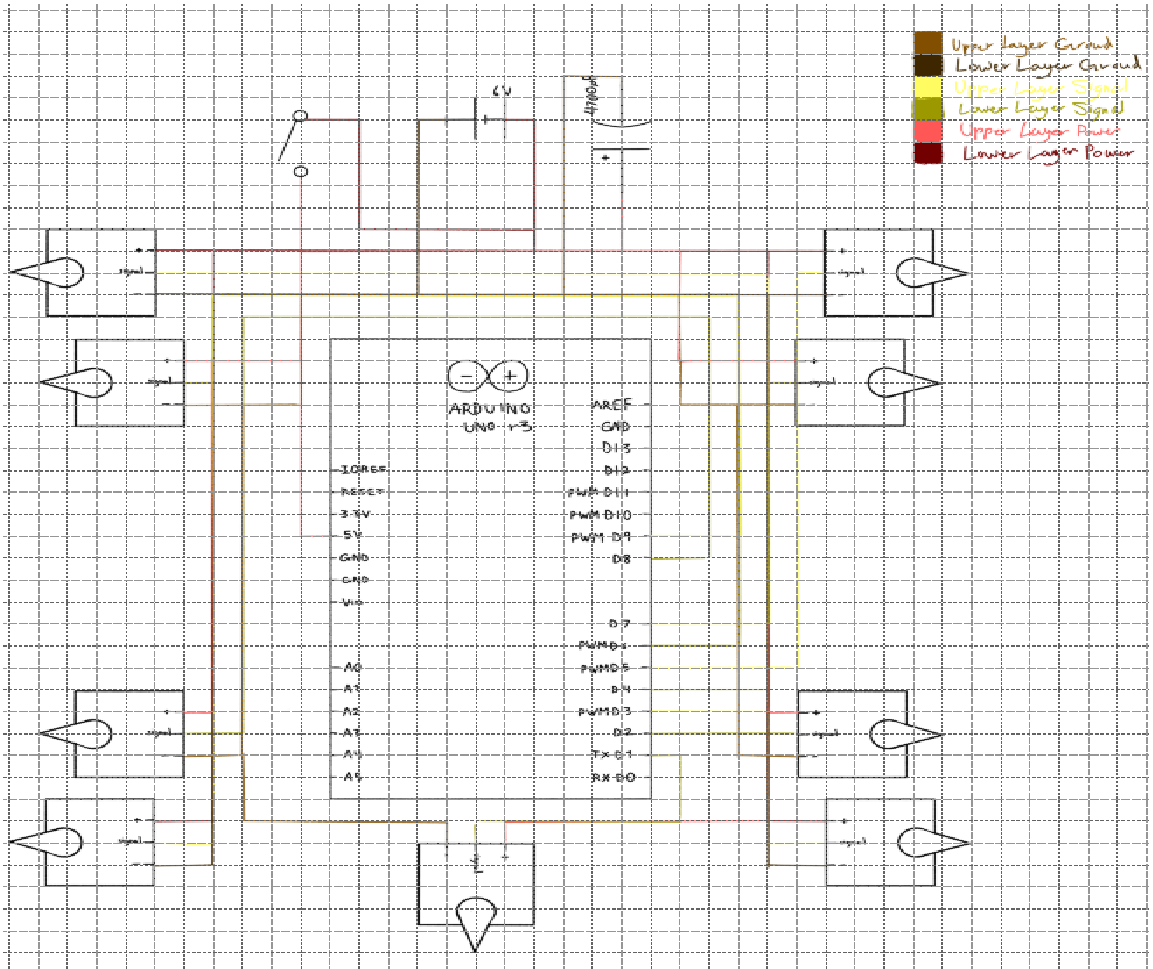

Figure 1.2 is a circuit schematic of the walking robot.

