A Continuous Differential Omni-Directional Drive Mobile Robot with an Adaptive Grip Claw and Tension Arm

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***Abstract*—Competitive robots are often required to perform complex tasks with a limited variety and quantity of sensors, actuators, and materials. The integration of mechanical transmission systems can maximize the degrees of freedom of a mobile robot while minimizing the number of actuators required. Adaptive end effectors, such as a Fin Ray®Effect inspired gripper, can manipulate multiple object forms in the competition whilst limiting the number of manipulators required. The latter mechanical systems increase the capabilities of the robot while not increasing the quantity of sensors or actuators required. When integrated into one robotic system, the latter subsystems are complementary to each other, increasing the capabilities of other subsystems in the robot. We present a novel mobile robot with continuous differential omni-directional drive and an adaptive grip claw and tension arm. The robot additionally is equipped with an autonomous driving mode to navigate a known static environment using only three ultrasonic sensors in a simplistic algorithm denoted "regional pursuit". The degrees of freedom of the proposed drive system create a functional extra degree of freedom about the Z-axis of the arm. The drive mechanism ultimately failed due to low fidelity parts with a high complexity system; the results of this project indicate the importance of balancing simplicity with technical innovation in competitive robots.**

I. Introduction

This competitive robot, designed for a specific competition, must autonomously navigate through a door, push a button, pick up a Ken doll and toy dinosaurs, and deliver them to various locations on a gameboard. The overarching strategy focuses on enhancing movement efficiency through horizontal translation. Traditionally, achieving horizontal movement necessitates turning, forward motion, and turning back, consuming time and risking errors requiring adjustments. Utilizing an omni-wheel facilitates rapid horizontal translation during autonomous operation and enables pivoting in place for object manipulation. To optimize actuator use, a servo is integrated to enable differential drive using a single DC motor, while another motor powers the omni-wheel.

Inspiration for this robot draws from VEX robotics competitions, which, like the current scenario, emphasize precise object manipulation on a game board. Horizontal mobility is a common feature among successful robots in such competitions, alongside forward movement and turning.

The design of the claw mechanism is inspired by biological grip mechanisms, minimizing the need for a secondary manipulator to handle diverse objects.

After encountering challenges with the proposed drive system's complexity, the team repurposed internal drivetrain components to develop direct drive wheels and a caster wheel. The robot used in competition is depicted in Figure 1.

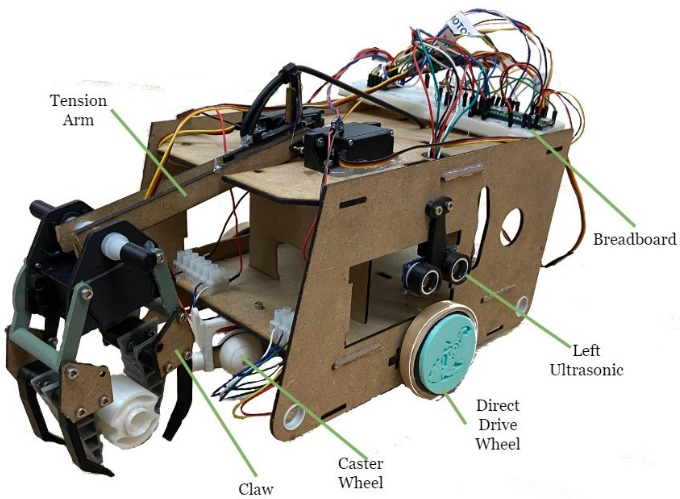

Fig. 1. A diagram of the complete robot system with the adapted drivetrain that was used in competition.

II. Methods

A. Claw Design

The robot used a single-sided clamping claw with adaptive TPU grippers as an end effector. A Hitec HS-422 servo motor was embedded in the core of the claw. A helical gear was press-fit to the servo shaft to drive a secondary gear which rotates about a stationary shaft to open and close the clamp claw as shown in Figure 2. The claw was designed to be capable of primarily picking up Ken, a 5-inch-across 180 gram doll, and additionally the dinosaurs upon retrieval of Ken, which are approximately 2-inches across and of variable weight below 100 grams. Thus, the clamp was dimensioned to have a maximum opening span of 6 inches, and a minimal span of 0 inches. The claw was attached to the end of the arm using a pin-joint such that, due to gravity, the claw would always hang downward.

