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Department of Aerospace Engineering
Faculty of Engineering & Architectural Science

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Submission by (Name):	**Student ID (XXXX1234)**	**Signature**
Babak Nassir Tafreshi	XXXXX3125	Tafreshi
Anton Bic	XXXXX8254	
Alan Rehani	XXXXX2820	Alan Rehani
Keith Ayok	XXXXX5022	KAyok

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Executive summary

This report documents the comprehensive process undertaken by our team to design, develop, and compete with a walking robot, aligned with the specifications and requirements set forth by the project outline. The project's goal was not merely to build a robot but to engineer a mechanism that could effectively translate motor rotation into a bipedal or multi pedal walking motion, capable of traversing a 3-meter track. This challenge required a blend of mechanical engineering principles, creativity in design, and practical problem-solving skills.

Design Phase

In the initial phase, our team embarked on a detailed survey of various walking robot mechanisms. This exploration was guided by a set of criteria that prioritized efficiency, stability, and the practicality of constructing the mechanism within the constraints of the provided materials. Out of numerous concepts reviewed, three distinct designs emerged as candidates for further development:

- Design 1: Experimented with another crank-rocker mechanism but with a different structure
- Design 2: Utilize crank-rocker mechanism for simplicity and ease of assembly
- Design 3: Leveraged crank-slider mechanism to obtain maximum velocity and efficiency

Each design underwent a thorough analysis using MATLAB simulations to visualize the walking motion and conduct velocity analyses. These simulations were crucial in identifying the strengths and weaknesses of each mechanism, informing our decision-making process.

Materials chosen for the robot's body were predominantly 1/8" thick Medium-Density Fiberboard (MDF), with selective use of corrugated cardboard for non-load-bearing sections and ABS plastic for parts requiring complex shapes or higher flexibility. The selection of materials was influenced by their weight, structural properties, and the ability of the lab to provide them.

Construction Phase

The construction phase was marked by planning and execution. MDF (Medium-density Fiberboard) was laser-cut to form the robot's main frame and the components of the walking mechanism, ensuring both strength and precision where needed. The assembly was carried out with an assortment of fasteners and adhesives, chosen based on their suitability for different materials and structural requirements, and the motor was mounted on the structure.

Throughout the assembly process, the team focused on optimizing the robot's weight distribution and ensuring the durability of the walking mechanism. These considerations were crucial for the robot's ability to maintain balance and achieve efficient forward motion.

Testing and Optimization

Subsequent to assembly, the robot underwent a rigorous testing regimen. This phase was essential for diagnosing and rectifying any issues related to stability, efficiency of the walking mechanism, and overall speed. Feedback from these tests led to iterative adjustments in the design, particularly targeting the enhancement of the walking mechanism's movement to increase stride length and minimize energy expenditure.

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Table of Content

1. Introduction

1.1. Introduction and Challenges

The evolution of robotics has always been one of the popular fields of engineering, blending complex mechanical systems with innovative control strategies to create machines capable of performing an array of tasks. Among the various challenges in robotics, achieving efficient bipedal or multi pedal locomotion remains a significant engineering challenge, requiring a sophisticated understanding of mechanics, dynamics, and control. This project is centered around the development of a walking robot, a machine that must effectively translate rotary motion into linear walking motion without the use of wheels, embodying the principles and challenges of robotic locomotion.

1.2. Project Scope and Objectives

The objective of this project is to design, build, and test a walking robot capable of crossing a predefined track of 3 meters as quickly as possible. This entails the development of a robot that uses mechanical linkages to convert the rotational output of a motor into a functional walking motion. The design constraints specify that no wheels or purely rotational motions are employed in the primary locomotion mechanism, presenting a unique challenge that requires innovative thinking and practical engineering skills.

This project is not only a practical application of mechanical engineering principles but also an exploration into the more complex aspects of robotics. The ability to design a walking robot that can successfully navigate a straight track underlines fundamental concepts of dynamics and control systems, which are critical in broader applications such as autonomous vehicles, prosthetics, and other areas where robotic mobility is essential.

By undertaking this project, students are expected to gain hands-on experience in:

- Designing mechanical systems that involve complex motion and force analysis.
- Applying theoretical knowledge from coursework to solve real-world problems.
- Collaborating in teams to manage, divide, and execute project tasks effectively.

- Developing skills in documenting and presenting technical work in a clear and structured manner.

The following sections will detail the design selection process, describe the mechanisms chosen, and discuss the analyses and outcomes of the constructed prototypes leading up to the competition. This report aims to showcase the innovative solutions and collaborative efforts that went into creating the walking robot, reflecting both on the successes achieved and the lessons learned throughout the project.

1.3. Background

1.3.1. Summary

Walking robots, also known as legged robots, represent a fascinating intersection of mechanical engineering, control theory, and biomimicry. Unlike wheeled robots, which rely on continuous contact with the ground, walking robots mimic the discrete step-taking action of biological organisms. This approach offers potential advantages in terms of maneuverability and adaptability to varied terrain, echoing the capabilities of animals and humans. The theoretical underpinnings of walking robots are grounded in several key areas:

1.3.1. Dynamics and Kinematics

The movement of walking robots is governed by the principles of dynamics and kinematics. Kinematics focuses on the motion of points, bodies, and systems of bodies without considering the forces that cause them to move. In the context of walking robots, kinematics involves understanding how the movement of individual legs—or segments thereof—translates into the overall motion of the robot. Dynamics, on the other hand, involves the forces and torques that cause motion, essential for designing robots that can efficiently propel themselves forward.

1.3.2. Stability and Control

Maintaining stability during walking is a critical challenge for legged robots. This is often addressed through control strategies that manage the robot's center of mass and ensure that at least one foot remains on the ground at all times, preventing the robot from falling over. Dynamic stability involves the robot's ability to maintain balance while in motion, a more complex challenge that requires sophisticated control algorithms. These might include feedback loops that adjust the robot's motion in real-time based on sensor input.

1.3.3. Energy Efficiency

Energy efficiency is a crucial consideration in the design of walking robots. The actuation systems must be designed to optimize the use of power, minimizing energy waste during movements such as lifting, advancing, and placing the legs. This involves careful selection of materials, actuators, and the design of the mechanism itself to ensure that the robot can operate for extended periods without requiring excessive energy consumption.

In summary, the development of walking robots encompasses a broad spectrum of theoretical and practical challenges. Success in this field requires an interdisciplinary approach, combining insights from mechanical engineering, control theory, biology, and computer science to create machines that can navigate the physical world with the grace and efficiency of living organisms.