1. Cut out the pieces shown in figure 1.1 with the dimensions shown out of the PVC board.
2. Attach the servo motors to the holes with two #0-80 x ¾ in. pan head Phillip screws per servo motor
3. Attach the 12.5cm x 9.2cm piece to the two “L” pieces on the longer side that faces towards the floor and the 3.2cm x 9.2cm piece using 8 6 x 3/4 in. flathead Phillip screws.
4. Attach the 7.5cm x 9.2cm piece parallel to the 3.2cm x 7.5cm piece to the smaller end of the "L" pieces using 6 6x3/4 in. flathead Phillip screws.
5. Attach the two 7.5cm x 3.5cm pieces using the PVC glue and 4 6 x 3/4 in. flathead Phillip screws.

6. When dried and bonded, carve out 1.3cm x 2.2cm x 1.1cm holes on both ends of the piece using the jigsaw.
7. Attach the two-pong servo horn to the 7.5cm x 3.5cm using two #0-80 x1/8 in. Panhead Phillip screws.
8. Attach the servo horn and PVC to the servo attached to the 12.5cm x 9.2cm piece using a #0-80 x1/8 in. Panhead Phillip screw.
9. Attach the circuit boards to the robot using PVC glue.
10. Attach the Arduino board's plastic cover using 4 #0-80 x ¾ in. pan head Phillip screws.
11. Carve out holes for wires with the jigsaw in the "L" pieces, at the bottom of the robot, in the battery space, and a small hole for each motor at the top of each leg segment.
12. Cut off the prongs of 8 servo horns until only the circular piece is left.
13. Hot glue the circular pieces into the top hole of each leg segment, unclogging the hole with a toothpick. This will allow for easy access later.
14. Screw the leg segments to the motors, with the smooth round pieces at the top, and the smaller pieces with a foot at the bottom go on the bottom using #0-80 x1/8 in. Panhead Phillip screws for each hole.
15. Hot glue extra wire to the edges of the legs, battery space, and axis.
16. Attach the wires, capacitor, toggle switch, and batteries to the Arduino as shown in Figure 1.2

Part B: Coding the Robot

1. Create a new file in the Arduino IDE program.
2. Like in the last program, you will write “#include <Servo.h>” first.
3. Write “Servo” followed by the names of your motor. Repeat for every motor. For organization, the motors are named Axis 1, Shoulder 1, Elbow 1, Shoulder 2, Elbow 2, Hip 3, Knee 3, Hip 4, and Knee 4.

4. Write the initial variables of each motor. There is no certainty that the motors would be placed perfectly in the robot so that 0 points towards the floor. The variables will differ based on the placing of the motors, but at the end, it should point straight down to the floor.
5. Write int variables for some delay. d1= 500, d2=1000, d3=50, d4=75, d5=100, and d6=3000.
6. In void setup() {}, between the brackets write the motors and attach them. For example, "axis1.write(a1); axis1.attach(1);" The order matters here, as it will help the robot stand. The pattern is axis1, hip3, shoulder 1, hip 4, shoulder2, knee3, elbow1, knee4, elbow2. Write the int position from earlier in the () of the .write. Do not forget the delays in between. The first four delays are d1, and the three after that are d2. The last one is d6.
7. Still under void setup() {}, write shoulder2.write(s2-30);, delay(d5);, knee4.write(k4+60);, delay(d5);, hip4.write(h4-30);, delay(d5);, elbow1.write(e1-60);, delay(d5);, shoulder1.write(s1+30);, delay(d5);, knee3.write(k3-60);,delay(d5);, hip3.write(h3+30);, and delay(d6);. The numbers added/subtracted affect the position of the robot for walking, as it cannot walk as well with straight legs. These numbers will be the opposites of each other because of what side they are on.
8. Create a new function called void walk1() {};
9. In void walk1() {}, between the brackets write shoulder2.write(s2-30);, hip3.write(h3+30);, delay(d5);, knee3.write(k3-60);, elbow2.write(e2+60);, delay(d5);, knee4.write(k4+70);, elbow1.write(e1-70);, delay(d5);, shoulder1.write(s1);, hip4.write(h4);, delay(d5);, knee4.write(k4+20);, elbow1.write(e1-20);, delay(d5);, shoulder1.write(s1+30);, hip4.write(h4-30);, delay(d5);, knee4.write(k4+60);, elbow1.write(e1-60);, and delay(d5);.
10. Upload to the Arduino using the A male to B male printer cable to connect the Arduino to the laptop.

