Carnegie Mellon University
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# Group4: Golf-Ball Collecting and Cleaning Robot

# Final Report


Amelia Zaripova

Andrea Piraneque

Junming Wang

Vrishabh Kenkre

Zikang Wu Zikang Wu


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# I. Problem Definition

## A. Problem description

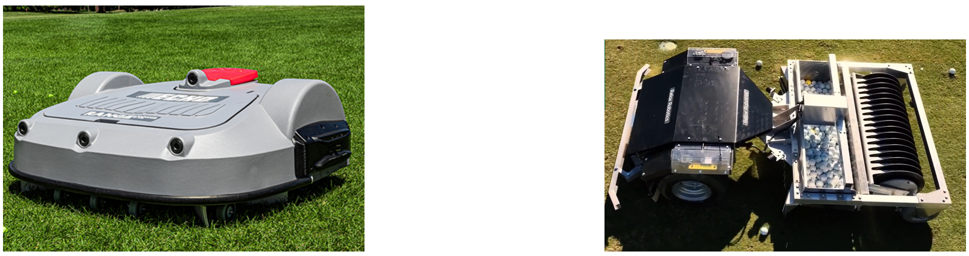
According to the National Golf Foundation, in a sports industry drawing 45 million individuals ages six and above, at least 18.4 million of these individuals participated exclusively in non golf course activities in 2023. These activities included driving ranges, golf simulators, or golf entertainment settings, such as Topgolf. To meet this demand, the United States boasts approximately 4,000 driving ranges that provide golfers with anywhere from 2 to 17 acres of space to practice their swing.

To meet the demands of a growing clientele base with such a large scale product and service, driving range managers and employees are posed with the challenge of maintaining an efficient workflow of collecting and cleaning their golf balls on a daily basis. Interviews with numerous driving range owners and managers revealed that an average weekday driving range in Pittsburgh, PA, USA collects and cleans about 30,000 golf balls before opening. On weekends, this number rises to 50,000 golf balls. This multi-step process begins with collecting these golf balls using a $3,000 to $7,000 collection attachment for a caged golf cart upwards of $4,000. The balls are then manually transported to a golf ball cleaning machine that can cost up to $8.000 and adds to the total 3 to 4 hours of the entire process. This process also depends on the manual labor of about 4 to 5 employees in various weather conditions. The Golf-ball Collect and Clean (C&C) robot seeks to address this time-consuming, labor-insensitive, and cost-intensive process. The C&C solution provides a novel design that integrates the collecting and cleaning processes onto a cost-efficient small-scale robot.

## B. Markets addressed and primary competitors

As part of the larger golf market, the Golf-ball C&C robot addresses the driving range management market and driving range equipment market. This solution directly impacts driving range stakeholders such as owners, management teams, employees, and golfers.

*1) Robotic Collection Competition:* Most comparable to the C&C robot, there are a small number of robotic golf ball collectors designed for high volume collection. These robots, however, do not compete with the C&C robot's novel integrated cleaning feature. The top competitors in this category include the Range Picker robot by Relox Robot and the Robot Golf Ball Picker by Echo Robotics.



(a) (b)

Fig. 1: (a) Robot Golf Ball Picker by Echo Robotics (b) Range Picker robot by Relox Robots

*2) Cleaning Competition:* The golf balls, collected either robotically or traditionally, are then transported to a mass cleaning machine. There are various sizes and scales of these cleaners on the market, with smaller scale cleaners around $2,000 and large scale cleaners around $8,000.

Key Features of the RS-Revolution Range Ball Washer (Large Scale Cleaner) include:

- Cleaning capacity of 30,000 golf balls per hour
- Water consumption rate of 1 gallon per minute

Fig. 2: RS-Revolution Range Ball Washer (Large Scale Cleaner) by Range Servant

### C. Assumptions

*1) Fleet Application:* It is assumed that in the use case of collecting and cleaning an entire driving range, the user would employ multiple C&C robots in a fleet. This provides the cost and time efficiency relative to competitors when comparing collecting and cleaning the same amount of golf balls. The quantity of C&C robots necessary in a fleet would be proportional to the size of the driving range.

*2) Terrain Navigation Robustness:* The robustness of the C&C's navigation assumes minimally unideal conditions. Ideal conditions can be considered as flat, smooth, and dry terrain. Minimally unideal conditions include slight inclines and roughness of terrain as well as potentially damp terrain. Improved robustness is assumed to be a target improvement for future iterations.

*3) Filtered Collection:* Collection is assumed to be solely of golf balls a non-critical size or amount of non-target objects. Golf balls are to be considered as the target objects and debris such as leaves, sticks, rocks, etc. is are to be considered as the non-target objects. Non-critical size or amounts of these objects can be considered as insufficient to break the collection, cleaning, navigation, or storing subsystems.

*4) Terrain Mapping:* It is assumed that the user will customize the driving range grid mapping definition (quantity of grids used to divide a driving range) to employ sweeping navigation.

*5) Scrubbing Quality:* It is assumed that the proven capacity of the cleaning scrubber to clean 90% of dirt from golf balls is considered a sufficient clean for the purposes of the Golf-ball C&C robot.

*6) Known Static Obstacles:* The layout of each driving range is unique to its topography and organization of obstacles such as flagsticks. It is assumed that these obstacles will be static and sufficiently constant that they will not be changed more frequently than once a year. This provides reliability in mapping navigation around static obstacles.

### D. Constraints

*1) Storage Volume:* Considering the high volume collection rates of competing collection methods as well as the Fleet Application assumption, a single C&C robot will hold at least 60% of the lowest robotic collection competitor's volume (300 balls). This ensures that, when applied in fleet, the C&C robots will surpass small-scale robotic collection competition. The possible storage volume is also constrained by the power of the C&C robot's motors. This results in a C&C storage capacity of 200 balls (approximately 20 lbs).

*2) Collection Rate:* The rate of collection from the collection subsystem is constrained by the size and number of collection wheels. Currently, the dimensions of the 5 collection wheels are a diameter of 9 inches.

*3) Cleaning Quality:* For the scrubber in the cleaning subsystem to provide a sufficient clean (approximately 90% clean), the surface area of the golf ball that is scrubbed must be maximized. This is constrained by type of sponge used, the pattern of how the plates of the scrubber are lined with the sponges, and the spacing between the sponge-lined plates.

*4) Cleaning Rate:* The rate of golf balls cleaned per minute is constrained by the cleaning subsystem's torque capacity, the required torque to clean one golf ball, and the number of pushing fins in the cleaning scrubber. The custom scrubber gear box has a stall torque at 6 volts of 510 lbin. The necessary torque to push one golf ball through the scrubber was calculated to be 7 lb-in. The scrubber was designed with 6 fins. This results in a capacity to scrub 29 golf balls per minute.

*5) Navigation Speed:* To achieve a navigation speed comparable to a human walking (average of 3 miles per hour), the robot was constrained by the selection of motor, number of motorized wheels, and size and weight of the robot. By motorizing four driving wheels with 7.5 lb-in stall torques the C&C robot is able to support 55 lbs of vehicle weight traveling at 3.5 mph.

## II. Stakeholders and Customer Needs

### A. *Stakeholder identification*

There are two main groups of stakeholders for the C&C robot: the primary group being driving range employees, and the secondary group being golfers visiting these driving ranges. The employees working at driving ranges are the people we would expect to be majorly in contact with the robot, interfacing to program its desired path and to unload the golf balls upon collection and cleaning. Their adoption of these robots over traditional collection carts and cleaning systems, as well as over other pre-existing golf ball collecting robots, is crucial to our product's success. Within this group, we are interested in the owners/managers of the driving ranges, as they will likely be the ones to lead decisions regarding the purchase of systems for collection and cleaning of their ranges' balls, in addition to those they employ to ensure the daily maintenance of their range who will be more frequently interacting with the robot itself. We are also interested in the opinions of our secondary stakeholders; while they are not directly involved in the cleaning and collection of golf balls, their frequency of driving range usage dictates some product functionalities. Additionally, the most common form of collection currently, golf ball collection baskets attached to golf carts, are often driven during open hours of the range, during which golfers can see them and may often attempt to hit the carts. This dynamic interaction with golfers thus necessitates further exploration of their perspectives on current methods and our product proposal. Manufacturers and distributors are identified as minor stakeholders in our case as it must be possible to produce and ship these devices in a safe, efficient manner, emphasizing the need for design for manufacturability constraints to be considered throughout this whole process.

### B. *Customer needs*

*1) External outreach:* To develop customer needs for this robot, the team conducted interviews using an open-ended questionnaire with both driving range employees and avid golfers. The purpose of these questions was to better understand the current systems driving ranges have in place to collect and clean balls, the current major pain points for driving range employees with these systems, and the frequency and depth of interaction between golfers with both driving ranges themselves as well as the existing collecting and cleaning systems. From these conversations, it was clear that current collecting and cleaning methods are still highly manual and time-consuming; however, driving range workers are comfortable with their current equipment, so the introduction of a novel system combining these two methods should eliminate the vast majority of labor required. A summary of the overall collection and cleaning systems in driving ranges now as described by these stakeholders is detailed in Fig.3.

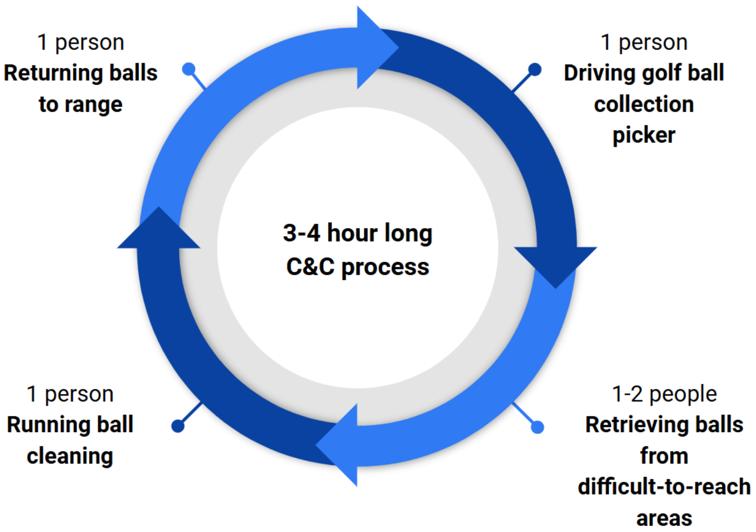



Fig. 3: Current C&C Process

In mapping out this process, there are some needs that we simply cannot realistically meet, like retrieving golf balls from difficult-to-reach areas like netting or ditches. The stages of collecting, cleaning, and returning, however, are areas on which we can begin to focus our basic customer needs.

We also explored the idea of more exciting features, like damaged ball detection or clean ball detection. From our initial round interviews, stakeholders mentioned damaged balls or dirty balls being refed to golfers on the range as an inconvenience, but the importance of this issue was still uncertain. Posing the question of how critical different issues that may arise at the driving range's ball dispenser gave us the insights described in Fig.8.

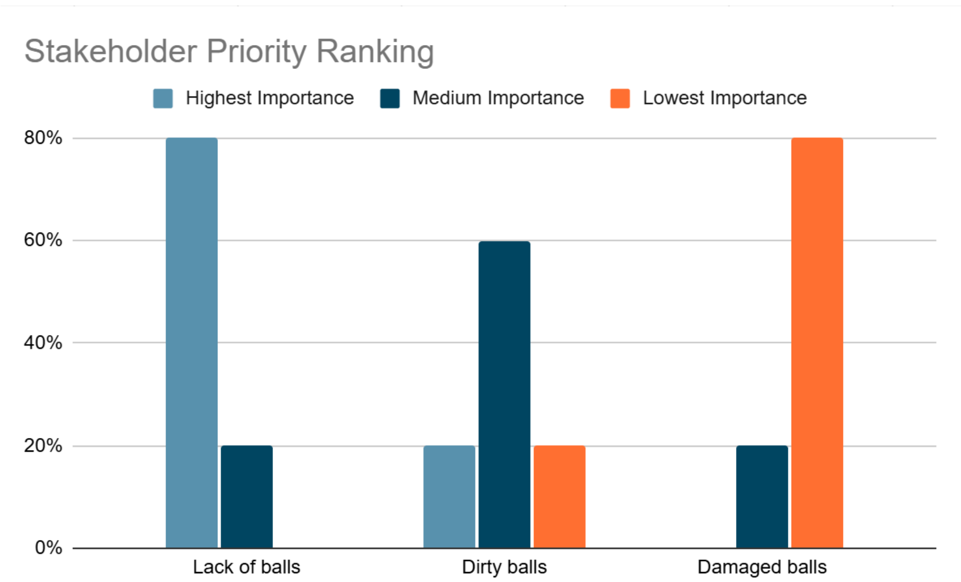



Fig. 4: Ranking of Potential Issues at the Ball Dispenser

From the analyses of our user surveys, the most critical need was ensuring our system efficiently collects golf balls. Given that this was of highest priority for our stakeholders, this need replaced the potential for developing a damaged or dirty ball detection. While cleaning optimally remains a priority as well given that it was commonly ranked of medium importance, developing this further with a dirty ball detection did not appear to be of much interest or significance to our stakeholders. Stakeholders also mentioned that the common current collection method of golf ball pickers attached to golf carts often warrants dynamic interaction from golfers at the range who enjoy the disturbance to the typical static range environment and the challenge of a moving target. The potential for this interaction to exist between golfers and our robot thus adds the opportunity for features beyond basic usability. Other aspects of our product's functionality were similarly guided by this user survey feedback.

*2) Internal generation:* Upon thorough interviews and analyses, the team generated a preliminary list of customer needs and began classification of these needs based on their overall associated functionality. These classifications were namely needs associated with the product 1) requiring low maintenance, 2) effectively collecting balls, 3) effectively cleaning balls, 4) enhancing the overall golf course environment, and 5) being durable. The Kano Model was used to further classify and guide the ranking of the developed specifications based on their assigned level of Basic, being needs that must be apparent for the product to succeed, Performance, which are needs that increase customer satisfaction as they are more thoroughly met, and Exciting, the unique or unexpected features a product may offer. The customer needs translated to engineering needs associated with our product are detailed in Table I; our most critical needs are ease of direction, reliability of ball collection, reliability of ball cleaning, and accuracy of robot's navigation.

TABLE I: Customer Needs

| **Category** | **Number** | **Description** | **Kano** |
|---|---|---|---|
| A) Low maintenance | 1 | Optimized power supply | P |
| A) Low maintenance | 2 | Minimal replacement interactions | P |
| A) Low maintenance | 3 | Ease of direction | B |
| A) Low maintenance | 4 | Low cost | P |
| B) Effective collection | 1 | Reliable collection | B |
| B) Effective collection | 2 | Minimizes labor previously spent collecting | P |
| C) Effective cleaning | 1 | Reliable cleaning | B |
| C) Effective cleaning | 2 | Minimizes labor previously spent collecting | P |
| D) Enhancement of range environment | 1 | Dynamically interacts with golfers | E |
| E) Durable | 1 | Withstands variable weather conditions | P |
| E) Durable | 2 | Withstands variable environmental conditions | P |

## III. Target Specifications

### A. Mapping of customer needs to metrics

After identification, the broader customer needs were mapped to metrics as indicated in Table III. Ranges were assigned to these metrics to evaluate how thoroughly each of these criteria are met through competitive analysis to the Robot Golf Ball Picker by Echo Robotics, RangePicker robot by Relox Robots, RS Revolution Range Ball washer, and P2 Golf Ball Washer when applicable. However, considering the novelty of our product, a perfectly comparable product does not exist on the market, thus requiring logical reasoning and research to establish other valid specs. For example, metric 11: position accuracy, was scoped based on the accuracy of existing sensors and a basic cost-benefit analysis of such sensors. For metric 20: withstanding water damage, the International Electro-technical Commission (IEC) developed standard of ingress protection (IP) ratings were referenced, with which our marginal performance requires the product to be dust-protected and protected against splashing water like rain and our ideal performance requires the product to be dust-tight and protected against water jets that may come from sprinklers on the range.

### B. Competitive analysis

A competitive analysis was conducted on the products listed in Table II and used for comparison based off of publicly available information. Further details on these metrics for our product and the chosen ranges based off this competitive analysis can be viewed in Table III.

