Design and Evaluation of a Two-Wheeled Autonomous Robot

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1 Abstract

The research conducted for the robot's design consisted of taking inspiration from existing two-wheeled robot designs and then shaping those ideas into the ideal robot design for accomplishing the goal of the competition. Once we settled on an initial design, there was a long process of trial and error to try and figure out what worked and what did not until the final design was fully realized. After completing the robot, the big conclusion the team reached was that the robot's arm was not optimal for lifting objects and would require more torque than the servo motors could give. The use of encoders for the autonomous mode instead of a line follower program also made a big difference as it allowed for more room for error. Overall, the robot's performance was satisfactory, however the results and conclusions drawn from the final design show that there are still improvements that could have been made.

2 Introduction

The design of our robot was guided by inspiration from both classical mechanical systems and proven robotic architectures. For mobility, we referenced the well-established two-wheeled differential drive robot configuration, as shown in the following [1].

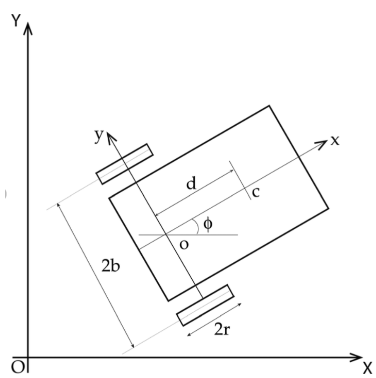

Figure 1: Two-wheeled differential drive robot

This architecture is a common foundation used mobile robotics, known for its maneuverability and control simplicity. The differential drive system allows for tight turns and precise control, making it ideal for our application where agility and directional accuracy are key. The use of encoders and feedback control in similar robots has proven effective for tasks involving mapping, navigation, and path-following.

For actuation, we looked closely at the crank-slider mechanism, a reliable method for converting rotary motion into linear displacement. This mechanism is widely used in applications like internal combustion engines and press systems due to its compactness and ability to produce smooth, repeatable motion. We were particularly influenced by the design described in "Multiple Degree-of-Freedom Counterbalance Robot Arm Using a Crank-Slider Mechanism" [2], where the authors demonstrate how this mechanism can be used to reduce the torque demands on actuators and provide an otherwise unattainable wide range of motion. As they explain, "The crank-slider mechanism can maintain a constant torque output over a wide range of motion" [2].

Our overall strategy is to combine the mechanical consistency of the crank-slider with the mobility and control advantages of a differential drive base. This hybrid approach enables us to execute precise linear actuation tasks while maintaining full mobility in a compact form factor. We hypothesize that the crank-slider will provide highly repeatable performance, particularly in tasks requiring consistent extension/retraction or lifting motions such as lifting and manipulating dinosaurs, while the differential drive will allow us to navigate and position the robot accurately.

3 Methods

The final design of the robot implemented a robust system of mechanical, electrical, and control elements precisely designed with the objective of the minigame in mind. The robot was designed with a focus on compactness and maneuverability while ensuring that all components were placed strategically to minimize weight and maximize efficiency. The dimensions of the final robot were carefully considered to ensure they met the size restrictions and functional requirements of the competition. The initial design of the robot is depicted below.

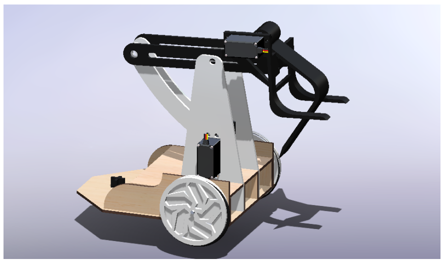

Figure 2: Final design of the robot

A detailed image of the completed robot design, including overall dimensions, is shown below. This image highlights the full layout of the robot, showcasing how the arm mechanism, drive system, and other components are arranged to achieve optimal performance.

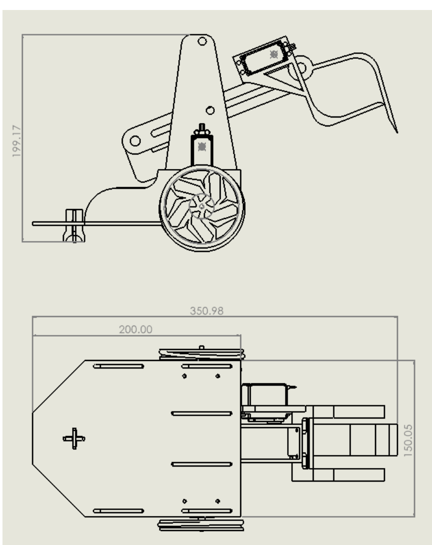

Figure 3: Final dimensioned drawing of robot

3.1 Mechanical Design

Throughout the project, an emphasis was placed on the mechanical design to enable precise object interaction and mobility, which were key requirements for the robot's performance. The final robotic design was refined through numerous iterations, requiring a fast-paced, iterative approach to guarantee that all subassemblies functioned seamlessly together in time for the final competition.