Part C: Testing the Robot

1. Mass the robot in kilograms.
2. Fully charge the batteries.

3. Measure the amps of the batteries.
4. Put some masking tape on the floor at the beginning of the hallway
5. Turn on the robot and place it on the floor behind the masking tape
6. Let the robot run in a straight line until it collapses.
7. Put tape where the robot collapsed.
8. Measure the amps of the robot again.
9. Measure the time and distance that the robot traveled.
10. Calculate the Cost of Transportation using the E/Mgd equation, with g being equal to 9.8 m/s^2.
11. Repeat for three trials for the three designs.

Design Results

Table 1.2

Cost of Transportation of Design A

Design A			
	Distance (m)	**Energy Used (V)**	**CoT**
Trial 1	0.10	5.47	0.01
Trial 2	0.54	5.59	0.04
Trial 3	1.20	5.35	0.08
Trial 4	0.14	5.21	0.00
Trial 5	1.02	5.53	0.00
Mean	**0.60**	**5.43**	**0.03**
SD	**0.45**	**0.14**	**0.03**
SE	**0.26**	**0.08**	**0.02**

Table 1.2 shows the distance walked in meters, the energy used in volts and the cost of transportation across five trials.

Figure 1.3

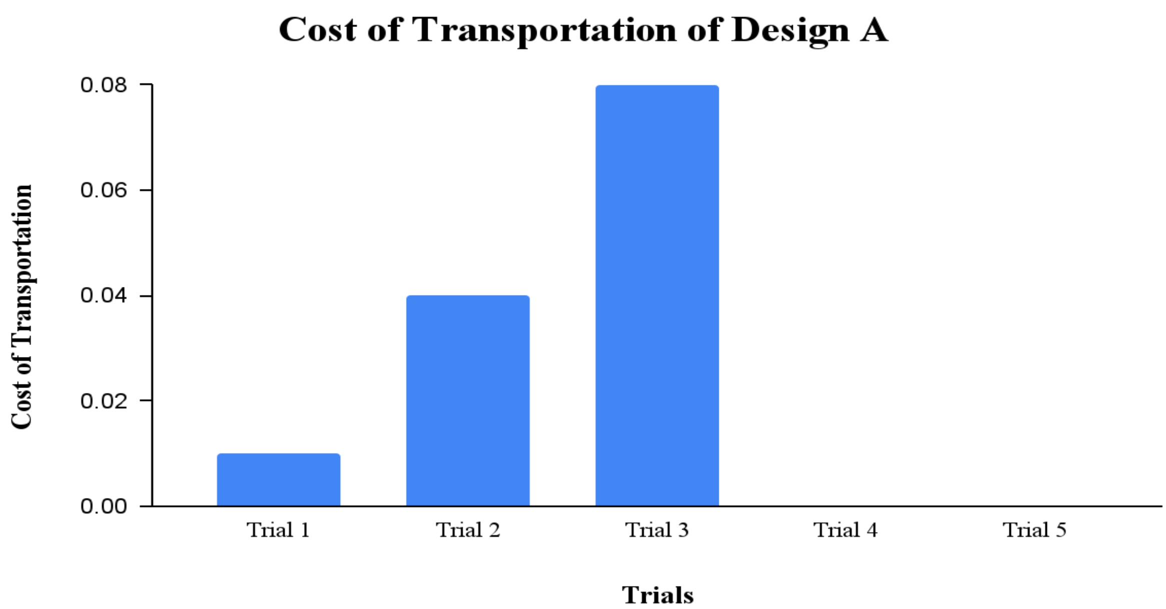

Figure 1.3 shows the cost of transportation of Design A through five trials.