TABLE II: Competitive Analysis

| **Metric** | **Robot Golf Ball Picker by Echo Robotics** | **RangePicker robot by Relox Robots** | **RS Revolution Range Ball washer** | **P2 Golf Ball Washer** |
|---|---|---|---|---|
| 1 - Charge time (mins) | 80 | 120 | | |
| 2 - Charge duration (hrs) | 2 | 6 | | |
| 9 - Cost (dollars) | 21,000 | | 2,000-8,000 | 1,375-3,250 |
| 12 - Travel speed (km/hr) | 3.5 | 5 | | |
| 13 - Ball storage capacity | 300 | 1,000 | | |
| 14 - Coverage area (square meters) | 24,281 | 60,000 | | |
| 17 - Cleaning speed (balls/hr) | | | 30,000 | 15,000 |

### C. Target specifications

TABLE III: Target Specifications

| Metric | Need Number | Description | Importance | Units | Marginal-Ideal Range |
|---|---|---|---|---|---|
| 1 | A1 | Low charge time | 3 | minutes | 120-60 |
| 2 | A1 | High charge duration | 4 | hours | 3-8 |
| 3 | A1 | Returns to charging base on its own | 2 | binary | no-yes |
| 4 | A1 | Returns ball to range on its own | 3 | binary | no-yes |
| 5 | A2 | Long single-sponge usage time | 3 | balls cleaned | 200-1200 |
| 6 | A2 | Ease of sponge replacement | 4 | installation time in minutes | 1-5 |
| 7 | A2 | Ease of golf ball storage release | 4 | installation time in minutes | 1-3 |
| 8 | A3 | Straightforward UI for robot direction | 5 | subjective | 5/10-9/10 |
| 9 | A4 | Low cost | 4 | dollars | 3,000-1,000 |
| 10 | B1 | High picking accuracy | 5 | percentage of balls picked in square foot of area | 85-95 |
| 11 | B1 | High position accuracy | 4 | m | 5-1 |
| 12 | B2 | Fast collection speed | 3 | km/hr | 3.5-5 |
| 13 | B2 | High ball storage capacity | 3 | number of balls | 200-600 |
| 14 | B2 | Large coverage area | 3 | square meters | 10,000-35,000 |
| 15 | C1 | High cleanliness results | 5 | percentage of dirt removed | 75-95 |
| 16 | C1 | Cleans only when necessary | 2 | binary | no-yes |
| 17 | C2 | High speed cleaning | 3 | balls/hr | 200-1,500 |
| 18 | D1 | Recognizes golfers in close range | 2 | distance from golfers in meters | 100-1,000 |
| 19 | D1 | Visually taunts golfers in a fun, competitive manner | 2 | subjective | 5/10-9/10 |
| 20 | E1 | Withstands water damage | 4 | IP (ingress protection) rating | IP54-IP65 |
| 21 | E2 | Withstands golf ball hits | 3 | lbs of force | 500-5000 |
| 22 | E2 | Avoids obstacles | 4 | percentage of obstacles avoided | 75-90 |

## IV. Functional decomposition

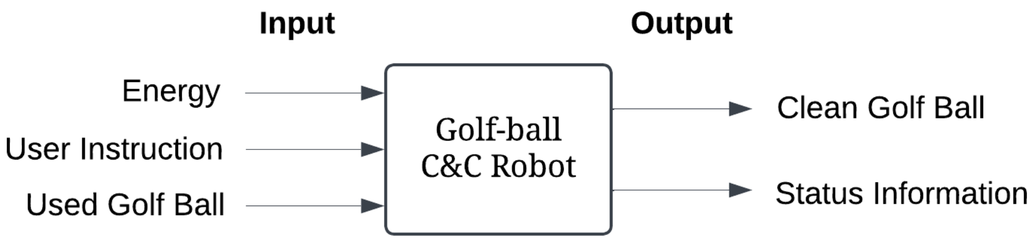



Fig. 5: Function Diagram.

Fig.5 shows the overall system function diagram.In the golf ball collection and cleaning robot, the system receives three primary inputs: energy, user instructions, and golf balls. Energy is essential for powering the robot's various subsystems, including motion for navigation and mechanical actions for cleaning. User instructions guide the robot's operational parameters and navigation, ensuring it performs tasks as intended in the specific areas. The golf balls themselves are the targets for collection and cleaning.

The robot processes these inputs through a series of integrated subsystems to produce two key outputs. The first output is clean golf balls, which are the result of the collection and cleaning processes involving spraying and scrubbing actions. The second output is status information, which provides real-time feedback on various aspects of the robot's operation, such as battery levels, and capacity status. This feedback is crucial for monitoring and optimizing the robot's performance, ensuring reliability and efficiency in its task execution. A detailed function diagram is shown in Fig.6

## V. Concept Generation

### *A. Collecting*

Table.IV describes our collecting concepts. The existing industrial standards (Fig.28) typically employ collecting wheels of various geometries, which are mounted at the front of a golf cart. Given budgetary constraints, we plan to reference these mechanisms and reverse-engineer our own collection systems.

TABLE IV: Collecting Concepts Description

| **Name of Concepts** | **Description** |
|---|---|
| Rotating Discs Fig.28 | The roller has a series of small disks, the disks have gaps or slots sized to fit golf balls but exclude larger debris. |
| Brush Wheels Fig.28 | Using stiff brushes arranged in a wheel configuration, these mechanisms roll over the ground, and the brushes sweep the golf balls into a collection area or conveyor |

### *B. Cleaning*

Golf ball cleaning mechanisms range from simple manual devices, such as hand-operated brushes and dipping baskets, to sophisticated automated systems including rotary drum cleaners and vibratory cleaners. Large-scale operations, such as driving ranges, may use conveyor belt washers that subject golf balls to sequential cleaning stages or ultrasonic cleaners that utilize high-frequency sound waves to

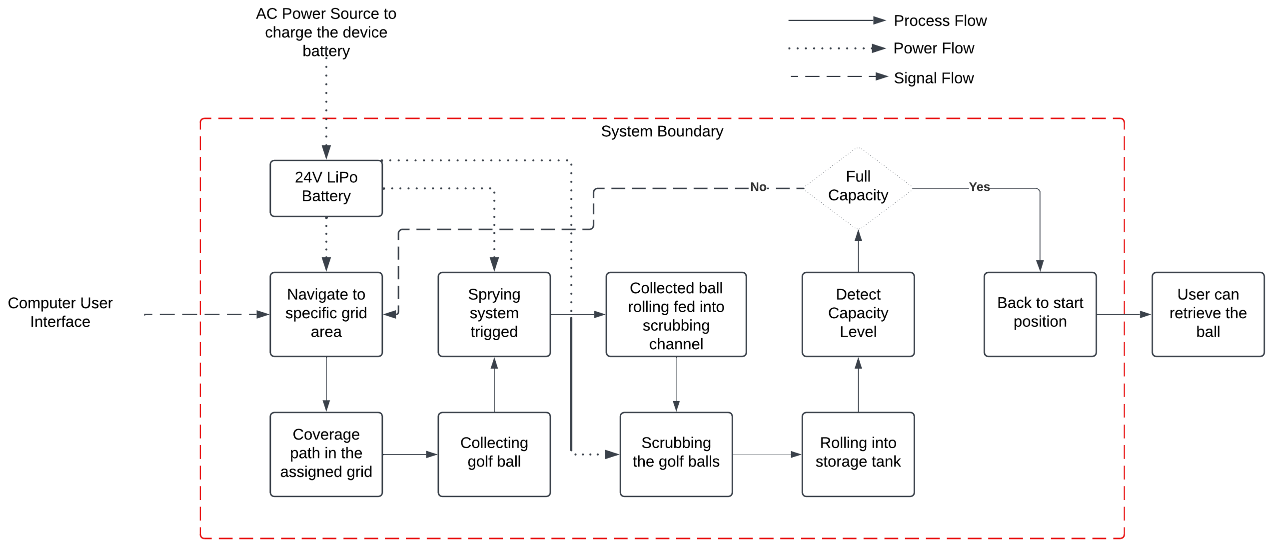



Fig. 6: Detailed Function Diagram.

thoroughly remove dirt without physical scrubbing. Some advanced systems integrate both collecting and cleaning functionalities, streamlining the process by directly transferring collected golf balls into onboard cleaning units, efficiently preparing them for reuse.Inspired by existing solutions, the descriptions for each concepts is shown in Table.V

TABLE V: Cleaning Concepts Description

| **Name of Concepts** | **Description** |
|---|---|
| Circular channel Scrubbing + spraying Fig.29 | The cleaning process begins with water spraying onto the surface of the golf ball, followed by the ball rolling into a circular scrubbing channel. A central rotational propeller will turn, pushing the golf ball along the channel, which is lined on the top and bottom with abrasive sponges. After thorough scrubbing, the golf ball will then drop into the storage basket. |
| Straight channel scrubbing + spraying Fig.30 | Rather than employing a central rotational propeller, this straight channel scrubbing mechanism will utilize a belt system. The teeth on the belt will propel the ball along the inside of the channel. |
| Vertical Rotational brushes + water tank Fig.31 | instead of spraying water, the golf balls are submerged in a water tank where large rotating brush clean and propel the balls forward. |
| horizontal rotational brushes + water tank Fig.32 | The horizontal rotating brush was replaced by two vertical brushes. |

## C. Chassis

The workflow of a golf ball through the C&C robot consists of collection to cleaning to storage. The purpose of the chassis is to integrate these subsystems onto a robotic driving base. The most significant design concerns including driving direction of the collection system and the method used for storing. Table.VI shows the descriptions:

TABLE VI: Chassis Concepts Description

| **Name of Concepts** | **Description** |
|---|---|
| Pulling Collection Fig.35 | By pulling the collection system and driving forward from the storage unit, the golf balls collected would follow an external collection path. This would then allow the ball to land and roll on a stopper ramp into the cleaning subsystem. |
| Pushing Collection Fig.36 | By pushing and driving forward from the collection system, the golf balls collected would follow an internal collection path. This would then require the ball to bounce off of an angled stopper onto a collection ramp into the cleaning subsystem. |
| Crate Storage **??** | To provide the user with an easily accessible container of the golf balls to transport from the robot to the golf ball dispensers, a simple crate on a wheeled based was considered as a first design. This design features a purchasable plastic crate that would determine the dimension of the robotic base it would sit on. It would sit within an 80/20 rail frame during collection. |
| Draw-String Bag Storage**??** | An alternative storage consideration is to employ a similar 80/20 rail frame as the robotic base and attach hooks onto the upper ends of these rails. These would be compatible for a custom draw-string mesh bag to be hooked onto and store the balls while collected. Once the user is ready to transport the balls, they can cinch the bag close for secure transportation without losing golf balls. |

### *D. Motion*

For the motion system of an autonomous golf cart, options range from basic configurations, such as fixed-speed direct-drive systems, to more complex setups including variable speed controls and automatic steering adjustments. At the simpler end, fixed axle systems provide consistent and straightforward navigation but lack flexibility. For more dynamic control, differential steering allows the cart to manage tight turns and navigate varied terrains by varying the speed of each wheel independently.

Advanced motion systems might incorporate GPS-based autopilot features that adjust the cart's speed and steering based on real-time location data, optimizing paths across the golf course. For enhanced terrain adaptability, some carts could be equipped with terrain response systems that detect surface changes and adjust motor torque accordingly. This ensures optimal traction and energy efficiency regardless of ground conditions. High-end models could integrate all of these features, providing a fully automated driving experience that adjusts in real-time to the environment, enhancing both safety and user experience on the golf course.

The approaches outlined above provide robust solutions by addressing specific needs and challenges, thus enhancing the adaptability and effectiveness of the robotic system in dynamic operational settings.

TABLE VII: Motion, Navigation, Power and Planning Concepts Description

| **Name of Concept** | **Descriptions** |
|---|---|
| Modular Mobility Units | 1. Interchangeable wheel and track modules: Allows for optimal traction and adaptability on varied terrains.<br>2. All-terrain wheel designs: Features wheels with variable tread patterns to enhance grip on different surface conditions. |
| Integrated Navigation Suite | 1. GPS with inertial systems: Enhances location tracking under signal loss.<br>2. LIDAR and vision fusion: Creates a detailed map for better obstacle navigation. |
| Distributed Power Management | 1. Modular batteries: Scales power capacity based on mission demands.<br>2. Energy harvesting systems: Supplements power to extend operational times. |
| Adaptive Path Planning Algorithm | 1. Machine learning-based route optimization: Improves routing efficiency over time.<br>2. Reactive obstacle avoidance: Quickly recalculates paths to bypass obstacles. |

### *E. Navigation*

Since the operation of a golf ball collecting robot closely resembles that of a household vacuum robot, we decided to draw inspiration from the path planning algorithms commonly used in robotic vacuum cleaners. By studying and adapting these algorithms, we aim to integrate efficient, systematic, and adaptable navigation strategies into our robot's design. This approach will enable our robot to cover designated areas effectively, avoid obstacles, and prioritize high-density zones for optimized collection performance. By combining and tailoring these proven algorithms, we can enhance our robot's ability to navigate large outdoor spaces with the precision and thoroughness required for golf ball retrieval.

TABLE VIII: Common Path Planning Algorithms for Robotic Vacuum Cleaners

| **Algorithm** | **Description** |
|---|---|
| Random Path Algorithm | The robot moves in random directions, changing direction upon encountering obstacles. This method is simple to implement and suitable for small spaces, but it has low efficiency and may leave some areas uncleaned or repeatedly clean the same area. |
| Spiral Path Algorithm | The robot starts from a central point and gradually moves outward in a spiral pattern. This algorithm works well in open spaces and can cover central areas effectively but is less efficient in rooms with obstacles or narrow spaces. |
| Zigzag or Lawn Mower Pattern | The robot moves in a back-and-forth zigzag pattern, similar to a lawn mower. This method is ideal for regular-shaped rooms and achieves high coverage efficiency, making it a common choice for commercial robotic vacuums. |
| Grid-Based Path Planning | The cleaning area is divided into smaller grids, and the robot cleans each grid systematically to ensure complete coverage. This approach is suitable for rooms with clear boundaries and uses sensors or localization systems to improve accuracy and coverage. |
| Vision-Based Path Planning | The robot uses cameras or sensors for visual recognition, detecting obstacles, dirt, or stained areas on the floor. Based on the recognition results, the robot dynamically plans the cleaning path, prioritizing dirtier areas. This method is ideal for complex environments, optimizing cleaning paths but requiring advanced processing and recognition algorithms. |

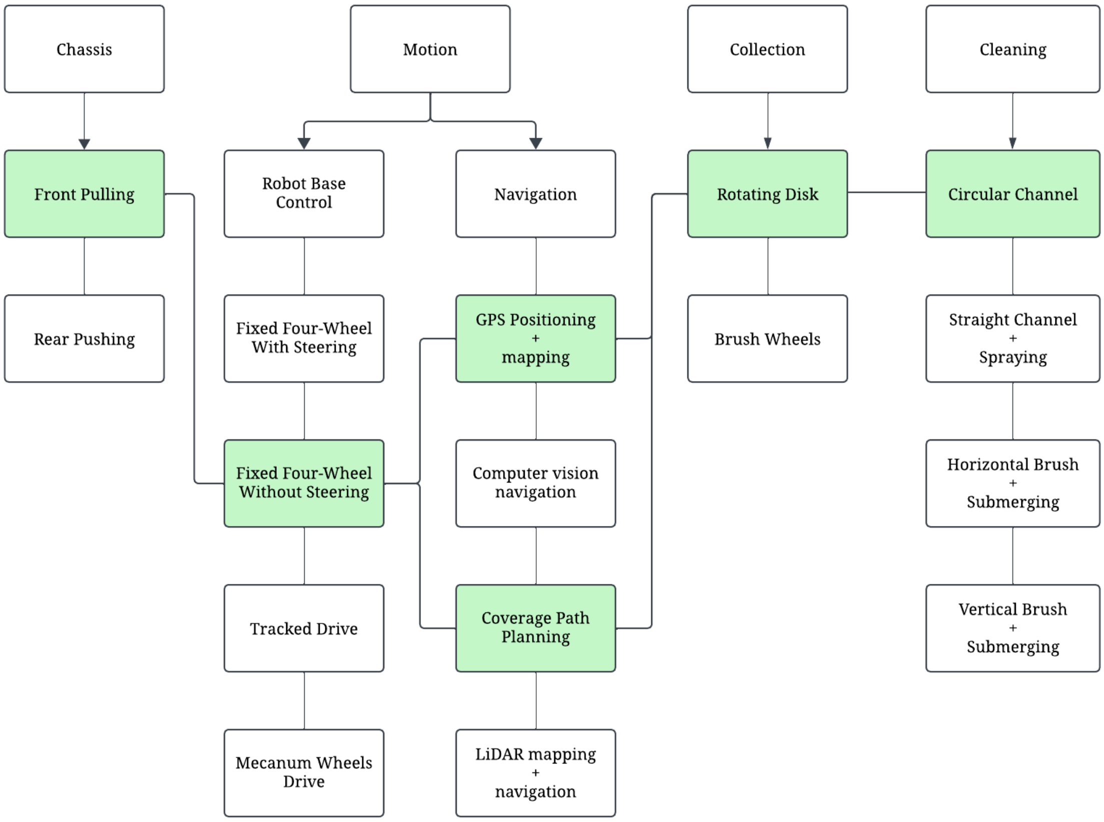



Fig. 7: Classification and Combination for subsystem concepts.