2. Design selection

2.1 Design objectives

1. Stability
    a. Minimize sway and range of inclination/rotation
2. Simplicity
    a. Joints and linkage design with least complexity
        i. For reliability
        ii. For assembly

3. Efficiency
    a. Minimizes energy losses in locomotion and power transfer from motor to transmission to the ground for propulsion is efficient
4. Mechanism type
    a. Constraint of no rotational motion including wheels

2.2 Design selection process

2.2.1. Design 1

Design 1 employs a four-bar double crank mechanism, uniquely configured with the coupler link extended beyond its joint with the input crank. This extension is critical for providing ground traction, which propels the robot forward. The mechanism's simplicity not only facilitates ease of assembly and manufacturing but also enhances durability, ensuring reliable performance over repeated use.

Stability and Efficiency

Although this design exhibits operational efficiency, the relatively long lengths of the links and their inherent movement dynamics result in a large displacement path for the output links. This extensive path may induce excessive sway during operation, potentially affecting the robot's stability. Careful consideration must be given to this factor, as it influences the overall balance and effectiveness of the robot's motion.

Power Transmission and Efficiency

A significant concern with this design is the potential loss of power due to the motion dynamics of the output links. Instead of directly propelling the robot forward, some of the motor's power is dissipated in the lateral movement of these links. This inefficiency is further illustrated by the fluctuating velocity profile of the mechanism, indicating varying power output levels throughout the robot's stride. At certain points in the motion cycle, there is substantial power transfer inefficiency, which could hinder the robot's performance in terms of speed and consistency.

Compliance with Design Constraints

One of the key advantages of Design 1 is its compliance with the specified project constraint against rotational motion. The output links of this mechanism perform a rocking motion back and forth, which effectively avoids producing a circular displacement path. This attribute ensures that the design adheres strictly to the competition's rules, focusing on a reciprocating motion that aligns with the project guidelines.

Conclusion

While Design 1 demonstrates a commendable simplicity and meets essential project constraints, its efficiency and stability under operational conditions require careful scrutiny. The large displacement paths and associated sway might compromise the robot's stability, and the inefficiencies in power transfer could impact its competitive performance. Enhancements in link configuration and possibly incorporating dampening elements to mitigate sway could be considered to optimize this design for better performance.

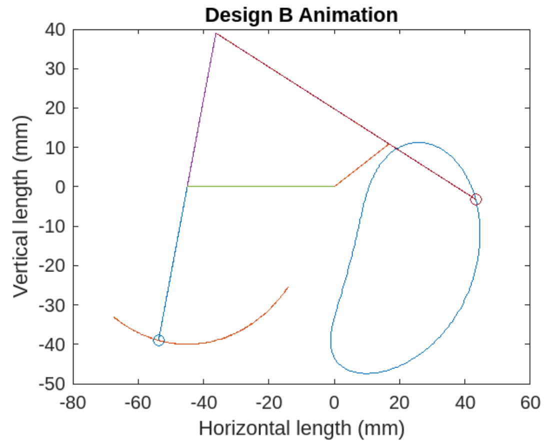

Figure 1 - Displacement Analysis of Design 1

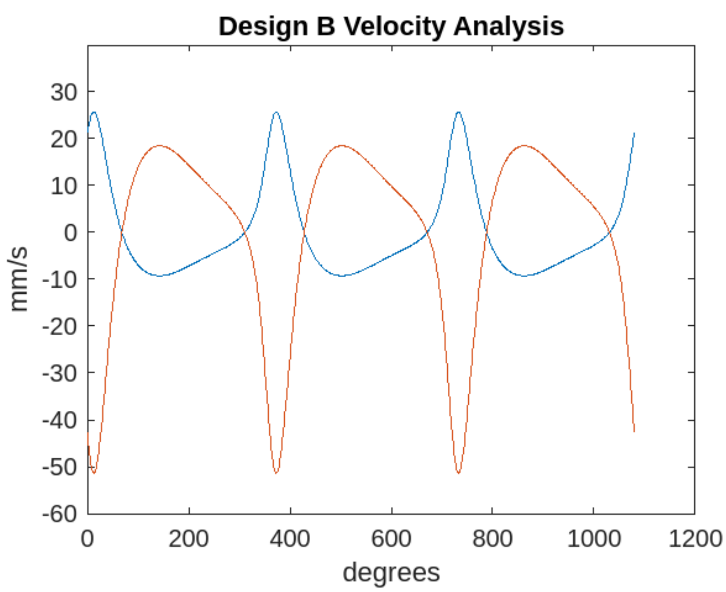

Figure 2 - Velocity Analysis of Design 1

2.2.2. Design 2

Design 2 incorporates a double crank four-bar linkage mechanism, which features an innovative three-sided bar as one of its links. The apex of this triangular link, situated between the two equilateral sides, serves as the primary contact point with the ground. This unique feature aims to enhance the robot's stability compared to previous iterations.

Stability and Motion Dynamics

This design represents an advancement in stability over its predecessors, though it still exhibits some challenges associated with large displacement of the output links. These dynamics result in noticeable sway and forward inclinations during operation, which could potentially impact the robot's directional control and overall balance. Addressing these issues will be crucial for optimizing the robot's performance in competitive settings.

Assembly and Durability

The assembly process for Design 2 is notably straightforward, making it easily replicable and quick to construct. This simplicity is a significant advantage, facilitating faster assembly times and reducing complexity during the manufacturing phase. Furthermore, the use of a common four-bar double crank mechanism contributes to the design's durability. This tried-and-tested mechanical configuration is known for its reliability and resilience, suggesting that the robot will maintain its integrity even after extensive usage.

Power Transfer Efficiency

However, a potential drawback of this design lies in its power transfer efficiency. As illustrated in Figure 4, the design displays a broad velocity profile, which suggests a wide range of power outputs throughout its operational cycle. This variability could lead to significant disparities between power input and power output, resulting in higher inefficiency values. Such inefficiencies could diminish the robot's effectiveness, particularly in terms of energy usage and operational endurance during the race.

Compliance with Design Constraints

A key feature of Design 2 is its compliance with project constraints concerning the nature of motion. The path described by the links avoids purely circular movements, adhering to the competition rules that prohibit rotational motion. This adherence to the guidelines ensures the design remains eligible and competitive within the stipulated project framework.

Conclusion

In summary, while Design 2 offers improved stability and simplicity in assembly, it faces challenges with power efficiency and control during motion due to the large displacement of output links. Future refinements might focus on optimizing link geometry and enhancing control mechanisms to reduce sway and improve power efficiency. This design's strong adherence to project constraints and its robust assembly attributes make it a promising candidate for further development and potential application in the competition setting.