Table 1.3

Design Criteria	What Makes Up this Design Criteria	Completion of on a Scale of 1-5
Functionality	• The robot is able to walk for at least 10 secs • The robot walks in a straight line, unless the axis is changed from set position	2
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise	5

Table 1.3 shows the completion of the design criteria for Design A.

Redesign Plan

Although the cost of transportation for Design A was low, there was a severe problem with the gait. The robot would not walk straight. Instead it would buck back and forth, often moving sideways instead of forward. One thing that could have caused the robot's jerking movement was the rapid movement of the motor. When the motor was called, the motor would instantly move to the new position. The delays only slightly fixed this issue. The best way to fix this was to create for functions that would make sure that the motors would slowly get to the new position a few degrees at a time.

Part D- Redesigning the Code

1. Create a new function called void walk3() {};
2. In void walk3() {}, between the brackets, insert for (m = 0; m <= 12; m += 1) {};
3. In the brackets of the for function, write: knee3.write(k3-60-m); delay(0); elbow2.write(e2+60+m); delay(15);
4. Write another for function for (m = 0; m <= 30; m += 1) {};
5. In the brackets for the second for function, write: shoulder2.write(s2-30+m); delay(0); hip3.write(h3+30-m); delay(15);
6. Insert function for (m = 0; m <= 24; m += 1) {};
7. In the brackets, write: knee3.write(k3-72+m); delay(0); elbow2.write(e2+72-m); delay(15);
8. Insert for (m = 0; m <= 30; m += 1) {}
9. Write in the brackets of the for function: shoulder2.write(s2-m); delay(0); hip3.write(h3+m); delay(15);
10. Write for (m = 0; m <=12; m += 1){};
11. In the brackets, write: knee3.write(k3-48-m); delay(0); elbow2.write(e2+48+m); delay(15);
12. Write for (m = 0; m <= 12; m += 1) {};
13. In brackets, write: knee4.write(k4+60+m); delay(0); elbow1.write(e1-60-m); delay(15);

14. Write for (m = 0; m <= 30; m += 1) {};
15. In brackets, write: shoulder1.write(s1+30-m); delay(0); hip4.write(h4-30+m); delay(15);
16. Write for (m = 0; m <= 24; m += 1) {};
17. In brackets, write: knee4.write(k4+72-m); delay(0); elbow1.write(e1-72+m); delay(15);
18. Write for (m = 0; m <= 30; m += 1) {};
19. In the brackets, write: shoulder1.write(s1+m); delay(0); hip4.write(h4-m); delay(15);
20. Write for (m = 0; m <=12; m+= 1){};
21. In brackets, write: knee4.write(k3+48+m);delay(0); elbow1.write(e2-48-m);delay(15);

Redesign Results

Table 1.4

Cost of Transportation of Design B

Design B

	Distance (m)	Energy Used (V)	CoT
Trial 1	6.44	5.89	0.38
Trial 2	2.15	5.32	0.14
Trial 3	2.09	5.67	0.15
Trial 4	1.54	5.58	0.00
Trial 5	1.65	5.71	0.00
Mean	**2.77**	**5.63**	**0.13**
SD	**1.85**	**0.19**	**0.14**
SE	**1.07**	**0.11**	**0.08**

Table 1.4 shows the distance in meters, the energy used in volts, and the cost of transportation across five trials.