## *F. Classifications and Combinations*

As shown in Fig. 7, the Motion subsystem is structured around Robot Base Control using a fixed four-wheel configuration without steering, providing stable and straightforward control. For navigation, the system integrates GPS Positioning and Mapping, ensuring precise location tracking, along with Coverage Path Planning to achieve efficient area coverage and optimal path management.

In the Collection subsystem, a Rotating Disk mechanism has been selected for its effectiveness and adaptability in collecting golf balls across different terrains. This design enhances collection efficiency while ensuring smooth operation.

The Cleaning subsystem employs the only Circular Channel . This choice eliminates water usage and maintenance demands while maintaining high cleaning standards. The mechanism ensures thorough cleaning of golf balls as they pass through the channel.

The Chassis subsystem is designed with a Front Pulling configuration, which provides a balance of stability and traction. This setup also facilitates easy detachment of golf balls from the collector through front pulling, improving operational efficiency.

# VI. Concept Selection

For the selection of key components across all subsystems of the robot, a structured concept selection process was utilized. This comprehensive approach involved evaluating a range of potential components and design configurations for motion, cleaning, collection, navigation, and base design. The process considered both external and internal options for each subsystem, ensuring that all components were optimally chosen to meet the project's requirements. Key metrics used for the evaluation included functionality, efficiency, power requirements, weight, durability, and compatibility with other subsystems. By applying these criteria, the most suitable configurations were identified to enable robust and reliable operation across all aspects of the robot.

## *A. Collecting*

In evaluating the rotating disk collection method versus the brush disk collection method for our golf ball collector, we focused on manufacturability, robustness in collection, and flexibility. The rotating disk method emerged as superior in manufacturability due to its simpler design and fewer moving parts, which are easier to produce and maintain. Its robustness is also notable; the rotating disks are highly effective at navigating varied terrain and consistently picking up golf balls without clogging or malfunctioning, a common issue with brush disks that can entangle debris. While brush disks offer flexibility in handling different sizes of debris other than golf balls, their maintenance and cleaning needs outweighed their benefits for our specific application. Consequently, we opted for the rotating disk method, as it best meets our operational requirements and offers a more reliable and cost-effective solution. A concepts screening charts is shown in Table.IX.

TABLE IX: Collecting Concepts Screening

| **Criteria** | **Rotating Discs** | **Brush Wheels** |
|---|---|---|
| Manufacturability | + | - |
| Collecting Robustness | + | 0 |
| Adaptivity | - | + |
| **Total** | +1 | 0 |
| **Continue?** | Yes | No |

## *B. Cleaning*

In our evaluation of four distinct golf ball cleaning concepts, we analyzed each based on manufacturing simplicity, water usage, waterproofing requirements for components, and maintenance demands. The first two ideas utilized a spraying system combined with a scrubbing channel: one featured a straight channel driven by a belt system, and the other employed a circular channel powered by a single actuator in the center. The other two proposals involved submerging the golf balls in a water tank where rotating brushes would perform the cleaning. After thorough consideration, we decided to proceed with the circular channel concept. This decision was driven by its ease of manufacturing—owing to fewer complex parts—and its efficient use of water, which reduces the need for extensive waterproofing of other components. Additionally, this method requires lower maintenance, making it a more practical and cost-effective solution for our needs. This design's streamlined operation and structural simplicity ultimately aligned best with our project goals and resource availability. A cleaning concepts screening and scoring table is shown in Table.X and Table.XI.

TABLE X: Cleaning Concepts Screening

| **Criteria** | **Circular channel** | **Straight channel** | **Vertical Brushes** | **Horizontal Brushes** |
|---|---|---|---|---|
| Cleaning Capacity | 0 | 0 | + | + |
| Structural complexity | + | 0 | - | - |
| Power Consumptions | + | + | - | - |
| Cleaning Efficiency | 0 | 0 | + | + |
| **Total** | +2 | +1 | 0 | 0 |
| **Continue?** | Yes | Yes | No | No |

TABLE XI: Cleaning Concepts Scoring

| | | Circular channel | | Straight channel | |
|---|---|---|---|---|---|
| Criteria | Weight | Score | WScore | Score | WScore |
| Cleaning Capacity | 0.2 | 3.0 | 0.6 | 4 | 0.8 |
| Structural complexity | 0.4 | 2.0 | 0 | 3 | 1.2 |
| Power Consumptions | 0.2 | 4.0 | 0.6 | 3 | 0.6 |
| Cleaning Efficiency | 0.2 | 3.0 | 0.6 | 4 | 0.8 |
| Total | | | 4 | | 3.4 |
| **Continue?** | | | Develop | | No |

### *C. Chassis*

To evaluate the chassis designs, we considered size and material reduction, internal transportation ease and reliability, golf ball volume handling capacity, and ease of moving and maneuvering. The two main chassis design selections necessary were regarding the direction of collecting (pulling or pushing the collector) and method of storing (crate or mesh bag).

The design concept of pushing the collector would prompt the golf balls collected to follow an internal collection path that would then have to be interrupted by an angled stopper. This stopper would have to be designed such that the deflection of the golf ball would be consistent and sufficient for the golf ball to bounce over and onto a collection ramp. This solution would also depend on the collection speed of golf balls and cost a higher price in manufacturing and time. By pulling the collector, the method used by all previously mentioned industry competitors, the golf balls would follow an external collection path and fall onto a stopper and collection ramp with much greater tolerance.

The design concept of the crate and wheeled framed heavily restricted the dimensions of the C&C robotic base as well as the possible volume of storage. To secure the crate during collection, a tall 80/20 rail frame would also be incorporated. However, this design added to the difficulty of removing the crate as the scrubbing subsystem lay over the crate for ease of dispensing cleaned balls, thus blocking the user from simply lifting the crate up. Contrarily, the draw-string bag concept allowed for a more modular design of the robotic base as well as greater ease in assembling and disassembling the storage unit. By having greater control over the design of the robotic base we are able to improve turning navigation.

The chassis concepts scoring are shown in Table.XII and Table.XIII.

TABLE XII: Collection Direction Concepts Scoring

| | | Pulling Collection | | Pushing Collection | |
|---|---|---|---|---|---|
| Criteria | Weight | Score | WScore | Score | WScore |
| Volume Collection | 0.5 | 5.0 | 2.5 | 4.0 | 2.0 |
| Internal Transportation Efficiency | 0.4 | 4.0 | 1.6 | 3 | 1.2 |
| Size and Material Efficiency | 0.3 | 4.0 | 1.2 | 3 | 0.9 |
| Total | | | 5.3 | | 4.1 |
| **Continue?** | | | Develop | | No |

TABLE XIII: Storing Method Concepts Scoring

| | | Draw-String Bag | | Crate | |
|---|---|---|---|---|---|
| Criteria | Weight | Score | WScore | Score | WScore |
| Volume Collection | 0.5 | 5.0 | 2.5 | 4.5 | 2.25 |
| (Dis)Assembly Efficiency | 0.4 | 5.0 | 2.0 | 3 | 1.2 |
| Size and Material Efficiency | 0.4 | 5.0 | 2.0 | 3 | 1.2 |
| Total | | | 6.5 | | 4.65 |
| **Continue?** | | | Develop | | No |

### *D. Motion*

- **Comprehensive Assessment:** Selecting the appropriate motor required a thorough assessment of the torque demands to ensure the robot's capability to transport a 20 kg load across grassy terrain while maintaining a target speed of 1.8–2 m/s. This decision entailed a careful balance between the torque needed to overcome environmental resistances and that required for dynamic operations such as acceleration and maneuvering.
- **Frictional Forces:** The torque analysis began by evaluating the frictional forces, which play a pivotal role in motion control. Given the terrain type, the coefficient of friction for grass was considered, leading to calculations that focused on the frictional torque required to counteract the resistance encountered by the robot's wheels on grass.
- **Dynamic Acceleration:** Following the initial analysis, attention was turned to dynamic torque, which considers the robot's acceleration needs. This involves the moment of inertia of the wheels and the necessary angular acceleration to reach the desired speed within the planned time frame. This component of torque is critical for determining the responsiveness and agility of the robot in reaching and maintaining its operational speed.
- **Total Torque Requirement:** The cumulative findings from assessing both frictional and dynamic torque requirements provided a comprehensive view of the total torque needed per motor. This total is crucial for ensuring that the motors are not only capable of initiating movement but also maintaining it under varying operational conditions.
- **Motor Selection:** Based on the total torque requirements, a motor was selected that offers a 19:1 gear ratio and operates at 12 volts, featuring a stall torque significantly higher than the calculated needs. This stall torque, considerably surpassing the minimum required, offers a robust safety margin that caters to unforeseen environmental challenges or additional loads.
- **Reliability and Adaptability:** The selected motor's high torque capacity ensures that the robot is well-prepared to handle diverse terrain and unexpected load increases, thus providing reliable and consistent performance. This adaptability is key to the robot's functionality, allowing it to perform effectively across a range of real-world conditions.

For detailed insights into the underlying principles, mathematical derivations, and engineering decisions made during these analyses, refer to the section on Detailed Design and Engineering Analysis.

The motor selection process aimed to identify motors that could achieve the desired torque and speed to drive a 20 kg robot over grassy terrain. The target linear speed of 2 m/s, achieved in approximately 1 second, established stringent requirements for both torque and acceleration.

TABLE XIV: Pugh Matrix for Motor Selection

| **Criteria** | **High-Torque Gear Motor** | **Brushless DC Motor** | **Integrated Servo Motor** |
|---|---|---|---|
| Torque | 0 | + | - |
| Efficiency | 0 | + | + |
| Weight | - | + | + |
| Fitting | 0 | 0 | - |
| Cost | 0 | - | + |
| **Total Score** | 0 | +2 | 0 |

Based on the Pugh matrix, the Brushless DC Motor with an external gearbox was selected as it provided the best balance of torque, efficiency, and weight.

*Final Motor Selection Justification:* The Brushless DC Motor was chosen for its high efficiency and compatibility with the robot's target speed and torque requirements. Its lightweight design supports the power demands for driving the robot at the specified speed, making it the optimal choice.

*1) Battery Selection:* The robot's battery was selected to ensure that it could provide sufficient power for continuous operation across all motor and sensor components.

*2) Motor parameters needed for battery selection:* To determine the appropriate battery, we assessed the power demands of the robot at peak load, ensuring that the battery could meet these requirements reliably. Here's a detailed breakdown of the power requirements assessment:

- **Motors:** The motors represent the primary power draw on the battery. Considering each motor's peak current under high load conditions, we aggregated the power needs for all four motors to determine their total impact on the battery's load.
- **5V Components:** The robot's 5V systems, which include the microcontroller, GPS, encoders, gyroscope, and other sensors, collectively require a specific amount of power. Given the efficiency of the DC-DC converter used to step down the 12V battery output to 5V, we calculated the necessary power input from the battery to sustain these components.

By summing the power requirements of the motors and the 5V components, we estimated the total power draw from the battery. This total was crucial for understanding the current draw from the battery at peak operational conditions.

The chosen 12V, 50Ah battery was evaluated for its capacity to support the robot's operation over a typical period. Considering the total current draw, we calculated an estimated operating time, determining how long the robot could function at peak load before the battery would need recharging or swapping.

This analysis confirms that the selected battery can sufficiently support approximately 2.05 hours of continuous operation at peak load, which aligns with the operational needs of the robot but highlights the necessity for potential recharging or battery swapping during extended tasks.

For a comprehensive understanding of the calculations and methodologies used in this analysis, please refer to the section on Detailed Design and Engineering Analysis.

The selection process considered different battery capacities and configurations.

TABLE XV: Selection Matrix for Battery Selection

| **Criteria** | **Weight** | **NiMH** | **Lead Acid** | **Li-Ion** |
|---|---|---|---|---|
| Energy Density | 0.4 | 3 | 5 | 4 |
| Weight | 0.3 | 2 | 5 | 3 |
| Cost | 0.2 | 5 | 4 | 4 |
| Charging Time | 0.1 | 3 | 5 | 4 |
| **Total Score** | | 3.1 | 4.8 | 3.7 |

*Final Battery Selection Justification:* The Li-Ion battery pack was selected for its high energy density, low weight, and efficient charging time, making it ideal for the robot's operational needs. Its compatibility with the 12V power requirements of the motors and micro-controllers ensures stable operation over extended periods.

*3) IMU Sensor (MPU-6050) Selection:* The IMU sensor selection for the robot was driven by the need for precise navigation and orientation capabilities to maintain an orientation error within $\pm 1^\circ$ during operation. The specifications for the IMU were derived from the robot's requirements for accurate and responsive measurements.

*a) Gyroscope Sensitivity:* The gyroscope's sensitivity was calculated to ensure it can accurately track the robot's angular velocity, which has a maximum expected value. The MPU-6050 was selected because its sensitivity specifications match the requirements for maintaining the desired accuracy in orientation changes.

*b) Accelerometer Range and Sensitivity:* For the accelerometer, the selection criteria included the ability to handle accelerations resulting from sudden directional changes or variations in terrain, which the robot might encounter during normal operations. The chosen IMU's accelerometer range comfortably covers the maximum expected accelerations, providing a substantial margin to account for unexpected forces.

*c) Sample Rate:* The sample rate requirement was determined based on the need to track the robot's movements accurately and with minimal delay, especially given its operational speed. The MPU-6050's capability to provide high sample rates ensures that it can deliver real-time data, essential for maintaining smooth and stable navigation.

These calculations and the rationale for the specifications were guided by detailed analyses of the robot's performance requirements and operational conditions. For in-depth information on the engineering calculations and decision-making process, please refer to the section on Detailed Design and Engineering Analysis.

TABLE XVI: Selection Matrix for IMU Sensor

| **Criteria** | **MPU-6050** | **LSM6DS3** | **MPU-9250** | **ADXL345** |
|---|---|---|---|---|
| Data Precision | 4 | 5 | 5 | 2 |
| Power Consumption | 5 | 3 | 3 | 4 |
| Cost | 5 | 3 | 4 | 5 |
| Ease of Integration | 5 | 4 | 3 | 3 |
| **Total Score** | 4.7 | 3.8 | 4.2 | 3.2 |

*Final IMU Sensor Selection Justification:* The MPU-6050 was selected for its balance of cost, low power consumption, and ease of integration with the Arduino Mega. The onboard Digital Motion

Processor (DMP) facilitates real-time sensor fusion, making it an efficient choice for maintaining stable orientation and accurate movement tracking.

*4) Microcontroller Selection:* The microcontroller was selected based on both quantitative and qualitative criteria, including processing power, power consumption, I/O capacity, cost, ease of integration, community support, and reliability.

TABLE XVII: Evaluation Matrix for Microcontroller Selection

| **Criteria** | **Arduino Mega** | **Raspberry Pi** | **ESP32** | **Teensy 4.0** |
|---|---|---|---|---|
| **Quantitative Criteria (1-5 Scale)** | | | | |
| Processing Power | 3 | 5 | 3 | 4 |
| Power Consumption | 4 | 2 | 5 | 4 |
| I/O Capability | 5 | 4 | 3 | 5 |
| Cost | 5 | 2 | 3 | 3 |
| **Total Quantitative Score** | 17 | 13 | 14 | 16 |
| **Qualitative Criteria (+/0/-)** | | | | |
| Ease of Integration | + | - | + | 0 |
| Community Support | + | + | + | 0 |
| Reliability | + | 0 | + | + |
| **Total Qualitative Score** | +3 | -1 | +2 | +1 |

*Final Microcontroller Selection Justification:* The Arduino Mega was chosen for its strong performance in both quantitative and qualitative evaluations, offering the best balance of I/O capability, low power consumption, and ease of integration.