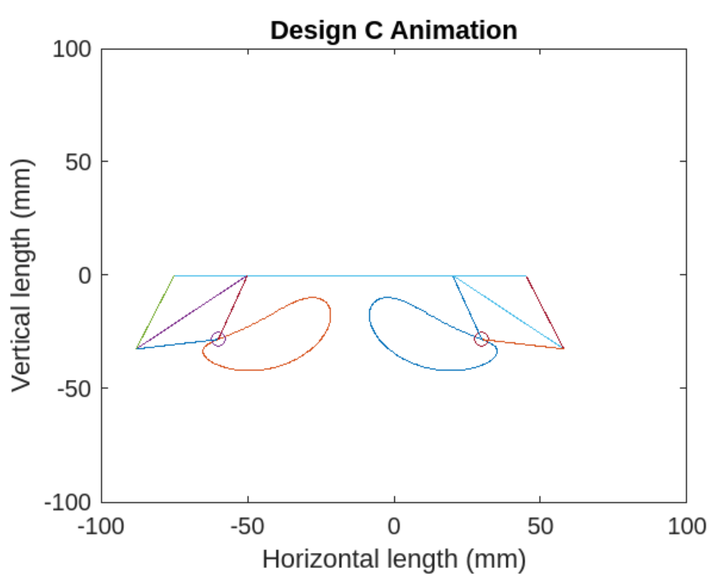

Figure 3 - Displacement Analysis of Design 2

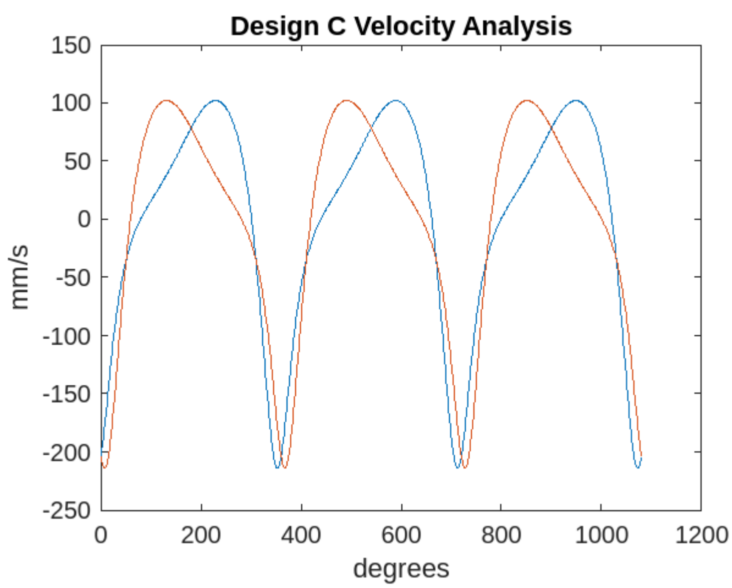

Figure 4 - Velocity Analysis of Design 2

2.2.3. Design 3

Design 3 implements an innovative crank-slider mechanism that is mirrored to synchronize the motion of both the front and back legs, utilizing a single crank driven by the motor. This design optimizes the robot's locomotion by linking the crank to one corner of a triangular link, with another corner connected to a slider. This configuration results in a streamlined, low-profile displacement that significantly enhances the robot's stability by minimizing sway and unnecessary inclination.

Stability and Assembly Efficiency

The low displacement profile inherent to this design substantially improves stability, making it particularly well-suited for environments requiring precise, controlled movements. Furthermore, the simplicity of the crank-slider mechanism means there are fewer parts involved, which simplifies assembly and reduces the likelihood of mechanical failures. This aspect is critical for ensuring quick build times and enhancing the overall reliability of the robot under competitive conditions.

Endurance and Wear Considerations

However, one area of concern is the slider component, which may experience relatively high levels of friction during operation. This friction could lead to increased wear and tear, potentially shortening the lifespan of the mechanism or causing mechanical inefficiencies over time. While endurance is not the primary concern given the short duration of a 3-meter race, it is important to consider the implications of wear for longer-term applications or repeated uses in similar competitive scenarios.

Power Transfer Efficiency

According to the angular velocity profile shown in Figure 6, Design 3 demonstrates a more consistent range of values over time compared to the previous designs. This consistency indicates a more uniform power transfer from the motor to the ground, which likely increases the overall power efficiency of the robot. By minimizing fluctuations in power output, this design ensures more effective utilization of energy, reducing instances of power waste and enhancing the robot's performance during the race.

Compliance with Design Constraints

Furthermore, Design 3 adheres to the project constraints by avoiding purely rotational movements in its mechanism. This compliance not only aligns with the competition rules but also demonstrates the design's capability to achieve locomotion through alternative mechanical motions, broadening its applicability and innovation potential.

Conclusion

Overall, Design 3 offers a robust solution that balances stability, efficiency, and simplicity in assembly. While considerations around the wear of the slider component suggest areas for future improvement, the design's effective power transfer and adherence to movement constraints make it a strong candidate for the 3-meter race and potentially other applications requiring reliable and efficient robotic locomotion.