Figure 1.4

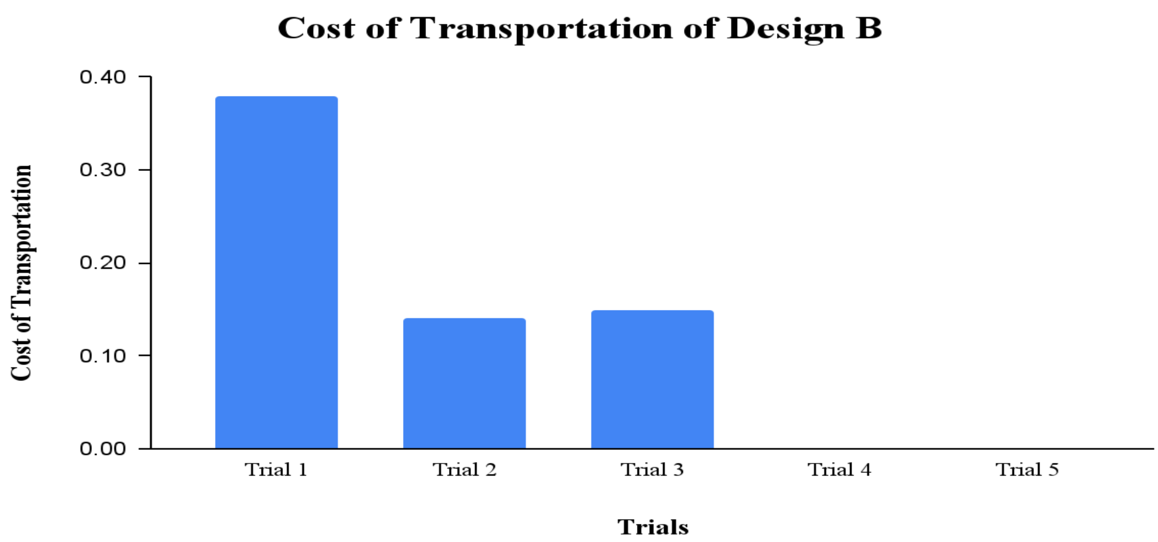

Figure 1.4 shows the cost of transportation of Design B across five trials.

Table 1.5

The Effect of Distance (m) and Energy Used (V) on Cost of Transportation

	Design A			**Design B**		
	Distance (m)	**Energy Used (V)**	**CoT**	**Distance (m)**	**Energy Used (V)**	**CoT**
Trial 1	0.10	5.47	0.01	6.44	5.89	0.38
Trial 2	0.54	5.59	0.04	2.15	5.32	0.14
Trial 3	1.20	5.35	0.08	2.09	5.67	0.15
Trial 4	0.14	5.21	0.00	1.54	5.58	0.00
Trial 5	1.02	5.53	0.00	1.65	5.71	0.00
Mean	**0.60**	**5.43**	**0.03**	**2.77**	**5.63**	**0.13**
SD	**0.45**	**0.14**	**0.03**	**1.85**	**0.19**	**0.14**
SE	**0.26**	**0.08**	**0.02**	**1.07**	**0.11**	**0.08**

Table 1.5 shows the distance, energy used, and cost of transportation of design A and design B.