3.1.1 Sliding Arm Mechanism

The final design of the arm mechanism takes inspiration from the aforementioned crank-slider mechanism, with a twist. This departure from the traditional implementation of this mechanism allowed for a greater range of motion, ensuring the robot could interact with objects in a more flexible and controlled manner.

The linkage design was first simulated using Linkage software as a proof of concept, enabling an initial validation of the motion path and functionality. The following image showcases the extensive range of motion enabled by this unique design.

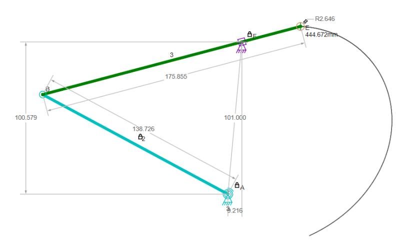

Figure 4: Linkage Motion Path

After validating the theoretical foundation for this linkage, the design was translated into a practical arm assembly using SolidWorks. The SolidWorks model allowed for further refinements to the geometry and provided valuable insights through simulations to confirm that the linkage would function as intended in real-world conditions. By optimizing the geometry based on simulation results, the design was iterated until it met the desired performance criteria.

The final design was carefully tested to ensure that the arm could provide the necessary range of motion without compromising strength, speed, or stability. The SolidWorks subassembly of the linkage is shown in Figure 5.

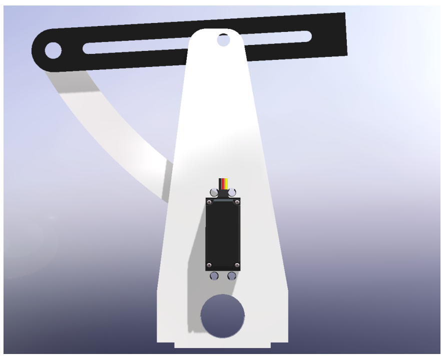

Figure 5: Linkage Design

3.1.2 Gripper Mechanism

After going through many different design iterations, the team settled on a final gripper model, as seen in Figure 2. It was designed to be small and light to ensure that the robot would have no trouble lifting it with the additional weight of a dinosaur or minion. It is mounted to the end of the arm with four screws and has a servo motor attached to its side. The servo allows the top half of the gripper to open and close with the press of a button, helping to secure anything it is holding. It has two prongs at the bottom that remain stationary and rest against the ground. This allows it to get under any object and lift it up as the top closes down to grab it. The design is simple but effective and was able to lift dinosaurs without any issue.

3.2 Electrical System

The electrical subsystem plays a crucial role in enabling the robot to function autonomously and perform precise tasks during manual mode. The components selected for the system, particularly the use of the motors and encoders, ensure that the robot can achieve optimal drive performance and control over its arm mechanism.

3.2.1 Motor Selection and Control

The drive system of the robot relies on two DC motors that effectively balance efficiency and precision. The chosen motors are the Metal DC Geared Motors with encoders (-6 V, 210 RPM, 10 kg*cm). These motors provide a relatively high output torque, which became crucial in allowing the robot to handle the various levels and surfaces on the game board.

Additionally, the integrated encoders on these motors provided critical feedback for odometry, enabling autonomous navigation. These encoders allowed the robot control system to track its position and trajectory, allowing it to correct its movement accordingly in real time. This precise feedback mechanism ensures that the robot can navigate its environment with a high degree of accuracy.

For controlling the robotic arm and gripper, three HS422 servos were used. Due to its compact size and torque specification (up to 4.5 kg*cm), it allows for precise arm control and smooth movement during tasks that require arm manipulation.

3.2.2 Electrical Schematic

The electrical schematic for the robot's subsystem is an integral part of the design, as it illustrates the relationships between the different components, including the motors, servos, and power supply. The electrical schematic is depicted below in Figure 6.