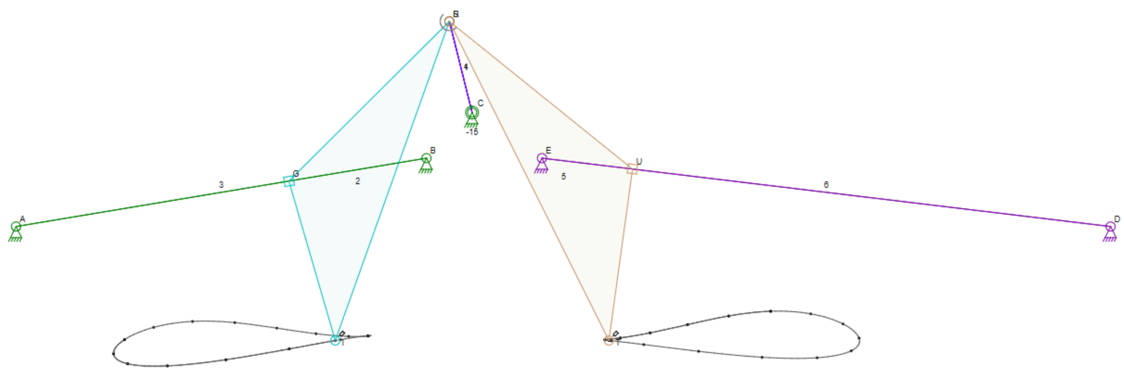

Figure 5 - Displacement of Design 3

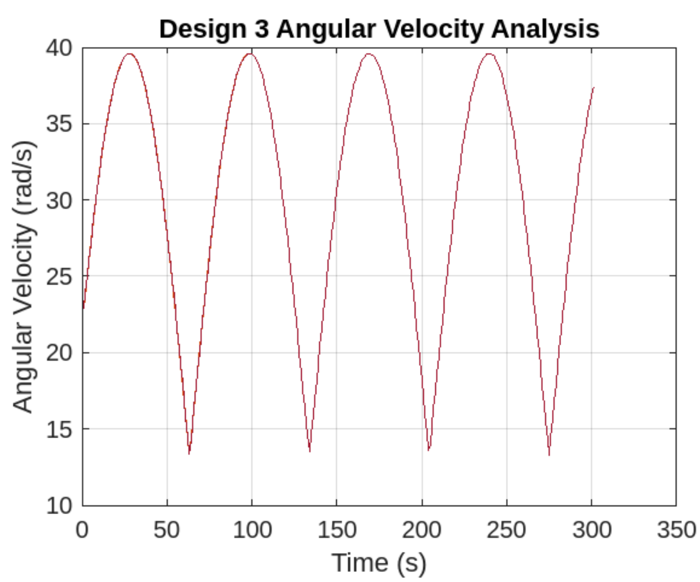

Figure 6 - Angular Velocity Analysis for Design 3

3. Final design

3.1. Design for manufacturing

The final design selected for our walking robot was Design 3, as it met our criteria for efficiency and practicality. The robot's design was meticulously developed using SolidWorks, a sophisticated CAD software that enabled precise modeling and verification of dimensions and feasibility.

3.2. CAD Modeling and Preparation

In SolidWorks, each component of the robot was carefully designed to ensure proper fit and function. This initial phase was critical as it allowed us to visualize the assembly and make necessary adjustments before proceeding to manufacturing. The accuracy and detail in this stage were crucial to the success of the subsequent manufacturing processes.

3.3. Laser Cutting Process

For the manufacturing of the robot, laser cutting was identified as the preferred method due to its precision and efficiency. To prepare for laser cutting, each component was laid out in a SolidWorks drawing file. These files were then converted into DXF formats, which are compatible with the laser cutter software, ensuring a seamless transition from design to manufacturing.

3.4. Prototype Testing

Consistent with our strategic emphasis on iterative development and testing, a decision was made to manufacture one side of the robot initially. This approach, as depicted in the accompanying figure, was intended to test the functionality of the mechanism and to identify any potential issues early in the manufacturing process. This step was crucial for validating the design under practical conditions and allowed for necessary refinements before committing to the full production of the robot.

The section of the robot to be first manufactured and tested is illustrated below. This phased manufacturing approach aligns with our goals outlined in the Testing and Optimization section of this report, underscoring our commitment to a methodical and measured approach to design validation and refinement.

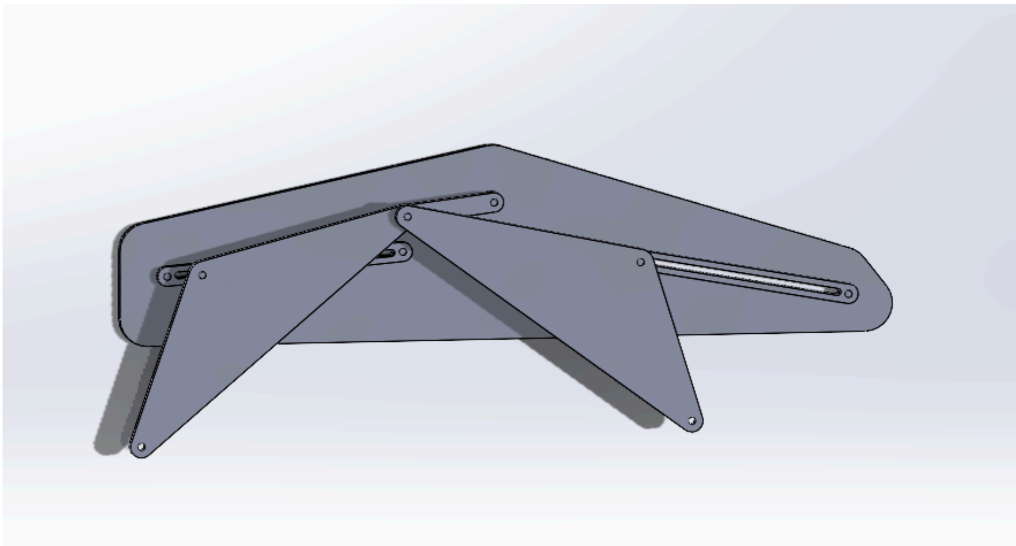

Figure 7 - Prototype for testing and finding problems

From this we could notice and make some changes such as the thickness of the legs and sliders from the holes which needed to be made enlarged significantly, also sanding the slider guide where the screws would go through to reduce friction.

Almost all of the parts for this robot were made using MDF and the rest were plastic washers and metal screws and bolts.