To complement the varying shapes of Ken and the dinosaurs, a soft robotic Fin Ray®Effect inspired gripper is used to conform to varied objects while the clamp grasps the object at the minimal possible grip span. The Fin Ray®Effect is derived from the physiological properties of fish fins, which are triangular with rigid crossbeams to deform around objects [1]. Fin Ray®grippers are typically manufactured using a combination of integrated soft and hard materials to create a complex mechanical structure, but can be entirely directly 3D printed using soft materials such as TPU or elastic resin [2]. Tiny raised triangular features on the inner side of the fingers can effectively increase friction between the object and the gripper, preventing slip [2]. The gripper fingers on the robot were 3D printed using TPU to be triangular of dimensions 60 x 28 mm with the described crossbeams and raised triangular surface. The ensure minimal risk of dropping objects in the event the grippers do not conform, a rigid cage was appended to the grippers. The grip system as it adapts to a circular object is shown in Figure 2.

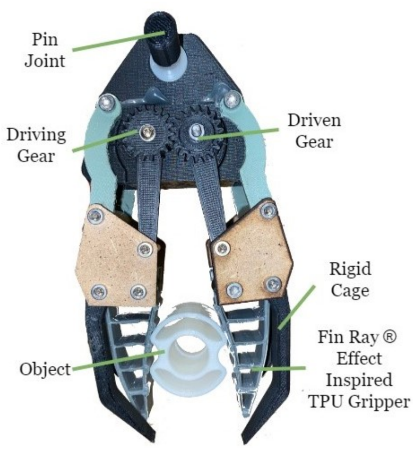

Fig. 2. A diagram of the adaptive-grip claw with a geared opening and closing mechanism.

B. Arm Design

The arm was designed to be driven using a single Hitec HS-422 servo with a torque of 3.3 kg/cm [3]. The arm was designed to be 12 cm long, such that a it has a lifting capacity of 2.75 N at the end effector. To increase lifting ability when gravity is maximized when the arm is parallel to the ground, the provided Buna N Cord was appended to the arm using a circular attachment and tensioned to the back of the robot, as shown in Figure 3. The tension in the Buna N Cord creates a constant upward spring force on the arm due to the geometry of the circular attachment. A second servo was added after the failure of the drivetrain design.

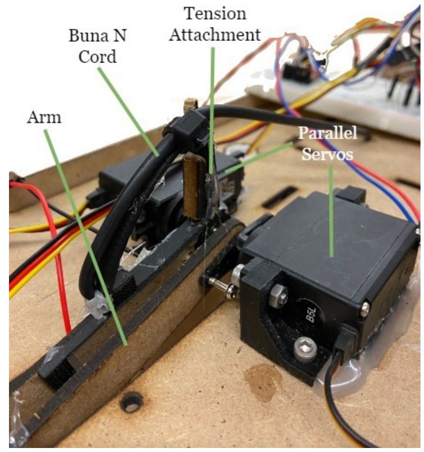

Fig. 3. A diagram of the tensioned two servo arm.

The arm only accommodated movement in one plane, with the intention that movement in the plane perpendicular to the ground would be achieved with the omni-drivetrain.

C. Drivetrain Design

The robot was designed to have translational capabilities as it would circumvent the issue of trying to turn a consistent number of degrees despite varying battery levels. To achieve this, a design based on omni-treads was used with one DC motor used to drive both. The method the team decided on was based on a mechanism demonstrated by James Bruton [4], wherein a spherical transmission was placed between two gears at 90 degrees to each other. By rotating the center axis of the sphere, the gear ratio between the two gears would change, allowing for the speed, as well as the direction of the driven gear to be changed. To avoid using two servo motors to control the spheres, a mechanism was designed to allow for one servo motor to control both transmissions. The mechanism the team designed is shown in Figure 4. To achieve this a set of equations that define the angles an end link would rotate through when a driven link rotates through 90 degrees were created, with one designed to rotate from -45 to 45 degrees, and the other from 45 degrees to 0 and back to 45. The outputs of these equations were plotted using desmos, and are shown in Figure 5. A set of appropriate linkage lengths were selected, allowing for both treads to turn in the same direction when the central steering plate is at 0 degrees, and in opposing directions when the plate is rotated 90 degrees.