*5) Motor Driver Selection:* The motor driver required high current-handling capability, cost-effectiveness, and efficient heat management.

TABLE XVIII: Evaluation Matrix for Motor Driver Selection

| **Criteria** | **BTS7960** | **L298N** | **TB6612FNG** | **VNH2SP30** |
|---|---|---|---|---|
| **Quantitative Criteria (1-5 Scale)** | | | | |
| Current Handling | 5 | 2 | 3 | 4 |
| Cost | 3 | 5 | 4 | 3 |
| Heat Management | 4 | 3 | 3 | 4 |
| **Total Quantitative Score** | 12 | 10 | 10 | 11 |
| **Qualitative Criteria (+/0/-)** | | | | |
| Compatibility | + | 0 | + | + |
| Ease of Use | + | + | + | 0 |
| Thermal Reliability | + | 0 | 0 | + |
| **Total Qualitative Score** | +3 | +1 | +2 | +2 |

*Final Motor Driver Selection Justification:* The BTS7960 was selected for its excellent current-handling capability and compatibility with the motor specifications. Its high scores in both categories confirmed its suitability for high-torque demands.

*6) Encoder Selection:* Encoders were evaluated based on resolution, cost, ease of installation, and compatibility.

*Final Encoder Selection Justification:* The Pololu 64 CPR encoder was selected for its balance of resolution, cost-effectiveness, and ease of installation, providing sufficient accuracy for navigation.

*7) Path Planning Algorithm Selection:* The path planning algorithm required efficient mesh grid navigation with a lawnmower pattern transition.

TABLE XIX: Evaluation Matrix for Encoder Selection

| **Criteria** | **Pololu 64 CPR** | **AS5048A** | **US Digital E4T** | **Rotary Encoder Module** |
|---|---|---|---|---|
| **Quantitative Criteria (1-5 Scale)** | | | | |
| Resolution | 3 | 5 | 4 | 2 |
| Cost | 4 | 2 | 3 | 5 |
| **Total Quantitative Score** | 7 | 7 | 7 | 7 |
| **Qualitative Criteria (+/0/-)** | | | | |
| Ease of Installation | + | 0 | 0 | + |
| Durability | + | + | + | 0 |
| Compatibility | + | 0 | + | - |
| **Total Qualitative Score** | +3 | +1 | +2 | +1 |

TABLE XX: Evaluation Matrix for Path Planning Algorithm

| **Criteria** | **A* on Mesh Grid** | **Dijkstra's on Mesh Grid** | **Greedy BFS on Mesh Grid** | **Hybrid A*/Waypoint** |
|---|---|---|---|---|
| **Quantitative Criteria (1-5 Scale)** | | | | |
| Path Accuracy | 5 | 5 | 3 | 4 |
| Computational Load | 3 | 2 | 4 | 4 |
| **Total Quantitative Score** | 8 | 7 | 7 | 8 |
| **Qualitative Criteria (+/0/-)** | | | | |
| Lawn Mower Transition | + | + | 0 | + |
| Efficiency in Grid Navigation | + | 0 | + | + |
| **Total Qualitative Score** | +2 | +1 | +1 | +2 |

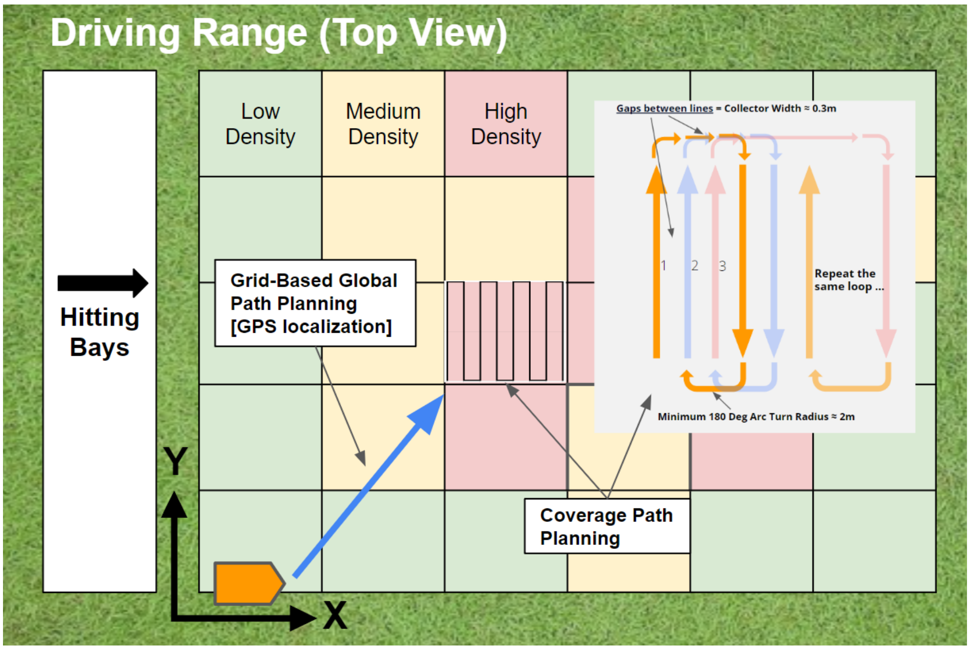



Fig. 8: Path Planning Algorithm Selection

*Final Path Planning Algorithm Selection Justification:* The Hybrid A*/Waypoint algorithm was chosen for its balance of path accuracy, efficiency, and computational load. This approach effectively combines A* for grid navigation and a waypoint-based method to enable smooth transitions to the lawnmower pattern.

*8) Final Justification for Motion Selected Components:* The selected components for the robot's motion and navigation subsystems—Brushless DC Motor, Li-Ion Battery, MPU-6050 IMU, Arduino Mega, BTS7960 motor driver, Pololu 37D Encoder, and the Hybrid A*/Waypoint Path Planning Algorithm—were chosen through a rigorous concept selection process. Each component was evaluated using selection matrices based on essential criteria such as power requirements, accuracy, computational load, compatibility, and cost.

The selected configuration meets the design requirements for an autonomous robot capable of efficiently navigating varied terrain and performing comprehensive area coverage.

- *Brushless DC Motor*: Provides a high torque-to-weight ratio, optimal for achieving the desired speed and maneuverability on grass.
- *Li-Ion Battery*: Ensures reliable power delivery with a high energy density and low weight, meeting the robot's operational duration requirements.
- *MPU-6050 IMU*: Facilitates accurate orientation control with onboard sensor fusion, reducing computational strain on the microcontroller.
- *Arduino Mega*: Chosen for its extensive I/O capacity and sufficient memory, the Arduino Mega effectively manages multiple sensors and controls.
- *BTS7960 Motor Driver*: Selected for its high current handling capacity, allowing robust and reliable control of the motors, especially on rough terrain.
- *Pololu 37D Encoder*: Offers sufficient resolution for precise speed and position feedback, essential for accurate navigation and obstacle avoidance.
- *Hybrid A*/Waypoint Path Planning Algorithm with Lawn Mower Pattern*: Efficiently navigates the mesh grid and performs systematic area coverage using a lawnmower pattern, optimized for the robot's computational limitations.

## VII. Detailed Design and Engineering Analysis

### A. Engineering Analyses and Calculations

This section details the analyses conducted for each subsystem of the final prototype, incorporating precise calculations, assumptions, challenges, and solutions.

*1) Motion Subsystem Analysis:* Ensure the robot can traverse grassy terrain carrying a 20 kg load, maintaining a target speed of 1.8–2 m/s with stability.

*Goals of Analysis:*

1) Determine torque requirements for motors considering friction and acceleration forces.
2) Evaluate power consumption and battery runtime.
3) Validate stability under load using kinematic modeling.

*Model and Calculations:*

1) *Torque Requirements:*

$$\begin{aligned}
\tau_{\text{total}} &= \mu \cdot m \cdot g \cdot r \cdot \cos(\theta) + I \cdot \alpha \\
\tau_{\text{friction}} &= 0.3 \cdot 5 \cdot 9.8 \cdot 0.1 = 1.47\,\text{Nm} \\
\tau_{\text{dynamic}} &= 0.005 \cdot 20 = 0.1\,\text{Nm} \\
\tau_{\text{total}} &= 1.47 + 0.1 = 1.57\,\text{Nm}
\end{aligned}$$

The selected motor provides a stall torque of 4.8 Nm, exceeding the required torque.

2) *Power Consumption:*

$$P_{\text{total}} = P_{\text{motors}} + P_{\text{electronics}} = 288 + 5.03 = 293.03\,\text{W}$$
$$I_{\text{total}} = \frac{P_{\text{total}}}{V} = \frac{293.03}{12} \approx 24.42\,\text{A}$$
$$\text{Runtime} = \frac{\text{Battery Capacity}}{\text{Current Draw}} = \frac{25}{24.42} \approx 1.95\,\text{hours}$$

3) *Stability Analysis:* Using center of mass modeling, the robot maintained a stable tilt margin of $30^\circ$ on inclines.

*Challenges and Solutions:*

- **Challenge:** Motors experienced heat buildup during prolonged operation.
- **Solution:** Motor mounts were adjusted to allow natural airflow, preventing overheating without additional components.

*2) Navigation and Sensor Integration:* Develop a navigation system capable of autonomously navigating to specified areas with $\pm 1.5$ m accuracy.

*Goals of Analysis:*

1) Validate GPS accuracy and sensor integration.
2) Test IMU feedback for real-time trajectory correction.

*Model and Calculations:*

1) *GPS Testing:*

$$\text{Error} = \sqrt{(x_{\text{actual}} - x_{\text{GPS}})^2 + (y_{\text{actual}} - y_{\text{GPS}})^2}$$
$$\text{Average error per trial} = 1.6\,\text{m}$$

2) *IMU Calibration:*

$$S_{\text{gyro}} = \frac{\text{ADC Resolution}}{\text{Full-scale Range}} = \frac{216}{250} = 0.131\,\text{LSB/(/s)}$$

3) *Feedback Integration:* IMU feedback enabled trajectory corrections within 3 degrees over 20 trials.

*Challenges and Solutions:*

- **Challenge:** GPS drift in low-visibility areas.
- **Solution:** Periodic recalibration using stationary IMU data to correct errors.

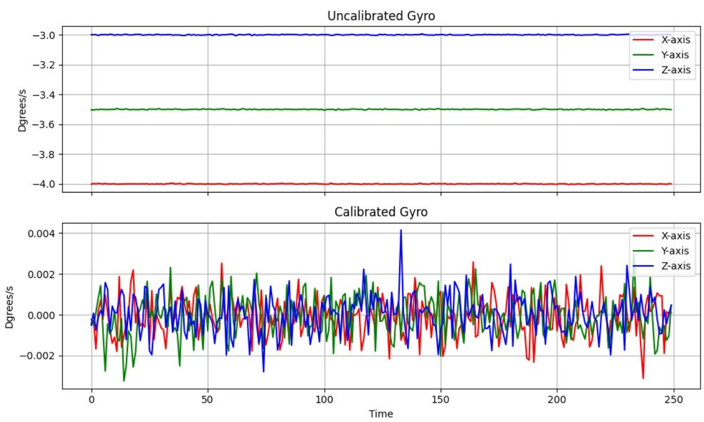



Fig. 9: IMU Calibration using Adafruit Library

*3) Navigation Using GPS:*

1) Enable autonomous navigation to specified GPS coordinates with ±1.5 m accuracy.
2) Utilize GPS and bearing calculations for directional control.
3) Ensure real-time trajectory adjustments using yaw error feedback.

*Model and Calculations:*

1) *Distance Calculation Using Haversine Formula:*

$$d = 2 \cdot R \cdot \arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

   Where:

   - $d$: Distance in meters,
   - $R$: Earth's radius ($6,371,000$ m),
   - $\phi_1, \phi_2$: Latitudes of current and target positions,
   - $\Delta\phi = \phi_2 - \phi_1$, $\Delta\lambda = \lambda_2 - \lambda_1$: Differences in latitudes and longitudes.

   *Example Result:* Average distance error per trial = 1.4 m.

2) *Bearing Calculation for Directional Control:*

$$\theta = \arctan 2\left(\sin(\Delta\lambda) \cdot \cos(\phi_2), \cos(\phi_1) \cdot \sin(\phi_2) - \sin(\phi_1) \cdot \cos(\phi_2) \cdot \cos(\Delta\lambda)\right)$$

   Bearing is normalized as:

$$\text{Bearing (degrees)} = (\theta \cdot \frac{180}{\pi} + 360) \mod 360$$

   *Example Result:* Yaw adjustments within ±2° ensured accurate heading alignment.

3) *Yaw Error Normalization and PID Control:*

   - *Yaw Error:* $\text{Yaw Error} = \text{Desired Yaw} - \text{Current Yaw}$
   - Errors are normalized within $[-180°, 180°]$ for smooth motor control.
   - PID-based motor speed adjustment ensures trajectory correction:

$$\text{Motor Output} = K_p \cdot \text{Yaw Error} + K_d \cdot \frac{\Delta\text{Yaw Error}}{\Delta t}$$

   *Example Result:* Motor adjustments kept yaw error below ±1.5° during navigation.

*Challenges and Solutions:*

- *Challenge:* GPS drift in areas with weak satellite visibility.
  - *Solution:* Use periodic recalibration by capturing stationary IMU data to correct heading errors.
- *Challenge:* Delays in real-time GPS updates.
  - *Solution:* Smooth positional data using moving averages and adjust update rates for faster feedback.
- *Challenge:* Inconsistent motor response during sharp turns.
  - *Solution:* Optimize PID parameters and implement proportional yaw control to prevent overshooting.

This integrated approach ensures robust and precise waypoint navigation, achieving consistent performance even in dynamic outdoor environments.

*4) Collection Subsystem Analysis:* Achieve $> 85\%$ collection success while minimizing jamming and ensuring secure handling of balls.

*Goals of Analysis:*

1) Optimize collection geometry for jam prevention.
2) Ensure secure handling of golf balls under dynamic loading conditions.

*Model and Calculations:*

1) *Force Analysis:*

$$F_{\text{compression}} = k \cdot d = 15\,\text{N/m} \cdot 0.01\,\text{m} = 0.15\,\text{N}$$

2) *Jamming Rate:* Reduced from 32% to 6% by introducing a passive actuation gate. The gate opens when the propeller blade hits it and closes using weights, aligning balls effectively with the grooves.

*Challenges and Solutions:*

- **Challenge:** Alignment issues and ball slippage.
- **Solution:** The passive actuation gate and silica gel grooves ensured secure handling without deformation.

*5) Cleaning Subsystem Analysis:* Remove $> 90\%$ dirt from golf balls with minimal maintenance.

*Goals of Analysis:*

1) Validate force and geometry for effective scrubbing.
2) Test cleaning efficiency under various conditions.

*Model and Calculations:*

1) *Scrubbing Force:*

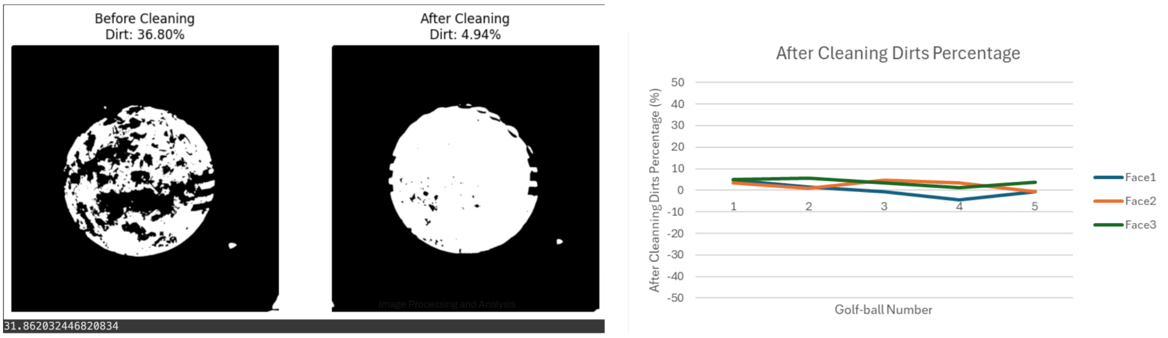
$$F_{\text{comp}} = k \cdot d = 25\,\text{N/m} \cdot 0.02\,\text{m} = 0.5\,\text{N}$$

2) *Cleaning Efficiency*:

   To assess the cleaning efficacy of the scrubbing channel, we devised a controlled experiment complemented by a computer vision (CV) based algorithm (Code in Appendix. . The experimental setup involved photographing each golf ball using an SLR camera under consistent lighting conditions facilitated by a specialized fixture. We examined three distinct surfaces on each golf ball, capturing three images per surface: the original condition, the dirty condition, and the post-cleaning condition.