Figure 1.5

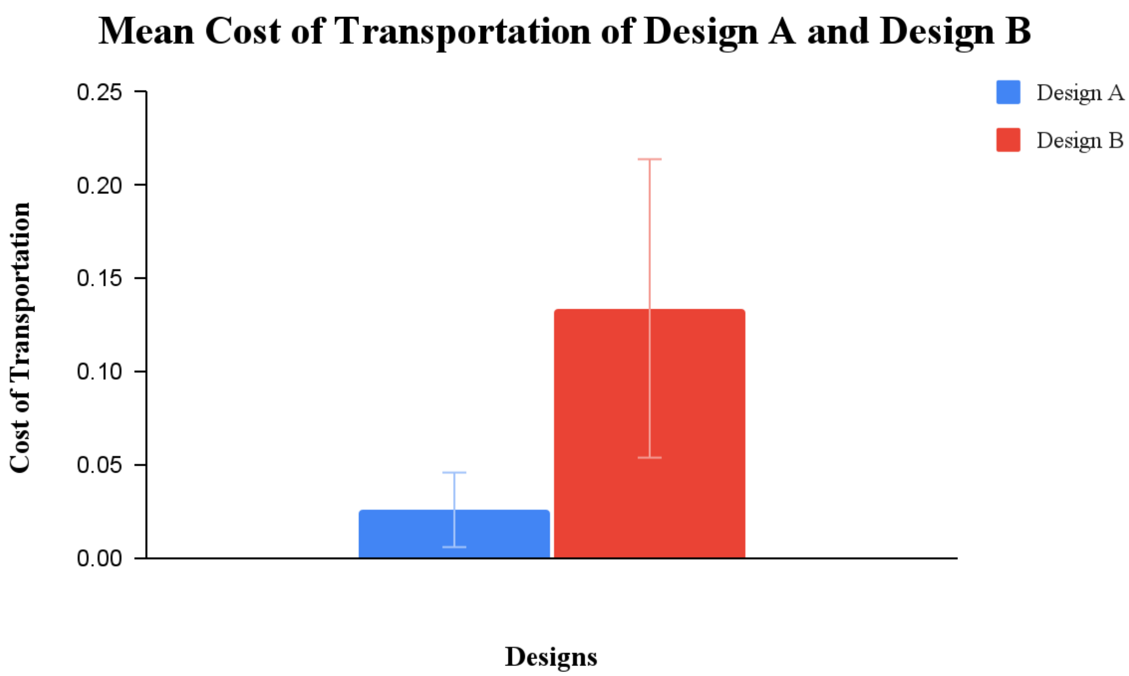

Figure 1.5 shows the mean cost of transportation between the two designs.

Table 1.6

Design Criteria	What Makes Up this Design Criteria	Completion of on a Scale of 1-5
Functionality	• The robot is able to walk for at least 10 secs • The robot walks in a straight line, unless the axis is changed from set position	4
Energy-Efficiency	• The robot has a median cost of transportation of around .15 or less • The cost of transportation is precise	4

Table 1.6 shows the completion of the design criteria for Design B.

Conclusion

The redesign improved the distance achieved by the robot, however, the average cost of transportation was affected negatively by the redesign. One reason for this could be that the for function has the motors pull less energy, but it's over more time, and because the motors are moving two at a time, versus the one-at-a-time movement of Design A, this caused the motors to pull more energy from the robot, with negatively affected their cost of transportation. However, Design A could barely walk, as it was jumping in all directions and could not move stably in one direction. By this logic, the poor performance of the robot should have negatively affected the cost of transportation, however, when the calculations were made, the robot was given a very low cost of transportation, even giving costs of transportation of 0.0 for both Designs A and B during Trials 4-5. These costs of transportations are probably an error. However, the more realistic scores of Design B were very good as well, especially in Trials 2-3, with scores of .14 and .15 respectively. Because of the higher cost of transportation in Trial 1 and the scores given to Design A being impossibly low, the average cost of transportation seems a lot higher than it was.

There were many errors in this investigation. For example, the robot does not walk in a straight line, so the distance measurements are not perfect, especially in Trial 1 of Design B, as the robot walked in a circle and then continued in a straight line as before, and the circle affected the accuracy of the distance the robot walked. The cause of the robot walking in a circle is unknown, and the robot hasn't done it since the first trial. The problem is also shared with all of Design A, with its jerking back and forth messing up the distance, as seen with the high standard errors of the distances (0.26 for Design A and 1.07 for Design B). Next year, the robot will have gyros attached to it to keep the robot in a straight line.

The purpose of this robot was to create an energy-efficient robot so that it would be more reliable for certain tasks which may not allow for the robot to be frequently recharged or constantly draining energy. However, as this design investigation shows, the cost of transportation is only a part of the equation of a reliable, energy-efficient robot. For example, Design A may be energy efficient but not reliable. Either way, the robot reached its goal of being relatively energy-efficient and reliable. However, many more changes can be made to improve the robot's reliability. Next year, the robot will become autonomous, making it easier to complete tasks without human control or supervision, as needed for any useful real-world applications.