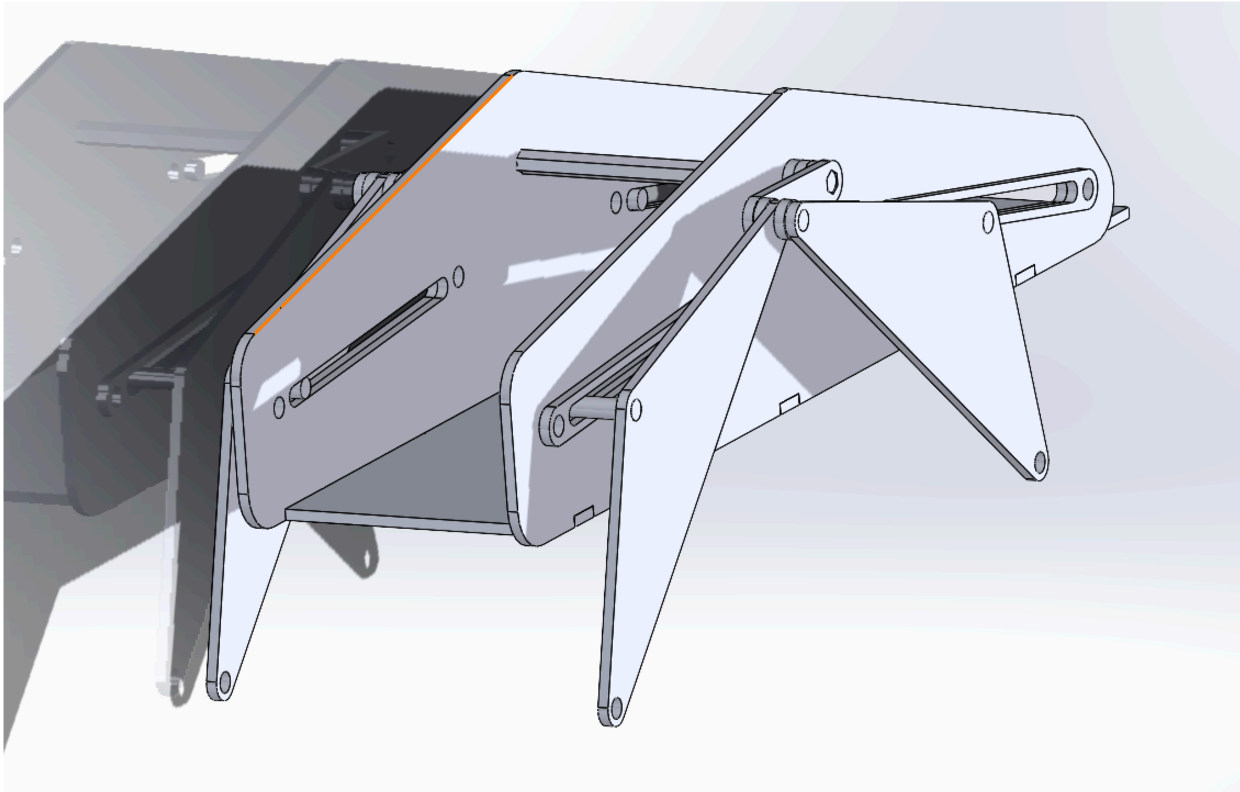

Figure 8 - Isometric View

4. Conclusions

Upon comprehensive evaluation and comparison of three distinct robotic designs intended for a 3-meter race, our analysis unequivocally identifies Design 3 as the most suitable option. This design excels in its ability to efficiently convert the motor's power into effective leg movements, ensuring optimal traction and propulsion across the track. Our decision is supported by rigorous assessments aligned with critical design objectives—stability, simplicity, efficiency, and compliance with designated constraints, which collectively underscore the design's superiority.

4.1. Design Merits and Analytical Justification

Design 3 stands out due to its streamlined mechanical configuration, which not only enhances the ease of manufacturing and maintenance but also minimizes the potential for operational failures. The stability offered by this design ensures that the robot maintains balance and consistent motion, a crucial factor for uninterrupted progress during the race.

Efficiency, a pivotal criterion, is markedly pronounced in Design 3, with its direct and effective energy transfer mechanism from the motor to the legs. This design adheres to the competition's stringent constraints, fully utilizing allowed materials and technologies without transgressing prescribed limits.

Detailed analytical evaluations, including displacement and velocity analyses, provided quantifiable data supporting this design choice. Displacement analysis confirmed optimal part movement relative to the overall mechanism, reducing stress and enhancing efficiency during walking. Velocity analysis projected that Design 3 would achieve the fastest times over the 3-meter distance, an essential advantage in the competitive environment.

Moreover, the mechanism analysis revealed an effective conversion of rotary motion into linear motion, pivotal for achieving a seamless and functional gait cycle. This analysis confirmed that the robot's walking mechanism is not only theoretically sound but also practically viable.

5. Workload distribution chart

Task	Name
Preliminary Research	- Mechanism/idea generation: Anton, Keith, Alan, Babak
Animation/MATLAB	- MATLAB animation, displacement analysis, velocity analysis: Alan, Anton
Report	- Executive summary: Babak - Introduction: Babak - Design Selection: Anton - Final Design: Keith, Anton - Conclusion: Anton
Manufacturing and Assembly	- CAD and manufacturing: Keith, Babak - Assembly: Keith, Babak, Alan

6. Appendix I: MATLAB code Appendix II:

Design 1 MATLAB code:

```
clc
close all
clear
%defining the link lengths
r1 = 45;
r2 = 20;
r3 = 60;
r4 = 40;
rBE = -30;
alpha = 0;
w2 = 8.5*2*pi/60;
for i = 0:1:360*3
%Calculates values
theta2(i+1) = -i;
BD(i+1) = sqrt(r1^2 + r2^2 - 2*r1*r2*cosd(theta2(i+1)));
phi_4(i+1) = acosd((r3^2 + r4^2 - r1^2 - r2^2 + 2*r1*r2*cosd(theta2(i+1)))/(2*r3*r4));
phi_3_prime(i+1) = acosd((r2^2 + BD(i+1)^2 - r1^2)/(2*r2*BD(i+1)));
phi_3_double_prime(i+1) = acosd((r3^2 + BD(i+1)^2 - r4^2)/(2*r3*BD(i+1)));
%Calculates phi 3 based on which branch it is in
if i < 180
phi_3(i+1) = -phi_3_prime(i+1) + phi_3_double_prime(i+1);
elseif i < 180+360 && i >= 360
phi_3(i+1) = -phi_3_prime(i+1) + phi_3_double_prime(i+1);
elseif i < 180+360*2 && i >= 360*2
phi_3(i+1) = -phi_3_prime(i+1) + phi_3_double_prime(i+1);
else
phi_3(i+1) = phi_3_prime(i+1) + phi_3_double_prime(i+1);
end
%Calculates theta 3 and 4
theta3(i+1) = theta2(i+1) + phi_3(i+1) - 180;
theta4(i+1) = theta3(i+1) + phi_4(i+1);
%calculates w3 and velocity at point E
w3(i+1) = (w2*r2*sind(theta4(i+1) - theta2(i+1)))/(r3*sind(theta3(i+1) - theta4(i+1)));
VE(i+1) = w3(i+1)*rBE;
%Calculates w4 and velocity at point F
w4(i+1) = (w2*r2*sind(theta2(i+1)-theta4(i+1)))/(r4*sind(theta4(i+1)-theta3(i+1)));
VF(i+1) = w4(i+1)*r4;
%this is calculating all the individual joints using the equations
%given in the lectures
J1(i+1, :) = [0, 0];
J2(i+1, :) = [-r2*cosd(theta2(i+1)), r2*sind(theta2(i+1))];
J3(i+1, :) = [-(r2*cosd(theta2(i+1)) + r3*cosd(theta3(i+1))), (r2*sind(theta2(i+1)) +
r3*sind(theta3(i+1)))];
J4(i+1, :) = [-r1, 0];
```

```
J5(i+1, :) = [-(r2*cosd(theta2(i+1)) + rBE*cosd(alpha + theta3(i+1))), (r2*sind(theta2(i+1)) +
rBE*sind(alpha + theta3(i+1)))];
J6(i+1, :) = [(r2*cosd(theta2(i+1)) + r3*cosd(theta3(i+1))) - 2*r1, -(r2*sind(theta2(i+1)) +
r3*sind(theta3(i+1)))];
end
%plots the velocity analysis
figure(1)
plot(-theta2, VE);
hold on
plot(-theta2, VF);
hold off
title('Design B Velocity Analysis')
xlabel('degrees')
ylabel('mm/s')
i = 360;
for j = 0:1:360
i = i - 1;
%plots the joints
figure(2)
plot(J5(:, 1), J5(:, 2));
hold on
plot(J6(:, 1), J6(:, 2));
plot(J1(i+1, 1), J1(i+1, 2));
plot(J2(i+1, 1), J2(i+1, 2));
plot(J3(i+1, 1), J3(i+1, 2));
plot(J4(i+1, 1), J4(i+1, 2));
plot(J5(i+1, 1), J5(i+1, 2), '-o');
plot(J6(i+1, 1), J6(i+1, 2), '-o');
%plots the links between each joint
line([J1(i+1, 1) J2(i+1, 1)],[J1(i+1, 2) J2(i+1, 2)]);
line([J3(i+1, 1) J2(i+1, 1)],[J3(i+1, 2) J2(i+1, 2)]);
line([J3(i+1, 1) J4(i+1, 1)],[J3(i+1, 2) J4(i+1, 2)]);
line([J1(i+1, 1) J4(i+1, 1)],[J1(i+1, 2) J4(i+1, 2)]);
line([J2(i+1, 1) J5(i+1, 1)],[J2(i+1, 2) J5(i+1, 2)]);
line([J5(i+1, 1) J3(i+1, 1)],[J5((i+1), 2) J3(i+1, 2)]);
line([J6(i+1, 1) J4(i+1, 1)],[J6((i+1), 2) J4(i+1, 2)]);
hold off
%gives the figure a title and labels
title('Design B Animation')
xlabel('Horizontal length (mm)')
ylabel('Vertical length (mm)')
%defines the limit of the axis
axis([-100 100 -100 100])
drawnow
end
```