D. Trunk Design

The addition of a trunk to hold dinosaurs during the competition was explored, but ultimately abandoned due to material constraints. The trunk would lie beside the arm such that when the arm raised to a 90 degree angle with the robot body, objects could be dropped in the trunk. The trunk was driven by a

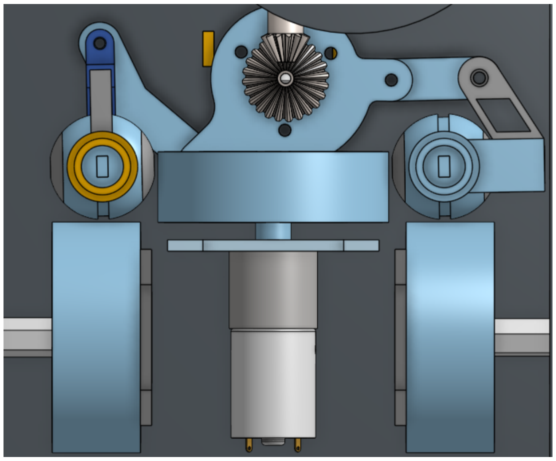

Fig. 4. 3D model showing the differential drive mechanism.

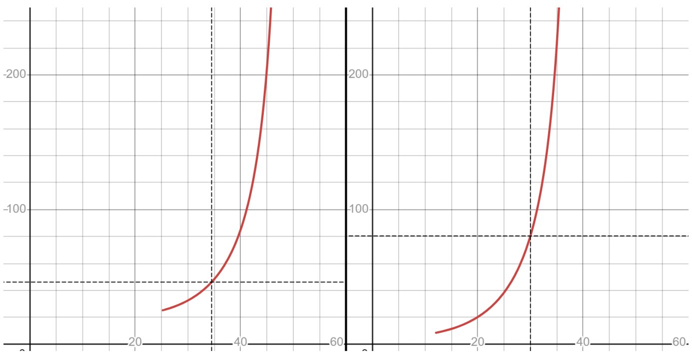

Fig. 5. Graphs showing the length of the tie pin on the x axis and link length of the steering plate for both CVTs on the y axis.

mechanism that allowed it to dump objects when the arm was lifted beyond a 90 degree angle from the robot body. The arm was appended with a spur gear, which drives a second spur gear after the arm surpasses a 90 degree angle, which lifts a lever, dumping the trunk. The trunk and mechanism design are shown in the CAD model in Figure 7.

E. Electrical System

The electrical system used to drive the robot's actuators and sensors is shown in Figure 8. A power distribution budget is provided in Table I.

The power bank, including 4 series 1.8 V batteries, has a total of 5V and 50 Watt-hours. Thus, using the power budget

TABLE I
POWER BUDGET OF ROBOT SENSORS AND ACTUATORS.

Component	Voltage	Current (A)	Current (A) MAX	Power (W)	Power (W) MAX
DC Motor 1	6	0.13	3.2	0.78	19.2
DC Motor 2	6	0.13	3.2	0.78	19.2
Claw Servo	5	0.15	0.8	0.75	4
Arm Servo	5	0.15	0.8	0.75	4
Drivetrain Servo	5	0.15	0.8	0.75	4
Rear Ultrasonic	5	0.02	0.02	0.1	0.1
Left Ultrasonic	5	0.02	0.02	0.1	0.1
Front Ultrasonic	5	0.02	0.02	0.1	0.1
Motor Driver	3.3	1.2	3.2	3.96	10.56
Raspberry Pi Pico	5	0.0099	0.0935	0.0495	0.4675
Total				**8.1195**	**61.7275**

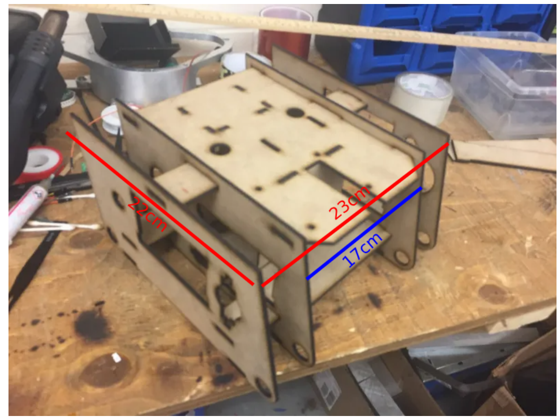

Fig. 6. A picture of the robot chassis with the original size in red and the moodified size in blue.