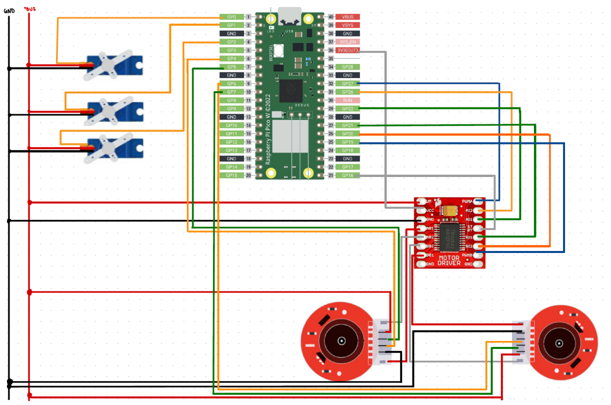

Figure 6: Electrical Schematic

3.3 Control Algorithms

The software aspect of this project was developed to enable remote controlled and autonomous operation of the mobile robot using solely a Raspberry Pi Pico W. It utilized a dual-loop architecture, allowing the first to handle the WiFi communication from a game controller, while the second focused on motion control through sensor feedback and motor actuation.

The game controller's analog stick input were mapped to the robot's movement, with joystick positioning mapping directly to the motor speed and direction through a proportional scaling function. This control system utilized a PI based speed controller that adjusted the motor power using PWM to maintain precise velocity. In manual mode, this behavior allowed the operator to control the robots movement, allowing the left stick to adjust the DC motors of the robot, allowing for smooth and intuitive maneuvering.

In autonomous mode, the system utilized encoder feedback to track wheel rotations and estimate the robot's position over time. The encoder data was processed to compute distance traveled using the odometry equation:

$$d = \frac{N}{C} \times \pi D$$

where:

d is the distance traveled per encoder count,
N is the number of encoder counts recorded,
C is the total number of counts per full wheel revolution,
D is the wheel diameter.

This odometry data was then used to implement closed-loop control strategies, allowing the robot to follow predefined paths or navigate based on sensor inputs. The control system relied on proportional adjustments to motor speed to correct deviations, ensuring accurate movement during autonomous operation.

3.4 Material Usage

To evaluate the material consuption for the project, a detailed print log was maintained, documenting the amount of filament used for each component. The total filament usage across all printed parts amounted to 189.88 grams, corresponding to a total print volume of 9.344 in^3.

Part Name	**Filament(g)**	**Quantity**	**Volume**
Motor Mount	1.22	2	0.060
Wheels	18.75	2	0.923
Marble Mount	2.28	1	0.112
Corner Brackets	0.72	4	0.035
Lower Arm	7.2	2	0.354
Upper Arm	12.91	2	0.635
Upper Arm	12.30	2	0.605
Gripper Piece	134.5	1	6.619
Total	**189.88**	**16**	**9.344**

Table 1: Print Log Summary

A significant portion of the material utilized in this project was MDF (medium-density fibreboard), which constituted approximately 40% of the total available MDF provided for the project. MDF was used for many of the robot's structural components due to its superior strength and durability, making it well-suited for load-bearing components such as the base and other structural elements.

4 Results

4.1 Testing and Design Process

Throughout the duration of the project, each of the robot's core subsystems was designed, developed, and tested individually. Initial testing of the arm mechanism showed promise as the original design provided the intended range of motion and control over the arm, and early movements without load were smooth. However, during testing with an actual dinosaur model, a major flaw became apparent. The friction between the PLA 3D-printed components and the aluminum rods was much higher than anticipated. This excessive friction significantly increased the torque requirement, ultimately exceeding the capabilities of the two servo motors powering the arm.

To address this, many mitigation strategies were explored. First, the length of the arm was shortened to reduce the torque demand. Additionally, the parts of the sliding mechanism were filed down to reduce surface contact and minimize friction. While these efforts improved torque performance, they created a new challenge: the arm was now too short to reach over the dinosaur cage as originally intended.

This limitation prompted a design shift. Instead of lifting the arm up and over the cage, we adapted the geometry of the crank mechanism to prioritize horizontal movement. This allowed the arm to insert the dinosaurs through the front of the cage rather than from above. Once these changes were implemented, the robot was able to pick up, maneuver, and place the dinosaur models with the desired level of precision and consistency.

The autonomous navigation system also underwent several iterations. The original plan was to use the DFRobotShop Rover Line Follower Sensor in combination with a PID control system to follow the line markings on the competition course. However, early tests revealed that the sensor's width made it unreliable for following the narrow track, resulting in inconsistent behavior and frequent course deviations.