Design 2 MATLAB code:

```
clc
close all
```

```
clear
%defining the link lengths
r1 = 45;
r2 = 20;
r3 = 50;
r4 = 35;
rBE = 30;
alpha = 30;
w2 = 8.5;
for i = 0:1:360*3
%Calculates values for analysis
theta2(i+1) = i;
BD(i+1) = sqrt(r1^2 + r2^2 - 2*r1*r2*cosd(theta2(i+1)));
phi_4(i+1) = acosd((r3^2 + r4^2 - r1^2 - r2^2 + 2*r1*r2*cosd(theta2(i+1)))/(2*r3*r4));
phi_3_prime(i+1) = acosd((r2^2 + BD(i+1)^2 - r1^2)/(2*r2*BD(i+1)));
phi_3_double_prime(i+1) = acosd((r3^2 + BD(i+1)^2 - r4^2)/(2*r3*BD(i+1)));
%calculates phi 3 based on the different branches
if i < 180
phi_3(i+1) = phi_3_prime(i+1) + phi_3_double_prime(i+1);
elseif i < 180+360 && i >= 360
phi_3(i+1) = phi_3_prime(i+1) + phi_3_double_prime(i+1);
elseif i < 180+360*2 && i >= 360*2
phi_3(i+1) = phi_3_prime(i+1) + phi_3_double_prime(i+1);
else
phi_3(i+1) = -phi_3_prime(i+1) + phi_3_double_prime(i+1);
end
%Calculates theta 3 and 4
theta3(i+1) = theta2(i+1) + phi_3(i+1) - 180;
theta4(i+1) = theta3(i+1) + phi_4(i+1);
%Calculates w3 and velocity at point E
w3(i+1) = (w2*r2*sind(theta4(i+1) - theta2(i+1)))/(r3*sind(theta3(i+1) - theta4(i+1)));
VE(i+1) = w3(i+1)*rBE;
%this is calculating all the individual joints using the equations
J1(i+1, :) = [0, 0];
J2(i+1, :) = [r2*cosd(theta2(i+1)), -r2*sind(theta2(i+1))];
J3(i+1, :) = [r2*cosd(theta2(i+1)) + r3*cosd(theta3(i+1)), -(r2*sind(theta2(i+1)) +
r3*sind(theta3(i+1)))];
J4(i+1, :) = [r1, 0];
J5(i+1, :) = [r2*cosd(theta2(i+1)) + rBE*cosd(alpha + theta3(i+1)), -(r2*sind(theta2(i+1)) +
rBE*sind(alpha + theta3(i+1)))];
end
%The following calculates the same values but for the second leg
for i = 0:1:360*3
theta2_n(i+1) = -i;
BD_n(i+1) = sqrt(r1^2 + r2^2 - 2*r1*r2*cosd(theta2_n(i+1)));
phi_4_n(i+1) = acosd((r3^2 + r4^2 - r1^2 - r2^2 + 2*r1*r2*cosd(theta2_n(i+1)))/(2*r3*r4));
phi_3_prime_n(i+1) = acosd((r2^2 + BD_n(i+1)^2 - r1^2)/(2*r2*BD_n(i+1)));
phi_3_double_prime_n(i+1) = acosd((r3^2 + BD_n(i+1)^2 - r4^2)/(2*r3*BD_n(i+1)));
if i < 180
phi_3_n(i+1) = -phi_3_prime_n(i+1) + phi_3_double_prime_n(i+1);
```

```
elseif i < 180+360 && i >= 360
phi_3_n(i+1) = -phi_3_prime_n(i+1) + phi_3_double_prime_n(i+1);
elseif i < 180+360*2 && i >= 360*2
phi_3_n(i+1) = -phi_3_prime_n(i+1) + phi_3_double_prime_n(i+1);
else
phi_3_n(i+1) = phi_3_prime_n(i+1) + phi_3_double_prime_n(i+1);
end
theta3_n(i+1) = theta2_n(i+1) + phi_3_n(i+1) - 180;
theta4_n(i+1) = theta3_n(i+1) + phi_4_n(i+1);
w3_n(i+1) = (w2*r2*sind(theta4_n(i+1) - theta2_n(i+1)))/(r3*sind(theta3_n(i+1) - theta4_n(i+1)));
VE_n(i+1) = w3_n(i+1)*rBE;
J6(i+1, :) = [-r2*cosd(theta2_n(i+1)) - 30, -r2*sind(theta2_n(i+1))];
J7(i+1, :) = [-(r2*cosd(theta2_n(i+1)) + r3*cosd(theta3_n(i+1))) - 30, -(r2*sind(theta2_n(i+1)) +
r3*sind(theta3_n(i+1)))];
J8(i+1, :) = [-r1 - 30, 0];
J9(i+1, :) = [-(r2*cosd(theta2_n(i+1)) + rBE*cosd(alpha + theta3_n(i+1))) - 30,
-(r2*sind(theta2_n(i+1)) + rBE*sind(alpha + theta3_n(i+1)))];
J10(i+1, :) = [-30, 0];
end
%plots the velocity analysis
figure(1)
plot(theta2, VE);
hold on
plot(theta2, VE_n);
hold off
title('Design C Velocity Analysis')
xlabel('degrees')
ylabel('mm/s')
i = 361;
for j = 0:1:360
i = i - 1;
%plots the joints and thepaths of the legs
figure(2)
plot(J5(:, 1), J5(:, 2));
hold on
plot(J9(:, 1), J9(:, 2));
plot(J1(i+1, 1), J1(i+1, 2));
plot(J2(i+1, 1), J2(i+1, 2));
plot(J3(i+1, 1), J3(i+1, 2));
plot(J4(i+1, 1), J4(i+1, 2));
plot(J5(i+1, 1), J5(i+1, 2), '-o');
plot(J6(i+1, 1), J6(i+1, 2));
plot(J7(i+1, 1), J7(i+1, 2));
plot(J8(i+1, 1), J8(i+1, 2));
plot(J9(i+1, 1), J9(i+1, 2), '-o');
%plots the links between each joint
line([J1(i+1, 1) J2(i+1, 1)],[J1(i+1, 2) J2(i+1, 2)]);
line([J3(i+1, 1) J2(i+1, 1)],[J3(i+1, 2) J2(i+1, 2)]);
line([J3(i+1, 1) J4(i+1, 1)],[J3(i+1, 2) J4(i+1, 2)]);
line([J2(i+1, 1) J5(i+1, 1)],[J2(i+1, 2) J5(i+1, 2)]);
```

```
line([J5(i+1, 1) J3(i+1, 1)],[J5(i+1, 2) J3(i+1, 2)]);
line([J10(i+1, 1) J6(i+1, 1)],[J10(i+1, 2) J6(i+1, 2)]);
line([J7(i+1, 1) J6(i+1, 1)],[J7(i+1, 2) J6(i+1, 2)]);
line([J7(i+1, 1) J8(i+1, 1)],[J7(i+1, 2) J8(i+1, 2)]);
line([J4(i+1, 1) J8(i+1, 1)],[J4(i+1, 2) J8(i+1, 2)]);
line([J6(i+1, 1) J9(i+1, 1)],[J6(i+1, 2) J9(i+1, 2)]);
line([J9(i+1, 1) J7(i+1, 1)],[J9(i+1, 2) J7(i+1, 2)]);
hold off
%gives the figure a title
title('Design C Animation')
xlabel('Horizontal length (mm)')
ylabel('Vertical length (mm)')
%defines the limit of the axis
axis([-100 100 -100 100])
drawnow
end
```