   For the analysis, these images were first converted to grayscale, and the CV algorithm quantified the black pixels representing dirt within the defined area of the golf ball surface. This process enabled us to calculate the percentage of dirt removed by the cleaning mechanism. Our results were consistent across the three tested surfaces, showing an average dirt presence of 15.89% before cleaning and 2.06% after cleaning, with a standard deviation in cleanliness of 2.68%. The average dirt removal efficacy was 90.87%.

   These findings underscore the effectiveness of the scrubbing channel, demonstrating that it can remove up to 90.87% of dirt from the golf ball surfaces, with the amount of residual dirt consistently low across various conditions. Based on these results, we plan to further refine the structural design of the scrubbing mechanism to enhance its cleaning performance in the subsequent development phase.




(a) (b)

Fig. 10: (a) Evaluation Output (b) Cleaning Evaluation Data Analysis

Residual dirt quantified via computer vision showed an average removal rate of $90.87\%$.

*Challenges and Solutions:*

- **Challenge:** Uneven sponge wear over extended use.
- **Solution:** Alternated sponge densities across the cleaning mechanism to ensure uniform wear.

*6) Structural Subsystem Analysis:* Ensure the frame withstands loads while minimizing deformation.

*Goals of Analysis:*

1) Validate frame strength using finite element analysis (FEA).
2) Optimize material usage for weight reduction.

*Model and Calculations:*

1) *Stress Analysis:*

$$\sigma = \frac{F}{A} = \frac{196\,\text{N}}{0.0025\,\text{m}^2} = 78.4\,\text{kPa}$$

$$\text{Yield strength of aluminum} = 276\,\text{MPa}$$

$$\text{Safety factor (SF)} = \frac{\text{Yield Strength}}{\sigma} = \frac{276}{0.0784} \approx 3.5$$

2) *Deformation Analysis:*

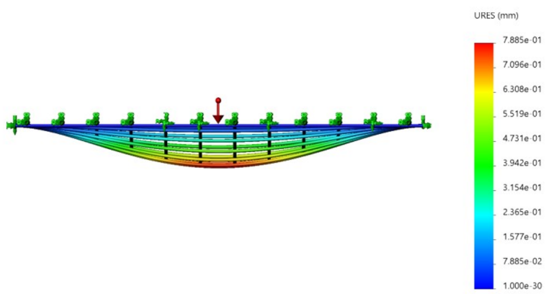



Fig. 11: Deformation FEA Analysis

- Maximum stress: $96.45\,\text{MPa}$, occurring at bolt attachment points.
- Maximum displacement: $0.28\,\text{inches}$, within safe clearance limits.

*Challenges and Solutions:*

- **Challenge:** Minor misalignment due to uneven bolt tightening during assembly.

- **Solution:** Ensured uniform tightening of bolts and used lock washers to prevent loosening under vibration.

**Conclusion:** Each subsystem was rigorously tested and optimized to meet the project goals. The final prototype demonstrated reliable operation, addressing challenges through innovative design adjustments and thorough analysis.

## B. *Failure Modes and Effects Analysis- Junming*

Failure Mode and Effects Analysis (FMEA)

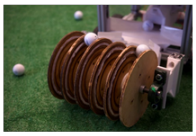
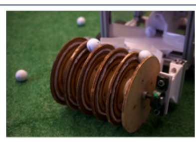
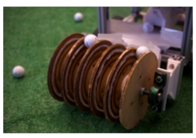
| Item | Function of sub item | Potential Failure Mode | Failure Mode Picture | Potential Effect(s) | Severity | Potential Cause | Occurrence | Detection | RPN | Recommended Action | Re-Evaluation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Action | Severity | Occurrence | Detection | RPN |
| Scrubbing Channel | Transfer the golf-ball from the collector, clean the golf-balls and distribute into the storage baskets | Outside-entrance ball jamming |  | Cause the collected golf balls to accumulate on the funnel ramp, eventually reaching maximum capacity. | 8 | The symetrical geometry at the scrubber entrance | 7 | 3 | 168 | Added unsymmetrical guider on the side walls to disalgined the golf balls | 6 | 3 | 3 | 54 |
| | | Inside-entrance ball jamming |  | Cause the propeller to jam with the golf ball, potentially damaging the structure. | 10 | The propeller will consistently strike the continuously contacting golf ball. | 10 | 3 | 300 | Added a passive gate system to only allow one ball rolling into the chamber | 2 | 2 | 3 | 12 |
| | | Passive gate fail to stop the coming ball |  | Cause two balls rolling into the chanber cause propeller jamming | 10 | The gate is too light to close it self instantly to stop the coming ball | 6 | 3 | 180 | Added weight on the gate to allow it falling down quicker to stop the coming ball | 3 | 3 | 3 | 27 |
| | | Uneven distribution at the exit into the storage basket |  | Cause shifting of the center of gravity of the robot base, or one side reaches to the storage capacity faster than another side | 8 | The uneven thickness of the scrubbing foam causes asymmetrical forces at the entrance | 9 | 3 | 216 | Redesigned the propeller geometry to ensure that when a ball drops on the propeller, it bounces evenly into one of the two storage baskets. | 1 | 1 | 1 | 1 |
| Collector | Collect the golf-ball and transfer the ball into the scrubbing channel | Failed to collect all the golf balls on flat ground |  | Cause missing golf-ball on the ground, reduce the collecting effciency | 6 | The manually applied silicon strip is inconsistent, resulting in uneven contact surfaces with the golf ball across different channels. | 8 | 3 | 144 | Reapplied the silicon strip with more consistance dispense rate | 6 | 6 | 3 | 108 |
| | | Failed to collect all the golf balls on uneven ground |  | Cause missing golf-ball on the ground, reduce the collecting effciency | 6 | Insufficient downward pressure prevents the collected ball from being fully clamped by the silicon strip. | 8 | 3 | 144 | Added weight on the sides to provide larger downward pressure | 6 | 6 | 3 | 108 |
| | | Collecting disk damged |  | Reduce clampping force and collecting effciency | 6 | Operating on snowy terrain causes water damage to the plywood. | 7 | 3 | 126 | Replace the plywood structrure with polymer material | 3 | 3 | 2 | 18 |

Fig. 12: FMEA Chart

### C. *Design For Manufacturing and Assembly- Junming*

#### 1) *BOM List:* See Table.XXI

TABLE XXI: Final BOM List

| **Category** | **Item** | **Amount** | **Total Price** |
|---|---|---|---|
| Scrubbing | 50 Assorted Golf Balls | 1 | $12 |
| Scrubbing | Eraser Sponges | 1 | $9.26 |
| Scrubbing | Bristles | 1 | $14 |
| Scrubbing | 25Pcs 6mm X 20mm Dowel Pin 304 Stainless Steel | 1 | $9.89 |
| Motion | 150:1 Metal Gearmotor 37Dx57L mm 12V | 1 | $32.95 |
| Motion | Pololu Stamped Aluminum L-Bracket Pair for 37D mm Metal Gearmotors | 3 | $29.85 |
| Motion | 19:1 Metal Gearmotor 37Dx68L mm 12V with 64 CPR Encoder | 4 | $207.80 |
| Power Systems | L298N Motor DC Dual H-Bridge Motor Driver | 1 | $5.99 |
| Power Systems | HiLetgo BTS7960 43A Dual H-Bridge Stepper Motor Drive | 4 | $43.96 |
| Power Systems | LeMotech DC 12/24v to 5v Converter | 1 | $6.49 |
| Power Systems | 4 Packs 12AWG Inline Fuse Holder | 1 | $7.99 |
| Power Systems | Dianrui Bus Bar 12V 250A Power Distribution Block Busbar 6 x 1/4” | 1 | $25.99 |
| Power Systems | DC HOUSE 12V 50Ah Lithium Battery with 12V 10A | 1 | $119.99 |
| Navigation | SparkFun GPS Breakout - NEO-M9N | 1 | $69.95 |
| Navigation | MPU6050 3 Axis Gyroscope | 1 | $9.99 |
| Navigation | Ultrasonic Sensor 40kHz DigiKey Part Number 1528-2711-ND | 1 | $3.95 |
| Robot Base | 12mm Hex Wheel Adapter for 6mm Shaft, Extended | 2 | $11.90 |
| Robot Base | 4pcs Rc Truck Tires,12mm/14mm Hex RC Wheels and Tires for 1/10 Slash 2WD 4×4 4wd | 1 | $39.99 |
| Robot Base | 80-20 rail corner connection - internal corner | 2 | $25.98 |
| Robot Base | Mesh Framing | 1 | $14.99 |
| | | Total | $976.17 |

*2) Final Prototype Assembly Process:* :

**- Scrubbing Subsystem:**

**Purchased Components**

- M3 Screws
- M3 Nuts
- M3 Heat Inserts
- M5 Screws
- 6mm Dowel Pins
- 686-2RS Deep Groove Ball Bearings

**Required Tools**

- Allen Key Set
- Hammer
- Screwdriver
- Loctite Plastic Glue

**Prototype Manufacturing Process**

- Fused Deposition Modeling (FDM) 3D Printing
- Heat Inserting

**Proposed Mass Production Process**

- Injection Molding

**Prototype Assembly Process Description**

*Center Planetary Gearbox Assembly*:

1) Insert three dowel pins into the bottom planetary gear housing using a hammer.
2) Place two washers and one ball bearing on each pin to prevent direct contact between the bearing and the plastic housing.
3) Position the top planetary gear housing over the assembly and secure it with three M3 screws and M3 heat inserts.
4) Repeat the process for the second stage of the gearbox.

*Motor Mounting and Assembly*:

1) Attach the motor to an L-bracket using M3 screws and nuts.
2) Secure the L-bracket to the motor housing.
3) Connect the motor housing and the two-stage gearbox assembly using M3 screws.

*Propeller Installation*:

1) Snap-fit six propellers into the center output ring gear housing.

*Connecting the Gearbox to the Scrubbing Channel Enclosure*:

1) Attach the center planetary gearbox to the right scrubbing channel enclosure using three M5 screws and heat inserts.
2) Tighten the screws through clearance holes in the gearbox housing flanges.

*Scrubbing Channel Enclosure Assembly*:

1) Align the left and right enclosures using alignment pins.
2) Secure the enclosures together using three M5 screws and heat inserts.

*Passive Gate Assembly*:

1) Apply Loctite plastic glue to secure the pin housing to the left and right enclosures.
2) Place the dowel pin and lever bar into the center of the housing.

*Funnel Ramp Assembly*:

1) Press-fit the funnel ramp into the scrubbing enclosure using alignment inserts.
2) Apply plastic glue to ensure additional security.

**- Collector subsystem**

**Purchased Components:**

- Pillow Block Bearings
- M10 Bolts and Nuts
- 15-Series Aluminum Extrusions
- L-Brackets
- Silicon Sealant
- Shaft Collars

**Required Tools:**

- Allen Key Set
- Caulk Gun

**Prototype Manufacturing Processes:**

- Fused Deposition Modeling (FDM) 3D Printing
- Laser Cutting

**Proposed Mass Production Process:**

- Injection Molding

**Prototype Assembly Process Description:**

*Center Disk Drum Assembly:*

1) Use a laser cutter to fabricate five identical disks from a plywood board, ensuring grooves are added near the edges of each disk.
2) Apply a consistent layer of silicon sealant along the grooves and allow 24 hours for the sealant to cure.
3) Assemble the 3D-printed spacers and plywood disks sequentially along the center shaft.
4) Secure the assembly by placing shaft collars at both ends of the shaft.

*Support Frame Assembly:*

1) Cut the aluminum frame to the desired lengths using a vertical band saw.
2) Secure the frame components using L-brackets.
3) Attach two pillow block bearings to the aluminum frame through 3D-printed adapters, fastening them with M10 bolts and nuts.
4) Finally, mount the assembled center disk drum onto the pillow block bearings to complete the assembly.

# VIII. Final Design Description

## A. Final Design Detailed CAD

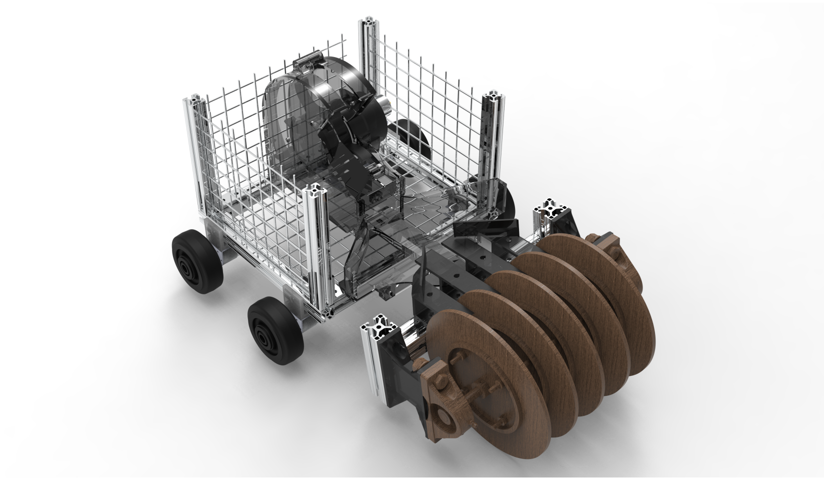


Fig. 13: Overall Structure


Fig. 14: System block diagram showing power distribution, sensor integration, and control flow for the autonomous robot.

## B. Design Problem Context

*a) Public Health and Safety:* In the design of the golf ball collection and cleaning robot, public health and safety were prioritized. The robot operates autonomously in golf course environments with minimal human interaction, reducing potential safety risks. To ensure safe operation, the integrated IMU (Inertial Measurement Unit) and GPS systems provide accurate navigation and direction correction, allowing the robot to avoid unintended collisions with obstacles and hazards. Emergency stop functionality and stable component installations further enhance operational safety, ensuring the robot performs reliably without posing risks to the public. Electrical components and wiring are safely encased or hidden from weather elements and unintentional human interaction. To further protect users, there are no exposed sharp edges on the chassis. The collection system is only capable of collecting golf balls or golf ball- like items preventing collection of small hazardous, sharp debris. The back side of the cage chassis is unobstructed for easy access to any internal complications.

*b) Economic Impact:* The implementation of the robot directly addresses the economic challenge of high labor costs for golf ball collection and cleaning as well as the high costs for large scale collection robots. By automating these tasks, golf courses can significantly reduce operational expenses, reallocating resources more efficiently. The use of cost-effective and readily available components, such as standard motors, sensors, and hardware rails, ensures that the robot remains affordable for production and maintenance. Additionally, the optimized path planning algorithm reduces operational time, enhancing energy efficiency and overall economic viability for long-term deployment. Apart from the custom scrubber, stoppers, and some connection adapters, all hardware is made from easily accessible and machinable materials (plywood, steel rails and wire mesh, etc.). This reduces manufacturing and assembly costs.

*c) Environmental Impacts:* The robot was designed with a focus on sustainability and environmental friendliness. To minimize its ecological footprint, the path-planning algorithm ensures optimal movement, reducing unnecessary energy consumption and carbon emissions. Physical cleaning mechanisms were implemented instead of chemical solutions, avoiding potential environmental pollution as well as water waste. Design measures were put in place to find the minimum functional size and weight for this robot to preserve fuel efficiency. Furthermore, recyclable materials were chosen for structural components, supporting sustainable development goals and reducing waste. The item that would potentially have to be replaced most frequently (the scrubber sponges) is also made from inexpensive, easily sourced, and easily repurposed material. The sponges themselves could easily be washed and reused. These considerations align with the growing demand for eco-friendly solutions in the robotics industry.

*d) Societal Impacts:* From a societal perspective, the robot reduces the need for manual labor, allowing workers to focus on more value-added tasks while improving the efficiency of golf course maintenance. This technology promotes automation in the sports and recreational sector, setting a benchmark for innovation. By enhancing operational performance and reducing costs, the robot contributes to making golf courses more accessible and affordable to maintain. Additionally, the project fosters advancements in robotics and automation, inspiring further technological developments with societal benefits.