In response, the focus was put on odometry-based control. This provided a more reliable solution, and after extensive testing and tuning of the PID controller, smooth and consistent autonomous motion was achieved. Several hours were spent fine-tuning the speed profiles, turning ratios, and encoder scaling factors to ensure accurate path following and timing. This ultimately resulted in a navigation system that could reliably complete the autonomous portion of the course—at least in testing.

4.2 Qualifying

Due to the time-intensive troubleshooting required for both the arm and autonomous systems, the robot was only able to complete one qualifying attempt before the final deadline. Unfortunately, during this attempt, the PWM pin controlling the left drive motor became disconnected just before the run. This failure caused the robot to spin uncontrollably and rendered it unusable in both autonomous and manual modes.

As a result, the robot was unable to navigate the course, and no points were scored. It was a frustrating outcome, especially considering the amount of work that had gone into tuning the system. Despite this, the qualifying run highlighted the importance of robustness and reliability in wiring and connections—something we would prioritize more heavily in future iterations of the design.

4.3 Competition

Despite the robot's poor performance during the qualifying rounds, the team continued to work on and improve it in preparation for the final competition. During the first round of the competition, the robot narrowly failed to exit out of the gate due to unexpected slipping of the wheels causing a slight misalignment, and the robot hitting the door but not navigating through completely. Once manual mode was activated, the team was able to score two dinosaurs and win the first round of the competition - thus showcasing that the overall robot was a success. The team was not able to continue due to an unforeseen motor issue resulting in the right motor becoming disabled during autonomous mode. As a result, the robot also failed to go through the gate on the second round and was only able to score one dinosaur in the end. Although the team was eliminated in the second round, the team is proud of the robot's performance, which met the key requirements of the game. Despite the early exit, the project was considered a success for its solid execution and effective design.

5 Discussion

The goal was to design a robot capable of autonomously navigating a course and manipulating dinosaur models with precision and reliability. While it achieved consistent performance during internal testing, the robot experienced a last-minute hardware failure during the qualifying round and was unable to complete the task successfully. As a result, the team was eliminated in the second round, but remained proud of the robot's overall design and performance, which aligned well with the competition's technical requirements and demonstrated strong potential.

Reflecting on the original hypothesis, which claimed that combining a crank-slider mechanism with a differential drive base would result in a precise and repeatable mobile robot manipulator solution for this game. The final iteration of the sliding arm mechanism proved capable of repeatable motion, especially after reducing friction and optimizing geometry. Testing confirmed that the system could consistently execute the required pick-and-place tasks within the limits of our design.

Nonetheless, several limitations emerged. The PLA-on-aluminum interface created unexpected friction, and the arm design was sensitive to small changes in geometry. The solution to reorient the mechanism worked, but compromised the original strategy for the game, invoking a severe restructuring of the robot and goals. In future iterations, using low-friction materials or integrated bearings would help maintain full arm reach without sacrificing torque performance.

On the autonomous side, the decision to abandon line-following in favor of encoder-based navigation improved performance dramatically. The encoder based, PID-tuned, odometry system delivered consistent results in lab testing. However, the competition run revealed a vulnerability in our electrical system: a single loose wire rendered the entire robot inoperable. More robust wiring and physical strain relief should be prioritized in future designs to prevent similar issues.

Overall, the project highlighted the importance of balancing mechanical reliability with electrical robustness, demonstrating that the physical construction, including the crank-slider and differential drive, combined with iterative design, could lead to functional and consistent performance under controlled conditions, supporting the hypothesis..

Author Contributions

Josh Westlake: Conceptualization, Methodology, Software, Writing – original draft - Introduction, Mechanical Design - Sliding Arm Mechanism, Electrical System, Control Algorithms, Material Usage, Results - Testing, Qualifying, Discussion, Writing - review and editing, Visualization - Figures and Presentation.
Paul Booth: Conceptualization, Methodology, Software, Writing – original draft - Abstract, Mechanical Design - Gripper Mechanism, Results - Competition, Writing - review and editing.

References

[1] E. Cobos Torres, S. Konduri, and P. Pagilla, "Study of wheel slip and traction forces in differential drive robots and slip avoidance control strategy," 06 2014, pp. 3231–3236.

[2] H. Kim, J.-K. Min, and J.-B. Song, "Multiple-degree-of-freedom counterbalance robot arm based on slider-crank mechanism and bevel gear units," *IEEE Transactions on Robotics*, vol. 32, pp. 230–235, 2016. [Online]. Available: https://api.semanticscholar.org/CorpusID:15246613