Design 3 MATLAB code:

```
clear
close all
clc
%Link legnths
AB=1.616; BC=3.841; CD=3.267; BD=6.244;
w=51; %Angular velcoity of crank in deg/s
th=6.142; %Angle of inclination of the slide
i=0; %Iterative counter for angualr velocity vector
for t=0:0.1:30 %Define time vector in 0.01 intervals and ending after 30s
%Equations of motion and velocities
th1=40.86-w*t; %Angle driven by motor (angle between crank link and horizontal), equation 1
B=[2.824+AB*cosd(th1), 0.62+AB*sind(th1)]; %Position of B over time, equation 2
VB=[-AB*w*cosd(90-th1),-AB*w*sind(90-th1)]; %Velocity of B over time, equation 3
C=[-1.572+VB(1)*t,-0.485*VB(2)*t]; %Position of C over time, equation 4
d=sqrt( ( C(1)-2.824 )^2+( C(2)-0.62 )^2 ); %d is the length between joint A and the slider over time,
equation 5
phi=acos( (d^2-AB^2-BC^2)/(-2*AB*BC) ); %Angle between crank AB and one side of the link, BC, equation
6
a=phi-26.12-90+th1; %Angle for determining position of D, uses phi, internal angle in link (between BC
and BD), and th1, equation 7
D=[B(1)+BD*sind(a), B(2)+BD*cosd(a)]; %Position of D over time, equation 8
VC=[VB(1),VB(2)]; %Velocity of C, equation 9
vD=sqrt( (AB*w)^2+(AB*w)^2-(2*(AB*w)^2)*cosd(90-th1-th)); %Magnitude of the velocity of D, equation 10
phi1=acos( (-vD^2)/(-2*AB*w*vD) ); %Internal angle between VD and VB, equation 11
thd=90-phi1+th1; %Angle between horizontal and VD, equation 12
VD=[-vD*cosd(thd), vD*sind(thd)]; %Velocity of D over time, equation 13
WBD=VD-VB; %Relative velocity vector between VD and VB, equation 13
i=i+1;
wBD(i)=sqrt( (WBD(1))^2+(WBD(2))^2 )/BD; %Angular velocity of the main link using side BD, equation 14
%PLot angular velocity versus time graph
figure(2)
```

```
plot(wBD)
title('Design 3 Angular Velocity Analysis')
ylabel('Angular Velocity (rad/s)')
xlabel('Time (s)')
grid on
hold on
%Plotting/animating the motion
A=[2.824, 0.62]; %Position of A which stays fixed
figure(1)
plot([A(1) B(1)], [A(2) B(2)], [B(1) C(1)], [B(2) C(2)], [C(1) D(1)], [C(2) D(2)])
hold on
title('Animation and Displacement Analysis of Design')
xlabel('Horizontal position (cm)')
ylabel('Vertical position (cm)')
grid on
axis([-50 50 -50 50])
drawnow
hold off
end
```

Toronto Metropolitan University
Department of Aerospace Engineering
Faculty of Engineering & Architectural Science