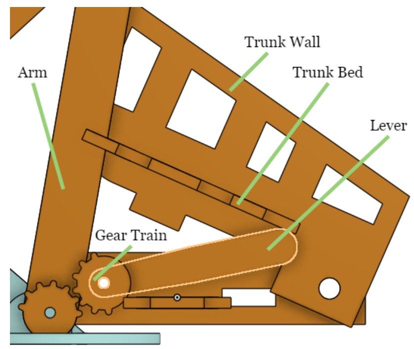

Fig. 7. A diagram of the arm-driven trunk dumping mechanism geared-lever.

it is observed that the robot can run at nominal power for 6.15 hours, and at maximum power for just 48 minutes. A voltage divider is created between the 5 V power bus and GND and connected to A0 such that the battery percentage can be checked to ensure safe operation of the robot.

F. Manual Control and Autonomous Driving

The robot was remotely controlled using TCP protocol over Wifi to facilitate communications between the Raspberry Pico microcontroller and commands from the laptop. A Logitech F310 gamepad was used to send commands to the robot. The controller command layout is provided in Figure 9.

The lower arm and raise arm functions are controlled using the analog left and right triggers, such that the arm position increments according to the amount at which each button is pushed. The robot is driven forward by pushing both sticks forward by the same amount; differential drive is activated by pushing one stick further than the other.

To drive the robot forward and back, "tank controls" are used wherein each joystick would control the speed of each tread. To accomplish this, the direction of the central drive wheel was controlled by the direction of the right stick. The right side transmission does not change the direction of the tread, hence the central wheel needed to be tied directly to the direction the right tread would travel. The drive servo was

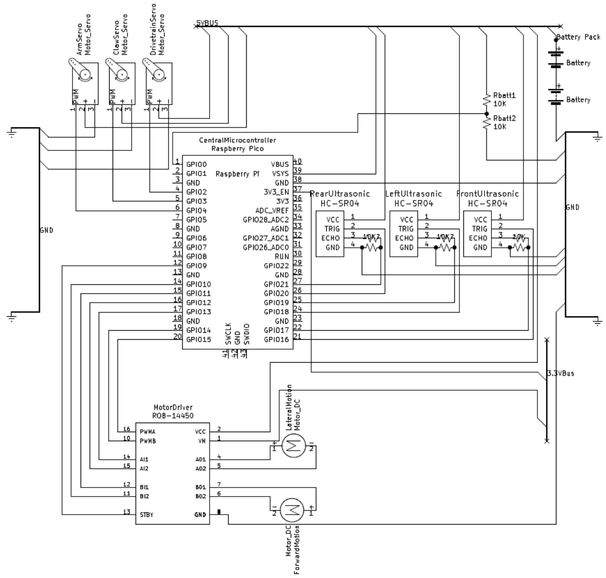

Fig. 8. Electrical schematic for the robot.

Fig. 9. Controller layout as functions of manual operation.

controlled by multiplying the sign of the joysticks, a positive result meant the transmission should by synchronous, causing the treads to turn in the same direction, hence the servo went to it's 0 degree position. The sign being negative meant that a turn should be done, hence the servo rotated the drive mechanism such that the treads would turn in opposite directions.

The robot switches into autonomous mode on start-up when the A button is pressed. The intention of the implemented autonomous mode is to navigate the arena to the button, press it, and go through the doors beside the button. Two possible algorithms were explored to implement this functionality, both of which used three ultrasonics on the left, right and back of the robot to navigate.

1) A Path Planning:* The A* Path Planning algorithm, or Geometric Goal Directed Search, is a modification of the Dijkstra algorithm which attributes the weight of each edge is appended with the lower bound of the distance between that edge and the target position [5]. The utilization of A* for this task was explored using an A* path finding graphical user interface, in which the task of finding the button on the gameboard layout was simulated [6]. The use of A* was ultimately abandoned due the technical complexity of (i) translating geometrically complex routes into a trajectory for the robot and (ii) localizing using only ultrasonic sensors in a route with many turns and approaches that are not parallel to walls.