*e) Ethical Implications:* Our design considers ethical implications in global, economic, environmental, and societal contexts. Globally, the robot's design promotes technological advancements without sacrificing environmental integrity. Economically, it ensures that automation benefits businesses while maintaining cost efficiency and accessibility. From an environmental perspective, the robot aligns with sustainability goals by minimizing energy use and waste generation. Societally, while reducing manual labor, the robot creates opportunities for workers to upskill and engage in higher-level tasks, thus encouraging ethical workforce transitions.

### C. Relevant Codes and Standards

TABLE XXII: Relevant Codes and Standards for Final Design

| Standard | Description | Application to Final Design |
|---|---|---|
| ISO 10218-1 | Safety requirements for industrial robots | Ensures safe operation of motors, sensors, and mechanical components. |
| ISO 12100 | General principles of safety for machinery | Guides risk assessment and integration of safety mechanisms. |
| ISO 13849 | Safety of machinery - safety-related parts of control systems | Ensures reliable operation of emergency stop systems and control logic. |
| IEEE 802.11 | Wireless communication standards | Provides reliable GPS data communication for navigation. |
| ISO 14001 | Environmental management systems | Ensures adherence to environmental sustainability practices in design and operation. |
| ISO 13482:2014 | Robots and robotic devices — Safety requirements for personal care robots | As a robot that assists with mobile service and physical assistantance and interacts with humans, these regulations ensure the human interactions will be safe. |
| ISO 3744 | Noise standards | Ensures robot stays within permisable sound levels. |

### D. Design Demonstration

For in-depth design demonstration and testing, please visit the Video Documentation Folder. For function by function video explanations of subsystems, please visit the Design Expo Presentation. The following is a summary of sub-system functionality demonstrated.

*a) Collecting:* The key elements of the Collection Drum involved 6 plywood wheels with engraved channels filled with silicone sealant. This sealant provided sufficient elasticity to compress the golf balls after the drum had passed over them. As the drum continues to roll behind the robotic chassis, the golf balls follow the external rotation path until their path is interrupted by the ramped stoppers. The ramp stoppers then guide the golf balls to a center rotation ramp above the chassis-drum u-joint connection. This ramp then guides the golf balls to the entry of the scrubber.

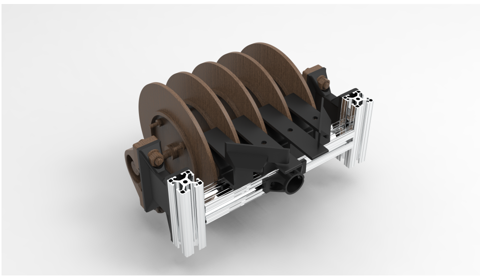


Fig. 15: 3D Model of Collection Wheel Drum

*b) Cleaning:* The key elements of the Cleaning Scrubber begin with a ramp entry funnel to hold high volumes of collected golf balls without jamming. This leads to a passive lever-activated entry gate triggered by the cycling scrubber fins that opens sufficiently for one golf ball to enter the scrubber. The fin then carries the golf ball in a vertical circular path lined with sponges to scrub the golf ball clean. As the golf ball completes its cycle and approaches the scrubber exit, the ball hits a small foam ramp on the back of the fin in front of it that directs it to either side of scrubber. These ramps alternate in direction and thus ensure equal distribution of golf ball storage. The fins themselves are driven by a custom planetary gear box powered by the main battery.

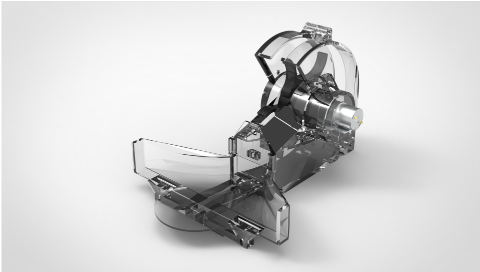


Fig. 16: 3D Model of Cleaning Scrubber

Fig. 17: Internal View of Cleaning Scrubber

*c) Robotic Base Control:* The robot base control code serves as the core of the robot's motion control system, achieving two primary functionalities: moving a specified distance in a straight line and performing an arc turn to a specified angle.

**Straight-Line Movement:** The robot achieves precise straight-line movement by controlling its four differential-drive motors. To correct any yaw deviation during movement, the system integrates an IMU (Inertial Measurement Unit) for real-time yaw angle feedback and employs a PID (Proportional-Integral-Derivative) controller for error correction. The PID controller adjusts the motor speeds dynamically, ensuring the robot maintains its intended direction. Additionally, the robot incorporates a GPS module for real-time position monitoring. The GPS measures and records the distance traveled, comparing it to the target distance. When the reported distance matches the preset value, the robot halts, achieving precise straight-line travel.

**Arc Turn to a Specified Angle:** The robot performs arc turns by controlling the speed difference between the left and right motors. During turning, the IMU provides real-time yaw angle feedback, which is compared to the target angle. The PID controller calculates and applies corrections based on the yaw error, ensuring smooth and accurate turns. This functionality allows the robot to execute precise turns ranging from $-180°$ to $+180°$, supporting the requirements of the path planning algorithm.

By integrating these two core functionalities, the chassis control code ensures stable and accurate robot motion, laying a solid foundation for the successful implementation of the overall system.

*d) Navigation:* The coverage path algorithm is designed to address the issue of the robot's large turning radius by adopting a segmented straight-line and turning-based loop pattern. Through well-structured path planning, the algorithm ensures complete cleaning of the target area. The specific execution steps are as follows:

1. **Initial Straight-Line Movement:** The robot starts from the initial position and moves straight for one grid length.
2. **First 90-Degree Turn:** The robot performs a 90-degree right turn, preparing for lateral movement.
3. **Lateral Movement:** The robot moves straight for **0.3m** (equal to the width of the collection system), covering the adjacent path segment.
4. **Second 90-Degree Turn:** The robot executes another 90-degree right turn to re-enter the next straight-line path.
5. **Return Straight-Line Movement:** The robot continues moving straight for one grid length, completing the current path unit.
6. **180-Degree Turn:** Upon reaching the end of the current path, the robot performs a 180-degree turn to transition into the next loop and begins the following iteration.

The above steps form a complete **loop unit**. By repeating this loop, the robot systematically and efficiently covers the entire target area.

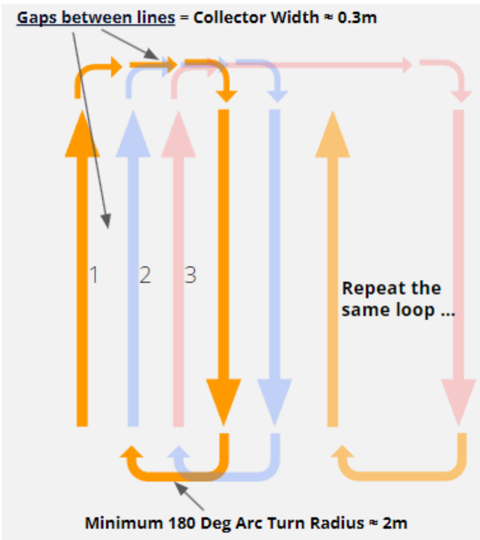



Fig. 18: Coverage Path Planning Design with 90-degree and 180-degree Turns

The path design ensures efficient and systematic coverage by aligning the robot's movement with the collection system's width 0.3m, avoiding overlaps or omissions. It adapts to the robot's physical constraints by combining 90-degree and 180-degree turns, resolving the issue of large turning radii. Real-time yaw angle feedback from the IMU and PID control maintains stability and accuracy during both straight-line movement and turning. Additionally, the algorithm is scalable to various working scenarios, as adjustments to grid size and starting position allow the robot to adapt to areas of different shapes and sizes.

The navigation system utilizes GPS data to autonomously guide the robot to specified waypoints with an accuracy of ±1.5 meters. It calculates the distance and direction to the target using GPS coordinates and dynamically adjusts its path using real-time yaw feedback from the IMU. A PID controller ensures precise alignment by correcting yaw errors, which represent the difference between the desired and current orientation. The robot continuously recalibrates its movement based on real-time updates from the GPS module, stopping once it reaches the target within a predefined threshold. This approach ensures reliable and efficient navigation even in dynamic outdoor environments.

### E. Testing and Results

*1) Testing of Collection Drum:* The testing of the collection drum sought to evaluate the percentage of golf balls in the collector's path that it could collect on the given terrain. The goal was to collect at least 85% of golf balls. Terrain varied from indoor cement floors, plastic grass mats, outdoor fields, and indoor/snowy turf terrain. The first method of testing was conducted by setting a set amount of golf balls in the path of the collection drum and manually rolling the drum over these balls. The golf balls not inside the collection wheels were subtracted from the collected total and the collection percentage was calculated. The second method involved placing 1-2 balls at a time in front of the robot as it navigated and tracking the quantity missed. Recorded results from both of these methods can be seen below.

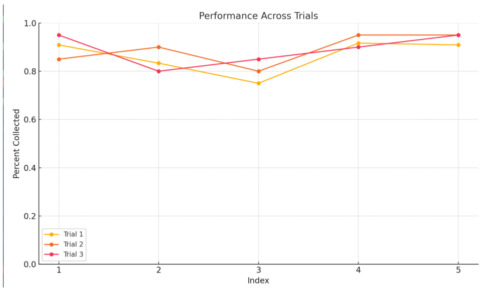


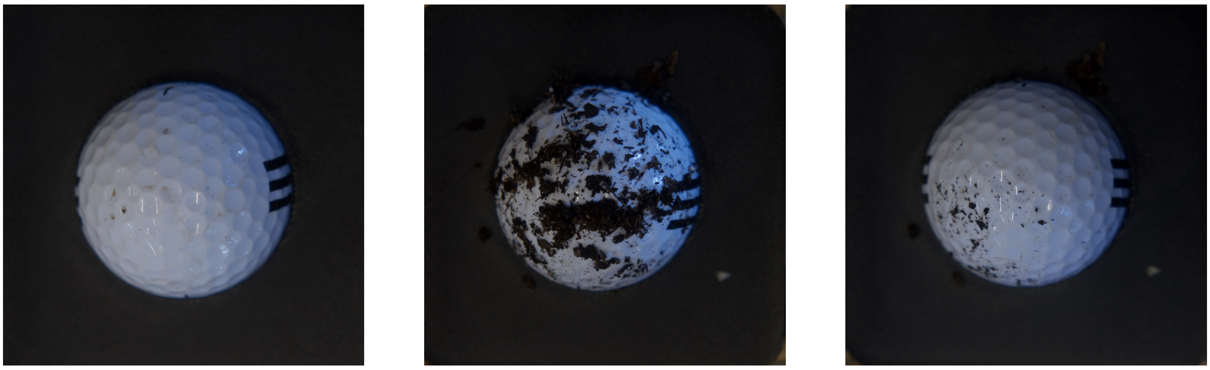

Fig. 19: Results from Mixed Method Collection Testing

In the figure below, this is depicted an example of the first testing method.

(a) (b)

Fig. 20: (a) 20 Golf Balls Before the Collection Drum (b) 20 Golf Balls After the Collection Drum

*2) Testing of Cleaning Scrubber:* The testing of the Cleaning Scrubber sought to evaluate the percentage of dirt removed from golf balls after passing through the dry scrubbing channel once. The goal was to clean off about 85% of the dirt. To conduct these tests, multiple golf balls were recorded as they had been purchased (used golf balls). The balls were then dirtied using a mix of mud, mulch, water, and sand. The balls were photographed in these conditions. The golf ball was then inserted into the entry of the scrubber and after exiting the scrubber, its surface conditions were recorded.The images below demonstrate the success of the dry scrubbing channel for cleaning, removing about 90% of the dirt.



(a) (b) (c)

Fig. 21: (a) Golf Ball Before Dirtying (b) Dirty Golf Ball Before Cleaning (c) Golf Ball After Cleaning

A critical element of cleaning performance also involved jamming prevention. In preliminary iterations of the scrubbing design, excluding the entry gate, a significant percentage of golf balls would jam during a collection and cleaning test. When the passive gate was implemented alongside guiding topography on the funneled entry ramp, this jamming percentage dropped from about 30% to between 0% and 10%.

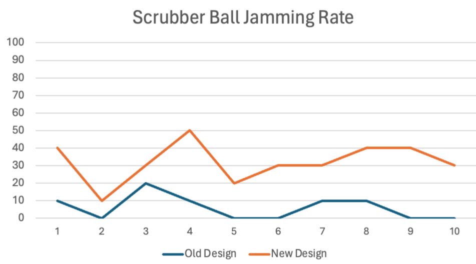



Fig. 22: Percent of Golf Balls Jamming at Cleaning Scrubber Entry

*3) Testing of Robot Base Control:*

*a) Experimental Setup:* The experiment was conducted on a soccer field with grass terrain to test the straight-line driving and turning precision of the robot chassis. The setup included a designated reference straight line for the straight-line test and predefined target angles for the turning test. A measurement system was used to record the deviations and actual turning angles, ensuring accuracy in the evaluation.

*b) Procedure:* For the straight-line test, the robot chassis was directed to move along the reference straight line for four different target distances: 5m, 10m, 15m, and 20m. At each distance, the test was repeated ten times to gather sufficient data. After each run, the lateral deviation of the robot from the reference line was measured at the target distance to evaluate the straight-line precision. In the turning test, the robot chassis was commanded to execute two specific turns: 90 degrees and 180 degrees. Once the robot completed each turn and came to a stop, the actual turning angle was recorded. Similar to the straight-line test, the turning experiments were repeated ten times for each angle to ensure reliable and consistent results.

*c) Measurements and Observations:* During the straight-line test, the lateral deviations from the reference line were observed and measured at the endpoints of the target distances. These deviations were recorded to determine how accurately the robot maintained its trajectory as the distance increased. For the turning test, the actual turning angles were compared against the expected 90-degree and 180-degree values to quantify any errors or deviations in the turning performance. Observations were made regarding any patterns in deviations, such as increasing lateral error with distance or consistent under- or over-turning during the angle tests.

*d) Results:* The results of the straight-line and turning deviation tests are presented below.

For the **straight-line deviation test**, the deviations remain small for shorter distances, such as 5m and 10m, where the average deviation is approximately 0.1m to 0.2m. As the target distance increases to 15m and 20m, the deviation grows significantly, with an average of 0.3m to 0.4m and a maximum deviation close to 0.8m. This trend indicates that small cumulative errors, likely caused by control inaccuracies and external disturbances such as uneven terrain, become more pronounced over longer distances.

For the **turning deviation test**, the results show that the robot's turning performance is relatively precise. For the 90-degree turns, the average deviation is approximately 0.8 degrees, with minimal spread among the data points. However, for the 180-degree turns, the deviations are slightly larger, averaging around 1.2 degrees, with a greater spread. This suggests that while the IMU-based feedback and control system are effective, larger turns accumulate more error, likely due to system lag and control precision limitations.

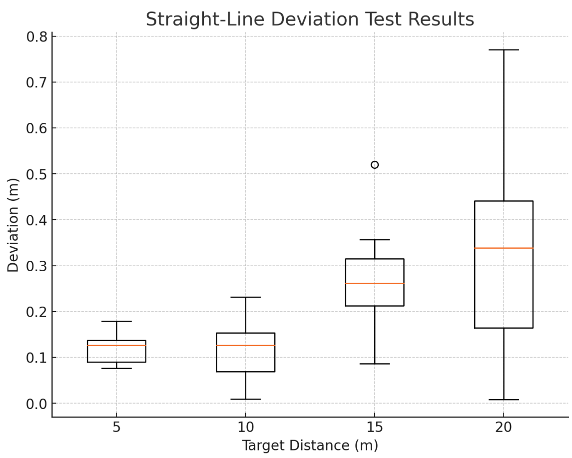



Fig. 23: Straight-Line Deviation Test Results

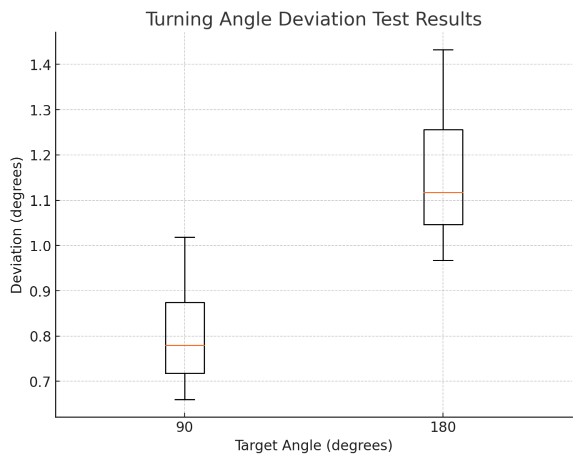



Fig. 24: Turning Angle Deviation Test Results

Fig. 25: Results of the Straight-Line and Turning Deviation Tests.