Reference List

Beam, R, Wilkin, M. K., Kuszynski, J.,& Darensbourg M. Y. (2017) Batteries: rechargeable vs. non-rechargeable batteries. Texas A&M University.https://www.chem.tamu.edu/rgroup/marcetta/chem362/HW/2017%20Student%20Posters/Batteries-%20Rechargeable%20vs.%20Non-rechargeable%20Batteries.pdf

Bellicoso, D., Bjelonic, M., Wellhausen, L. & Holtmann, K. (2018) Advances in real-world applications for legged robots. Journal of Field Robotics. DOI:10.1002/rob.21839

Bhounsule, P. A., Cortell, J., & Ruina, A. (2012). Design and control of ranger: An energy efficient, dynamic walking robot. Adaptive Mobile Robotics, 441–448. https://doi.org/10.1142/9789814415958_0057

Biswal, P. & Mohanty P. K. (2020). Development of quadruped walking robots: A review. *Ain Shams Engineering Journal*, 12(2).https://doi.org/10.1016/j.asej.2020.11.005

Bräunl, T (2013) Embedded robotics: Mobile robot design and applications with embedded systems. Springer Berlin Heidelberghttps://www.google.com/books/edition/Embedded_Robotics/5rntCAAAQBAJ?hl=en&gbpv=0

Brindley, K. (2016) Starting electronics: All you need to get a grounding in practical electronics. Elsevier Science. https://www.google.com/books/edition/_/PQP9BAAAQBAJ?hl=en&gbpv=0

Blum, J. (2019) *Exploring arduino: Tools and techniques for engineering wizardry.* Wiley.https://www.google.com/books/edition/Exploring_Arduino/XQm5DwAAQBAJ?hl=en&gbpv=0

Gong, D., Wang, P., Zhao, S., Du, L. & Duan, Y. (2018) *Bionic quadruped robot dynamic gait control strategy based on twenty degrees of freedom.* IEEE. 10.1109/JAS.2017.7510790

Hutter, M., Gehring, C., Jud, D., Lauber, A., Bellicoso, C. D., Tsounis, V., Hwangbo, J., Bodie, K., Fankhauser, P., Bloesch, M., Diethelm, R., Bachmann, S., Melzer, A., & Hoepflinger, M. (2016). ANYmal:A highly mobile and dynamic quadrupedal robot. 2016 IEEE/RSJ International

Conference on Intelligent Robots and Systems (IROS). https://doi.org/10.1109/iros.2016.7758092

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

Kashiri 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

Morris, A. (2022) Tiny robotic crab is smallest-ever remote-controlled walking robot. Northwestern. https://news.northwestern.edu/stories/2022/05/tiny-robotic-crab-is-smallest-ever-remote-controlled-walking-robot/

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

Patterson, M. (1996) What is energy efficiency? Concepts, issues and methodological issues. Energy Policy, 24(5).https://www.researchgate.net/publication/222171789_What_is_energy_efficiency_Concepts_issues_and_methodological_issues

Saunders, H. et al. (2021) Energy efficiency: What has research delivered in the last 40 years? Annual Review of Environment and Resources, 46.https://doi.org/10.1146/annurev-environ-012320-084937

Todd, D. J. (2013). *Walking machines*. Springer US.https://www.google.com/books/edition/Walking_Machines/zb_SBwAAQBAJ?hl=en&gbpv=0

Westcott, S., & Westcott J. R. (2020) Basic electronics: Theory and practice. Mercury Learning and Information.https://www.google.com/books/edition/Basic_Electronics/mkbrDwAAQBAJ?hl=en&gbpv=0

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. https://doi.org/10.1088/1742-6596/1969/1/012003

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