2) Regional Pursuit: To combat the aforementioned complexities of implementing the A* algorithm, a simpler algorithm for autonomous mode, coined as "Regional Pursuit" was implemented into the robot. Based on the robots region, R, either in the start location (*START*), before the far wall (*APPROACHWALL*), at the wall (*FARWALL*), or near the button (*PUSHBUTTON*), determined by the ultrasonic sensor values, the robot will move linearly in some direction on the gameboard in order to get to the next position. The robot will continue to move until it reaches the button, at which point it will ram into the button and internally note that the button has been pushed (P). Then it will move down until it reaches the middle of the doors (*APPROACHDOOR*), and continue forward (*ENTERDOOR*). The robot turns only such that it is in its initial position, with its claw facing out of the walled-in-gameboard, or turned to the right by 90 degrees from this position. The position is monitored and the ultrasonics switch positions (i.e., at a right turn the rear ultrasonic is now the "right ultrasonic" and the left the "rear ultrasonic". The algorithm for determining the region of the robot with respect to the gameboard is shown in Algorithm 1.

Algorithm 1 Regional localization using left, right and rear ultrasonic sensors.

0: $R \leftarrow START$
0: $P \leftarrow False$
0: **if** $PTrue$ and $U_{rear} \leq 8$ **then**
0: $\quad R \leftarrow APPROACHDOOR$
0: **else if** $PTrue$ and $U_{rear} \geq 8$ **then**
0: $\quad R \leftarrow ENTERDOOR$
0: **else if** $U_{left} \leq 2$ and $U_{right} \leq 2$ **then**
0: $\quad R \leftarrow START$
0: **else if** $U_{right} \geq 2$ **then**
0: $\quad R \leftarrow APPROACHWALL$
0: **else if** $U_{left} \geq 2$ and $U_{right} \leq 2$ and $U_{rear} \leq 2$ **then**
0: $\quad R \leftarrow PUSHBUTTON$
0: $\quad P \leftarrow True$
0: **else if** $U_{left} \geq 2$ and $U_{right} \leq 2$ **then**
0: $\quad R \leftarrow FARWALL$
0: **end if**=0

G. Material Selection and Usage

Approximately 90% of the provided MDF was used to fabricate the body, arm, part of the claw and the omni-wheel. 15.32 in^3 of the allotted 15.4 in^3 of 3D print filament were used to create the project, including reprints. A breakdown of 3D print material utilized in the project is provided in Table II.

TABLE II
3D PRINTER FILAMENT USAGE BREAKDOWN.

Part	**Volume** (in^3)	**Material**
Arm Base	1.00	PLA
Arm Tension Attachment	0.1	PLA
Claw Core (and reprint)	1.91	PLA
Claw Link Limbs (2)	0.5	PLA
Claw Gear Limbs (2)	0.3	PLA
Claw Grips (2)	1.38	TPU
Claw Cage (4)	0.92	PLA
Omniwheels	0.69	PLA
Differential Components	7.3	PLA
Treads	0.15	TPU
Ultrasonic Mounts	1.07	PLA
Total (in^3)	**15.32**	

III. RESULTS

A. Arm and Claw Lifting and Grip Performance

The arm was successful in lifting both Ken (180 grams) and the dinosaurs (100 grams) using the tension arm with dual servo motors. The arm was unsuccessful in lifting either category of object with only one servo motor and no tension; the addition of tension to a dual motor arm caused the arm to lift at a slow rate for some angles. Due to the drivetrain not working, freeing up the servo motor to be used for differential drive, a second servo motor was added to the arm in parallel with the first servo motor, which caused the arm to work at all angles. The performance of the claw with the described setups over various angles (measured from parallel to ground) under the load of the claw and Ken (approximately 0.4 kg) is provided in Figure 10.

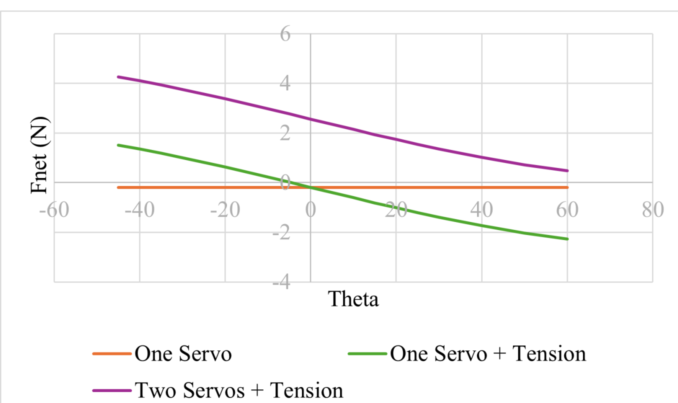

Fig. 10. Torque of the arm as a function of the mechanism used.