These results validate the overall performance of the robot's base control system. The straight-line precision is acceptable for shorter distances, but further improvements in control algorithms are needed to reduce deviations for longer paths. Similarly, the turning accuracy can be further optimized to minimize errors, especially for larger angles.

*4) Testing of GPS:* The GPS testing focused on evaluating the accuracy and reliability of the NEO-M9N GPS module under real-world conditions. The setup involved defining a straight-line path of 40 meters and testing the module's ability to measure the distance accurately while maintaining a positional accuracy of ±1.5 meters. The test environment included outdoor conditions that mimicked potential use cases, such as golf courses or open fields.

*Description of GPS Testing Results:*

The NEO-M9N GPS module successfully demonstrated a positional accuracy of approximately 1.5 meters, as per its specifications. Over 20 trials, the recorded average distance was 38.9 meters, which closely aligns with the expected 40-meter path. These results confirmed the reliability of the GPS module for outdoor navigation tasks where meter-level accuracy is acceptable.

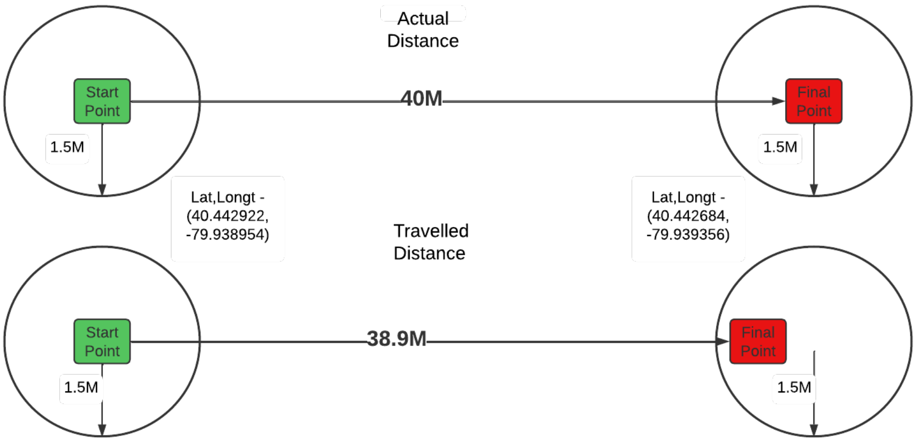



Fig. 26: GPS Testing over 20 trials

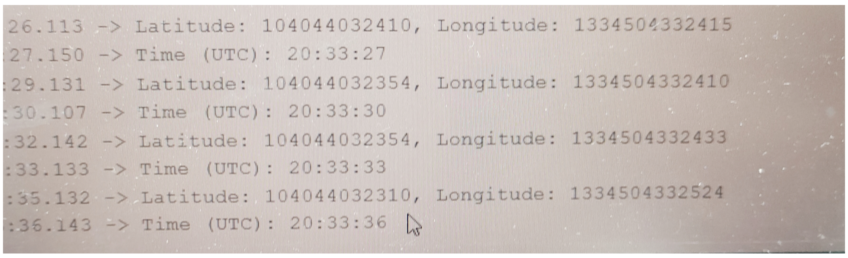



Fig. 27: Latitude and Longitude Values

*5) Testing of GPS and IMU Integration:* To enhance navigational accuracy and stability, the NEO-M9N GPS module was integrated with the MPU6050 IMU. The IMU provided real-time orientation data, including roll, pitch, and yaw angles, complementing the GPS data to correct signal discrepancies and improve positional accuracy. This test aimed to validate the sensor fusion system for precise path tracking and dynamic orientation adjustments.

*Screen Recording Demonstration:*

A screen recording was taken during this phase to showcase the integration of GPS and IMU data. The video highlights the system's ability to process real-time data from both sensors and demonstrate how the fusion improves navigational accuracy.

*Screen showing real-time values:* Real-time Values Video

*Description of Integrated System Results:*

The combination of GPS and IMU data provided enhanced positional and directional accuracy. By utilizing the IMU for real-time orientation corrections, the system effectively mitigated GPS signal drift and maintained accurate tracking of the predefined route. The sensor fusion approach proved to be highly effective for tasks requiring reliable navigation in dynamic outdoor conditions.

The final phase of testing involved integrating the GPS and IMU system with motor drivers, controlled via a PID algorithm. This complete setup was tested for its ability to navigate a robot along a designated path while dynamically adjusting its movement based on sensor inputs. The PID control allowed for precise adjustments to motor speeds and directions to maintain accurate trajectory and orientation.

*Code Repository:*

The code for integrating GPS, IMU, and motor drivers with PID control has been uploaded and is available here: GPS and IMU Code Repository

*Description of Navigation System Results:*

By integrating GPS and IMU data with PID control, the system achieved a highly responsive and accurate navigation capability. The robot was able to follow the path within the required ±1.5 meters of accuracy and dynamically adjusted its movement to account for real-time positional and orientation feedback. This phase validated the robustness of the system in managing outdoor navigation tasks.

## IX. Conclusions

Throughout the course of this project, our team learned the value of thoroughly diving into and planning the design process of a complex project, facing but ultimately overcoming a variety of challenges when finalizing overall designs, manufacturing custom parts, purchasing parts, and integrating sub-assemblies.

In regards to finalizing the overall design of our C&C robot, we learned important lessons on project management and thorough analysis of all sub-systems of our assembly as soon as possible. Early on, we made the critical assumptions that a purchased robot base, wet cleaning system, and a pushing collection drum would be key to our overall design. As a result, a great deal of time was spent on other components, like the overall cleaning sub-system itself and navigation simulations, as we did not foresee any inherent issues with these components and believed our other components to be simple enough that we did not need to start developing them yet. However, as we made further progress, we quickly realized that no robot base on the market matched our desired performance and price targets, a wet cleaning system added unnecessary weight that a robot base, regardless of it being purchased or developed, would struggle with, and a pushing collection drum, despite the more natural ball flow and potentially higher collecting rate, posed further issues with stopping and feeding the balls into the cleaner. Although we were able to quickly pivot and resolve these issues, our time could have been optimized had we spent more time in the earlier project planning stages fleshing out our overall design. Unfortunately, given the complexity of our system and numerous sub-systems and corresponding features, these assumptions were made for the sake of simplicity.

On the other hand, our team also demonstrated the capability to thrive even as details were being decided on the fly and adapt when necessary. Resolving the aforementioned issues proved that despite the challenges thrown at us, with a bit of time and proper prioritization, success was in reach. For example, when our collection wheel radius needed to be reduced, we creatively ideated a vertical scrubber to reduce ball entry height. Again, when the size of our robot restricted navigation efficacy, we quickly integrated a U-joint to allow for more flexible movement. Along the way, we learned that thinking outside the box and building off previous ideas but re-imagining them in a slightly different perspective could solve nearly any problem we came across.

When manufacturing, designing complex, precise components such as our scrubber or ball stopper teeth was much easier in theory than it was to build them physically. Thus, it was necessary to turn to

3D printing time and time again to construct these unique pieces. The value of quick and adaptable manufacturing methods is now ingrained in us, as our robot could never have functioned without such available methods.

Purchasing parts was a simple yet incredibly important step in our process. While we were often able to rely on our own manufacturing methods, it was obviously still necessary to order parts from reliable sites. These steps often added time that we did not previously account for when managing our project plans, which unfortunately resulted in cram sessions before prototype demos. Understanding the factors outside of our control and then controlling those as best we can with proper planning is another important takeaway from this project.

Our final quest to conquer was the integration of all of our sub-systems. Initially, we hadn't even paid this step much attention and didn't include it as apart of our functional decomposition. Again, given the complexity of our system, we were much more focused on the sub-systems in silo and assumed these to be the needed primary focuses, while integration would come as an easy last step. However, near our second prototype, we began to understand just how large the problem we had chosen to tackle was and how much of a challenge integration posed. While we were able to successfully integrate our robot, we learned the value of maintaining a big-picture view and not getting caught up in the details that might exceed quality in a small, specific area but potentially detract from overall performance.

Besides understanding these lessons earlier to potentially avoid some of these challenges, we might have also chosen to approach our problem on the broad level differently. We chose a very complicated robot with multiple sub-systems that were also incredibly complex and could have even been taken on as projects of their own. For example, just a condensed automated scrubber or automated collection robot could have been feasible projects. While we shot for the stars and ultimately landed somewhere pretty close, different choices could have been made when evaluating the scope of what we wanted to achieve to allow for more focus on a concentrated area. Despite this limitation, we were a large, determined group with high expectations of what we could achieve, and this minimized the potential for our complex system to interfere with our success.

Despite the progress made, a few challenges remain unresolved. For example, the robot battery's runtime has yet to be fully explored, and testing whether it can meet the demands of larger driving ranges without recharging or the necessity/number of additional robots in a swarm for a certain defined area would be valuable product information to know. Given that we anticipate our product being apart of a swarm, detailing plans for how these robots might interact together would also be useful for actually launching our product. Additionally, automated return to the charging base, ball capacity detection, and an app meant to interface with the driving range employee to direct the robot itself are critical components of our product that have yet to be developed. Developing the controls necessary for the robot to return to a location and connect itself to charge when battery is low, depending on how close or far the robot is to the charger, would minimize user interactions and improve the efficacy of our product. Further adding sensors to detect maximum ball capacity and developing similar controls for the robot to return the balls it has collected to a storage location can enhance our robot. An app that could provide battery, ball collection, and robot location updates in real time in addition to easy control over the robot's region of interest is another great feat to tackle.

Future design teams who could continue this project might benefit from taking the progress we've made and addressing the previously mentioned unresolved challenges. Most of these issues are computational in nature, which may be desirable for groups who would like to gain more experience on that end of things. On the other hand, groups who desire more of a focus on the electronic and mechanical structures themselves could enhance the performance of our robot on more rugged terrain or in non-ideal weather conditions so that this product is a more feasible solution for driving ranges or even potentially expand to hilly golf courses.

# X. Appendix

Work Distribution:

Junming - Design: User research, new scrubbing sub-system design and optimization,U-joint connection,electrical housing,final assembly and test, Report: Executive Summary, Concept Generation (Functional Decomposition, Collection, Cleaning, Full System Concepts), Concept Selection (Collection, Cleaning, Detailed Models), FMEA, DFMA

Andrea - Design: User research, scrubbing sub-system design + testing, chassis development and assembly, collection wheel manufacturing, stopper design, Report: Problem Definition, Concept Generation (Chassis), Concept Selection (Chassis), Design problem context (Collector and Cleaner), Demonstration of the design (Collector and Cleaner), Testing and results(Collector and Cleaner).

Amelia - Design: User research, spraying sub-system design + testing, collection drum development, Report: Stakeholder and Consumer Needs, Target Specifications, Prototype Summary (Cleaning - Spraying), Conclusion

Vrishabh - Design: User research, planning and motion sub-system design + testing, algorithm application test on Robot Car,Hardware and electronics circuit design and assembly, IMU testing and Calibration ,GPS testing, GPS and IMU Sensor fusion and also integrating this with the motor controls and PID for efficient navigation. Report: Concept Generation (Motion), Concept Selection (Motion, Assessment + Justification of Top Concepts), Prototype Summary (Motion sub-system design), Detailed Design and Engineering Analysis - Engineering Analyses and Calculations, Design For Manufacturing and Assembly- BOM List, Final Design Description - System Block Diagram, Testing and Results - GPS, GPS and IMU Integration.

Zikang - Design: User research, Grid-based path planning algorithm simulation, Robot base control code and coverage path planning algorithm design, Hardware and line integration, final assembly and test. Report: Concept Generation (Navigation), Project Planning, Design Problem Context, Design Demonstation (Control & Navigation section), Testing & Results (Control section)

(a) (b)

Fig. 28: Existing Solutions for golf-ball collecting mechanisms (a) Rotating Disk (b) Brush Wheels.