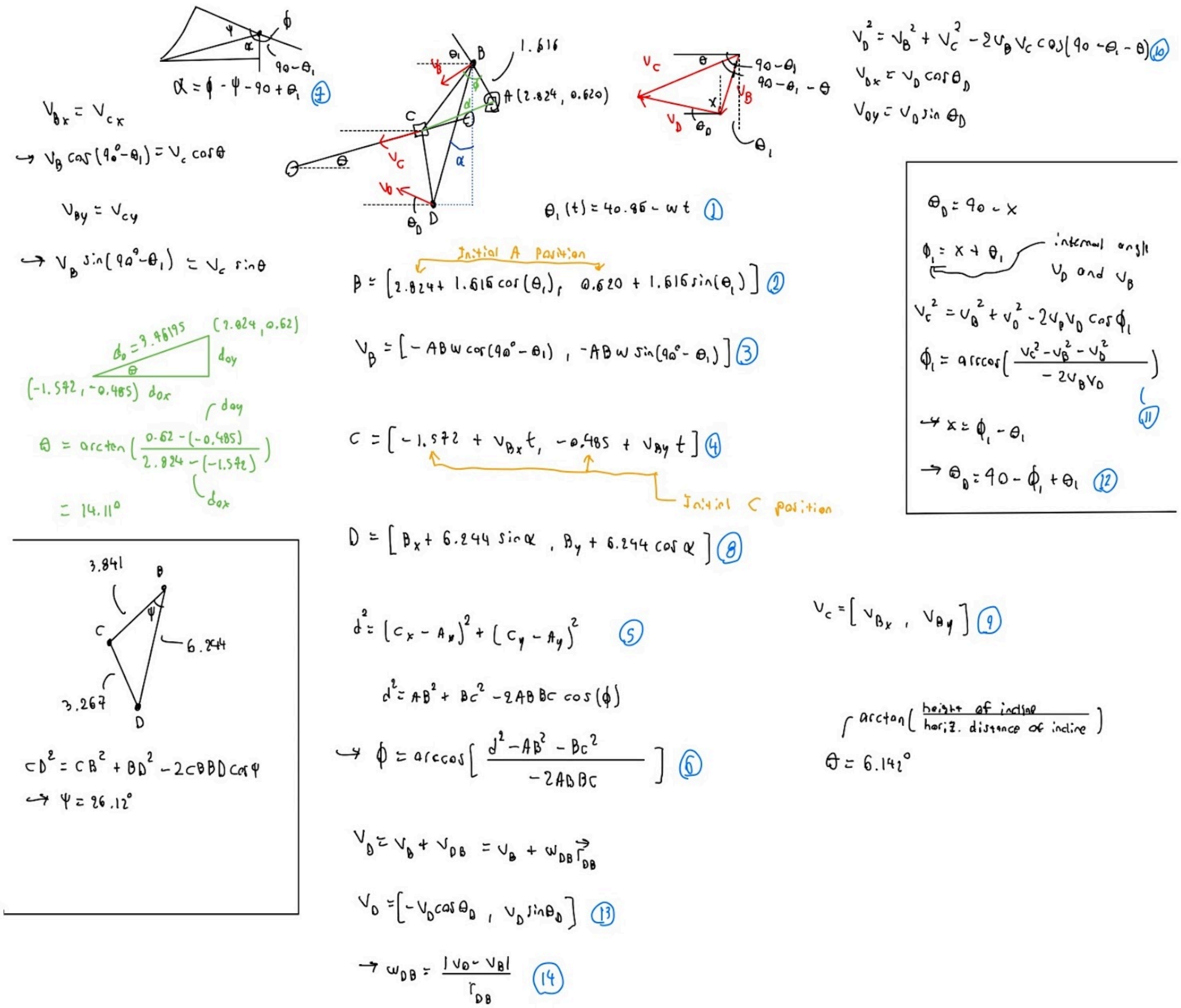

Figure 9 - Reference for MATLAB code and calculations for design 3

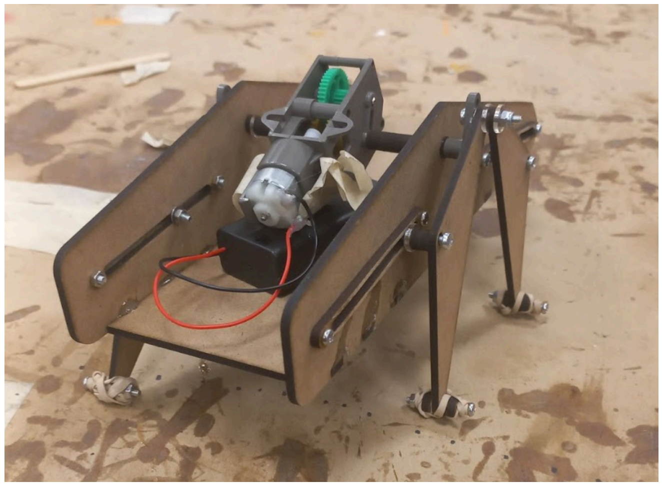

Figure 10 - Finished Robot View 1

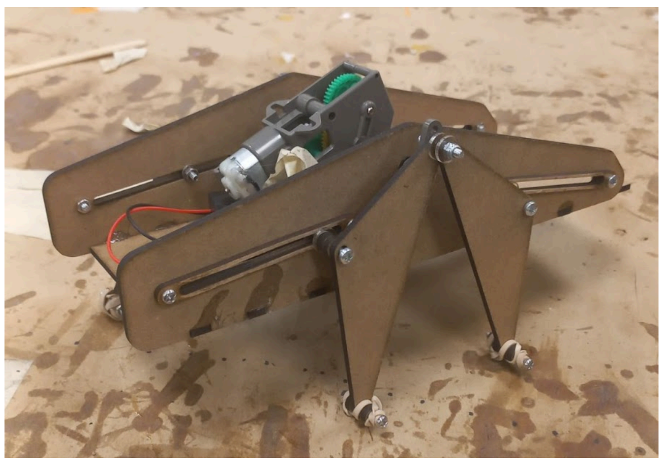

Figure 11 - Finished Robot View 2

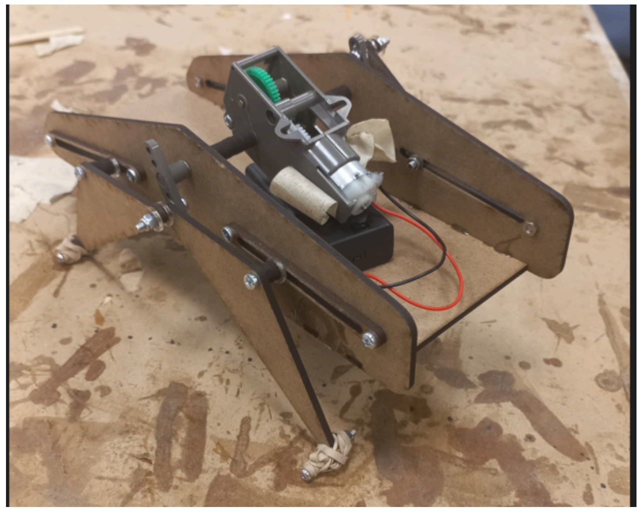

Figure 12 - Finished Robot View 3