B. Drivetrain Performance and Contact

Attempts to keep sufficient friction in the drive mechanism without having too much such that it jams, were unsuccessful. Attempting to remedy this by adding rubber bands to increase the diameter of the wheel created another issue where the wheel was too large, and hence would get stuck against the transmission, unable to rotate. While a certain diameter of the wheel was able to contact the transmission without getting stuck, it was unable to transmit enough torque to transfer this motion to the wheels, as the rest of the drive mechanism was fairly stiff. The group came to the conclusion that without remaking many of the parts, which the group had insufficient material to manufacture, that the robot would need to be remade using the parts already available.

C. Adapted Drivetrain Using Original Parts

The central drive mechanism was replaced with a DC motor on either tread hence forgoing the ability to translate. However, the grooves on the drive gears for the tread to fit into were not deep enough, hence in trying to drive the treads the gears would only slip. It became necessary to use the driven wheels from the drive mechanism as ground wheels, to facilitate this, the motors had to be moved below the lower plate. Holes were drilled into the sides to mount the motors on and the wheels were then attached. The robot had problems with stability as the motors were mounted roughly in the center of the robot, hence, the robot would drag against the front portion of the chassis, and would rock forward and back whenever the robot would accelerate or stop. To remedy this, one of the spherical transmissions was repurposed, and used as a caster wheel. Overall this proved to be a somewhat effective design, however, it didn't have any distinct benefits.

D. Challenges in Power Distribution

The robot experienced difficulties in using both the DC motors and servo motors concurrently, though all could be used in isolation, using the power distribution setup. However, even when the DC motors did successfully turn in isolation, their maximum speed was 30 RPM with maximum (5V) voltage input. This can be attributed to current draw; each of the three HS-422 motor has a stall current of 800 mA [3], while each of the two DC motors draws 3.2 A when stalling [7]. The battery pack, containing four AA batteries in series, can be expected to support just over 2A [8]. Thus, the stalling of any one servo will cause current to leave the DC motors, hindering robot movement. Stalling occurs in the case where the servos are under load, which is always true due to the dead load of the claw on the arm servos.

E. Regional Pursuit Autonomy Simulation

Each of the proposed autonomous mode algorithms were tested in Python simulation environments. The regional pursuit algorithm simulation had a computational time of 0.1 s including plotting. The algorithm was demonstrably effective under the assumption that each ultrasonic had minimum error such that the proposed limits which define the robot's region remain valid. Figure 11 displays the robot's path on the gameboard using the simulated regional pursuit algorithm.

IV. DISCUSSION

A. Technical Complexity

In this project scenario, the robot's technical complexity exceeded the constraints of time and available materials. The

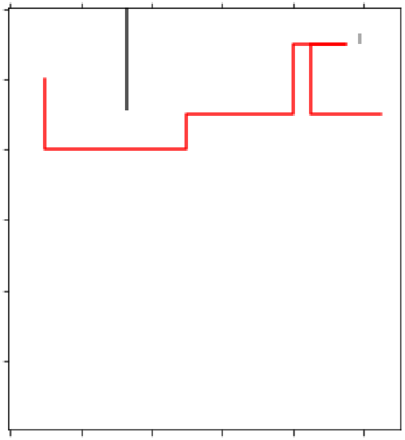

Fig. 11. The path (red) of the regional pursuit autonomous mode algorithm, where the robot begins at the upper left corner (walled-in section) of the gameboard. Grey represents the button on the upper right corner.

inherent complexity of a design correlates with the number of iterations required for its optimization, demanding increased time and material resources. Given the limitations in both time and material, a simpler design would have been more suitable. However, the team's objective of incorporating horizontal translation capabilities led them to pursue a complex design despite this constraint. Investing additional time at the project's outset to devise a solution maintaining this capability while simplifying the design would have significantly benefited the team, affording more integration time.

1) Drivetrain Adaptation: One change that may have been able to make the original drive design work would be to include tires between the transmission and wheels. Tires were a part of the original design as presented by James Bruton [4] however, due to the difficulty of printing TPU, and the limited print volume, the group had originally assumed their inclusion, while helpful, was unnecessary. As seen by the problems this caused later in the project, this assumption turned out to be untrue. Another possible way to ensure the interaction of the transmission and wheels, would be to eliminate the need for slip between the wheel and transmission by using something similar to an ABENICS gear [9]. This mechanism is typically actuated by two specially designed gears to recreate a motion similar to a ball and socket joint, however, by fixing one of the axis in the same way the sphere in the original design is held, this gear would allow for the same kind of transmission as the sphere based design, while allowing for the drive wheel to be replaced with a gear, eliminating the possibility of slipping. While in theory this would remedy the issues faced by the original design, designing an ABENICS gear would likely not be feasible in the scope of this course. Hence a better solution would be to replace the omni tread design with another that would serve the same purpose. One possibility would be to use mecanum wheels, by mounting two pars of wheel to either motor

B. Project Management

Improved adherence to project management guidelines would have mitigated subsequent project issues. Initially, time allocation for sub-tasks in robot design adhered to a deadline-driven approach rather than task duration-based scheduling. This oversight obscured the complexity of the robot's design relative to the project timeframe. Additionally, integrating periods were not factored into the project's original timeline, necessitating late-night work sessions for team members. A further oversight was the omission of manufacturing lead times from project planning. While initially assumed unnecessary, multiple instances arose where part fabrication preceded subsequent work, underscoring the necessity for scheduling manufacturing timelines, accommodating potential delays such as unavailability of prototyping facilities, to ensure uninterrupted progress.

Author Contributions

Sabrina Button: Conceptualization, Methodology, Software, Validation, Writing - original draft (Abstract, Introduction, Methods - Claw Design, Methods: Arm Design, Methods - Trunk Design, Methods - Electrical System, Methods - Material Selection and Usage, Results - Arm and Claw, Results - Autonomy Simulation, Results - Power Distribution.), Visualization, Writing - review & editing.

Michael Farah: Conceptualization, Methodology, Software, Validation, Writing - original draft (Introduction, Methods - Drivetrain Design, Results - Drivetrain Performance and Contact, Results - Adapted Drivetrain using original Parts, Discussion), Visualization, Writing - review & editing.

References

[1] W. Crooks, G. Vukasin, M. O'Sullivan, W. Messner, and C. Rogers, "Fin ray® effect inspired soft robotic gripper: From the robosoft grand challenge toward optimization," *Frontiers in Robotics and AI*, vol. 3, 2016. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2016.00070

[2] Y. Yang, K. Jin, H. Zhu, G. Song, H. Lu, and L. Kang, "A 3d-printed fin ray effect inspired soft robotic gripper with force feedback," *Micromachines*, vol. 12, no. 10, 2021. [Online]. Available: https://www.mdpi.com/2072-666X/12/10/1141

[3] *Hitec HS422 Servo*, Hitec, 5 2017.

[4] J. Bruton, "One-motor cvt robot arm 1 - gearbox." [Online]. Available: https://www.youtube.com/watch?v=iU1sePYPq1g

[5] D. Delling, P. Sanders, D. Schultes, e. J. Wagner, Dorothea", D. Wagner, and K. A. Zweig, *Algorithmics of Large and Complex Networks: Design, Analysis, and Simulation*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, ch. Engineering Route Planning Algorithms, pp. 117–139. [Online]. Available: https://doi.org/10.1007/978-3-642-02094-0_7

[6] OlliePugh, "Olliepugh/a-star-pathfinding: Python pygame script which provides a user interface for performing a* searches." [Online]. Available: https://github.com/OlliePugh/A-Star-Pathfinding

[7] "6v dc motor 10kg-cm 210rpm w/encoder." [Online]. Available: https://ca.robotshop.com/products/6v-dc-motor-10kg-cm-210rpm-encoder?gad_source=1gclid=Cj0KCQjwiYOxBhC5ARIsAIvdH518rqzqbt4rBTlJ7BeDU

[8] "Mp3424 single aa battery boost solution." [Online]. Available: https://www.monolithicpower.com/en/mp3424-single-aa-battery-boost-solution

[9] K. A. K. T. R. Tadakuma, "Abenics: Active ball joint mechanism with three-dof based on spherical gear meshings," *IEEE Transactions on Robotics*, vol. 37, no. 5, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9415699