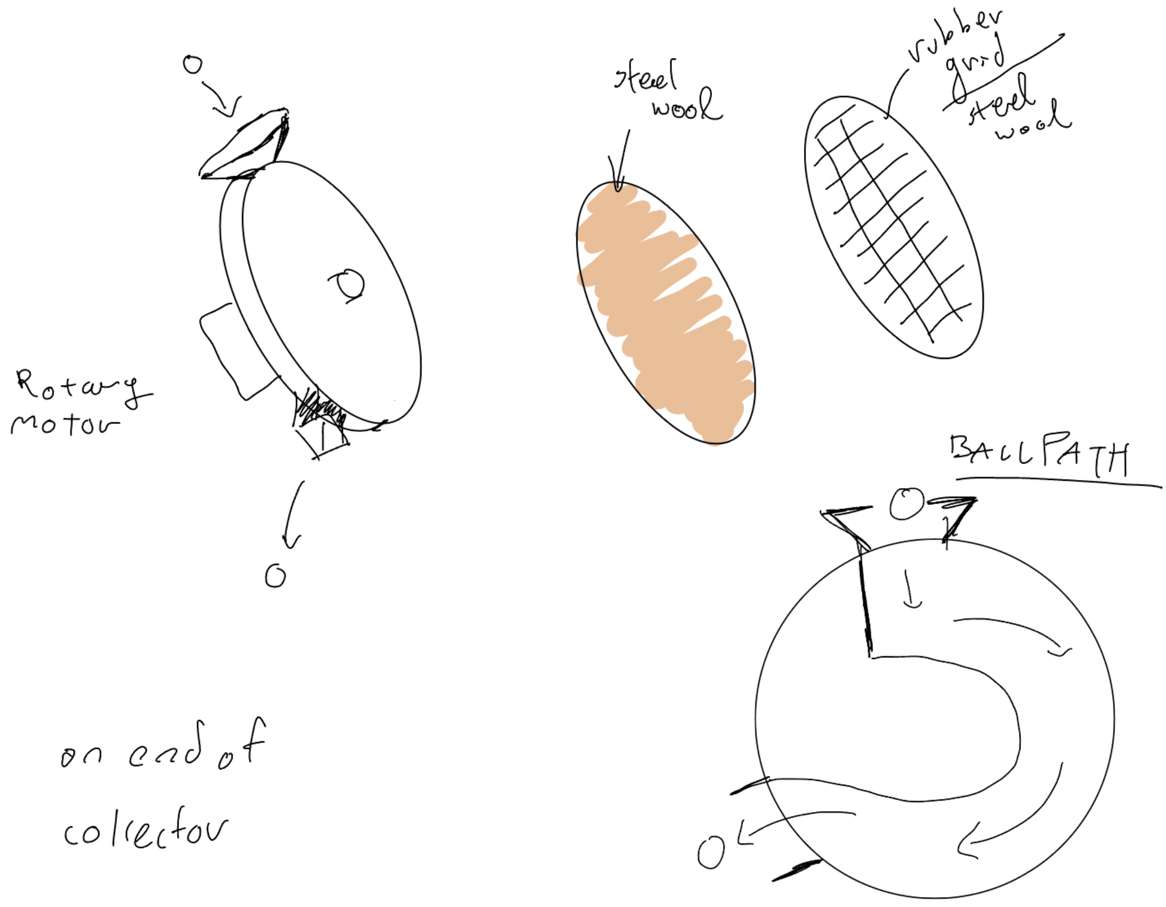



Fig. 29: Circular channel Concept by Junming

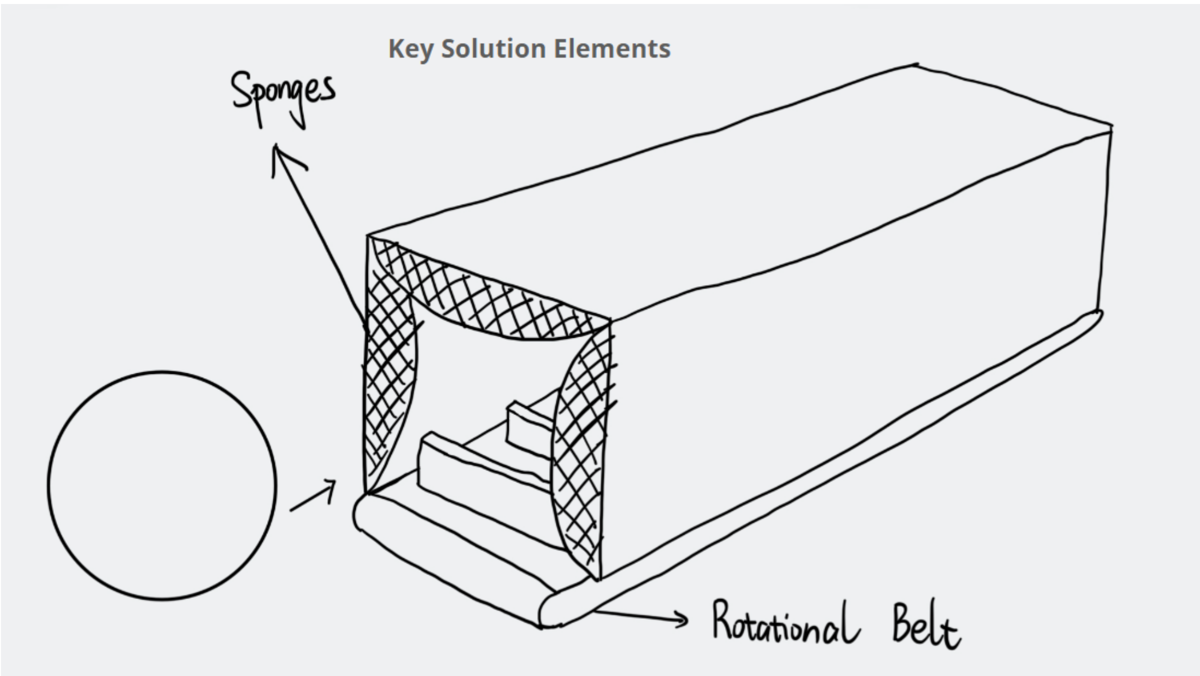



Fig. 30: Straight channel Concept by Junming

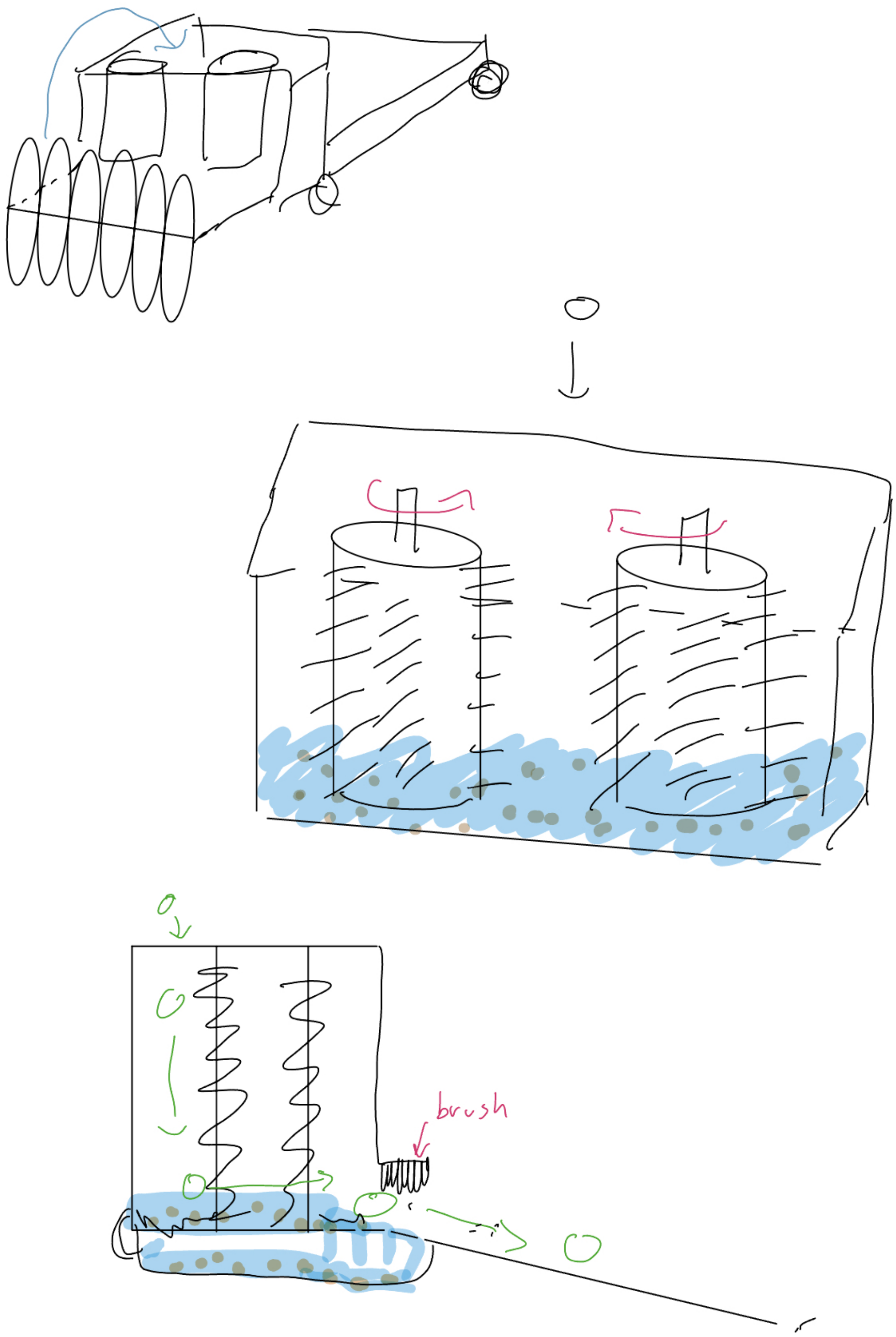



Fig. 31: Vertical Brushes Concept by Andrea

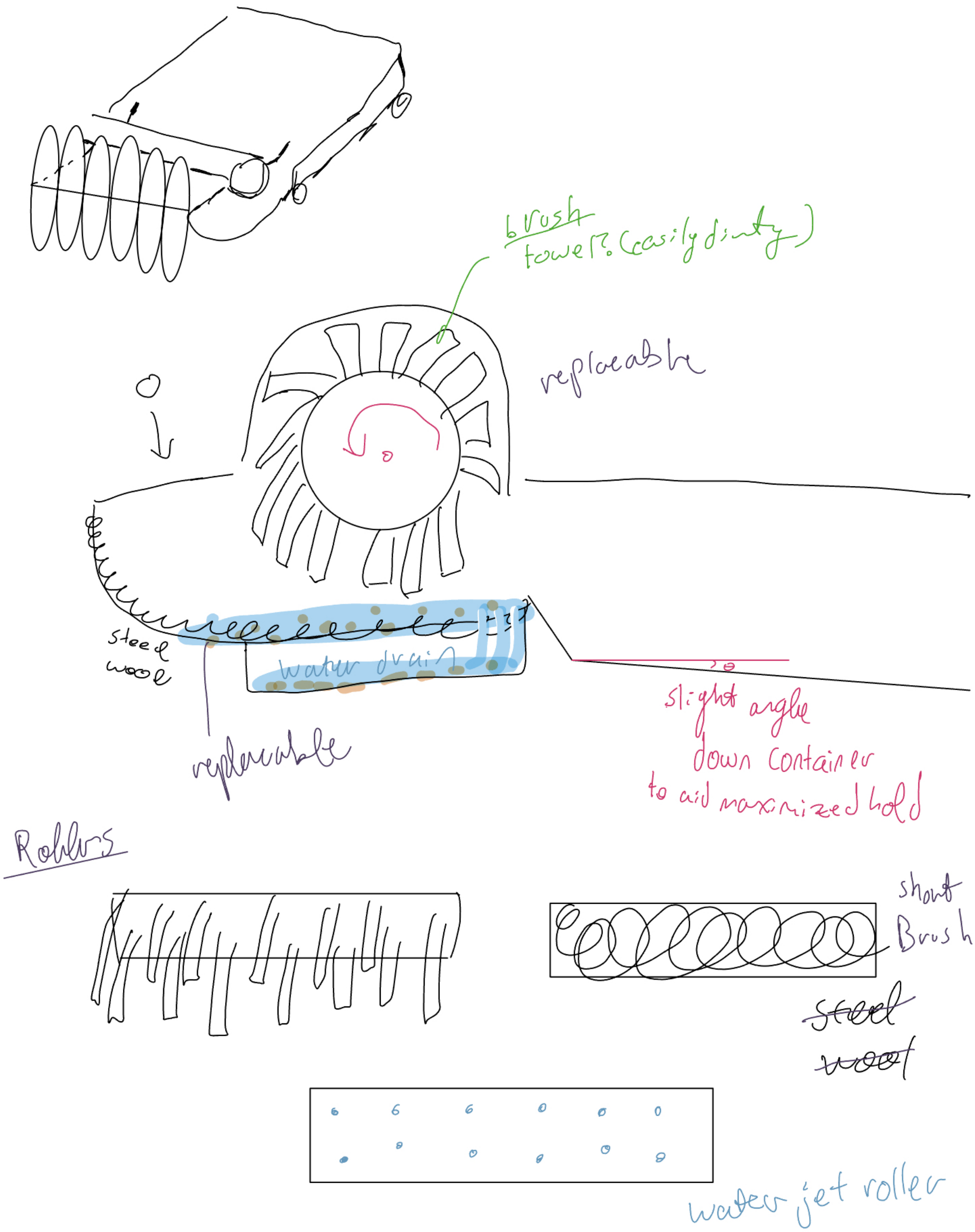



Fig. 32: Horizontal Brushes Concept by Andrea

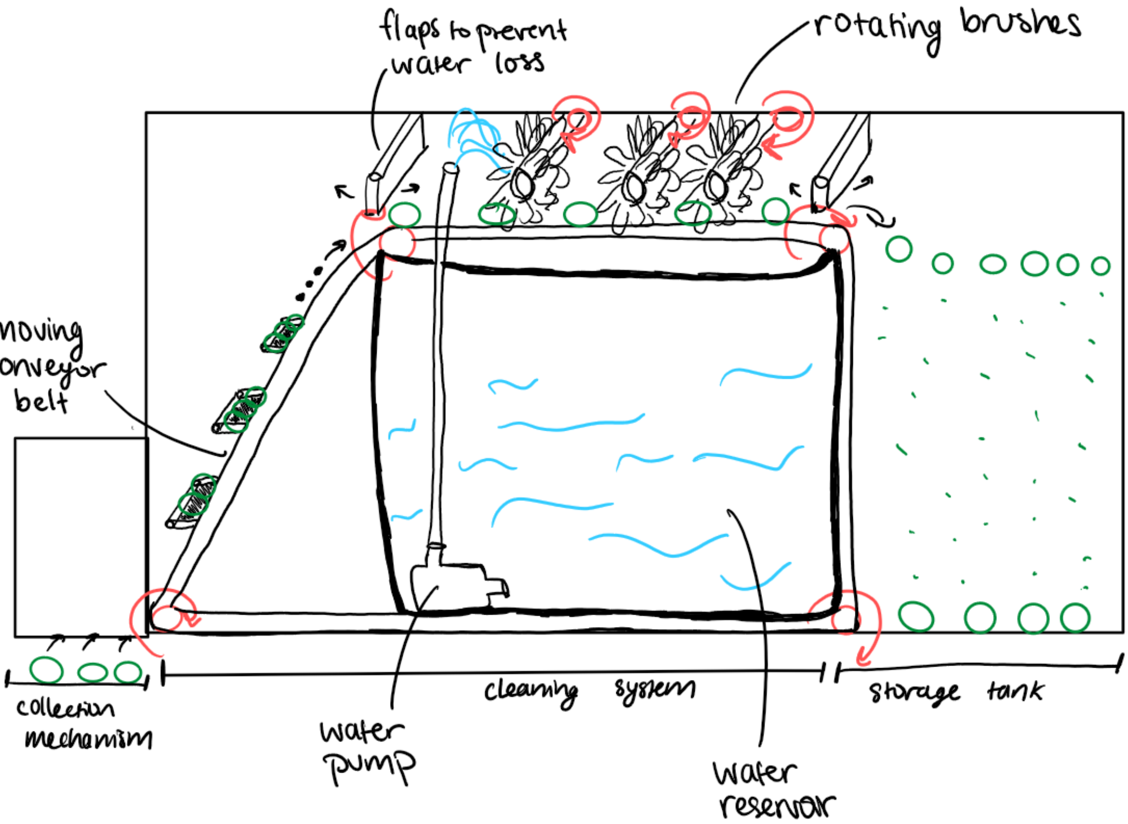



Fig. 33: Overall System Concept by Amelia

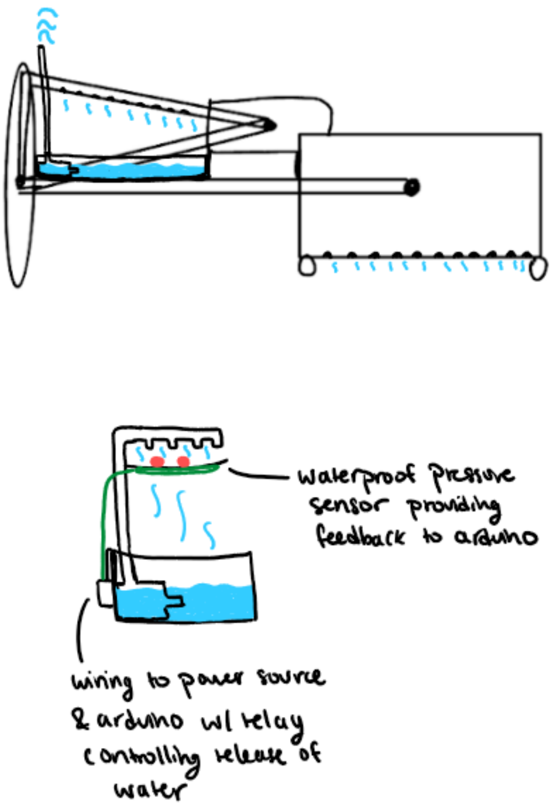



Fig. 34: Spraying System Concept by Amelia

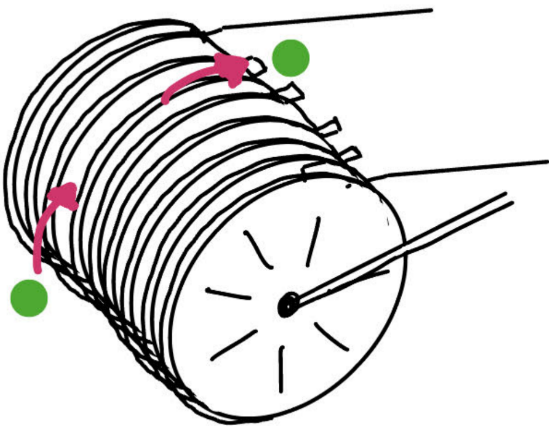


Fig. 35: Pulling Direction of Collection

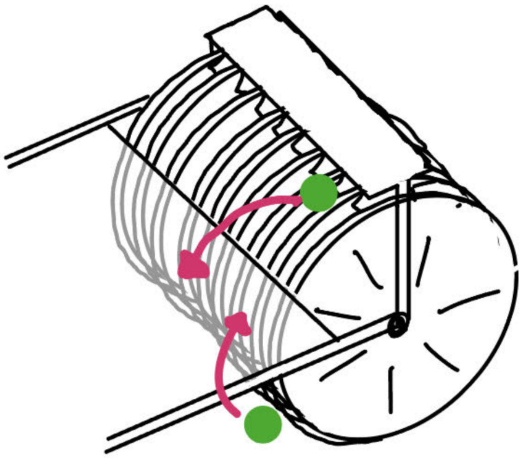


Fig. 36: Pushing Direction of Collection

```python
import cv2
import numpy as np
from matplotlib import pyplot as plt

# Function to adjust threshold and apply filters
def identify_dirt(base_path,before_path, after_path, threshold_value=128, apply_blur=False, blur_kernel=(5, 5)):
    # Load the images
    base_img = cv2.imread(base_path)
    before_img = cv2.imread(before_path)
    after_img = cv2.imread(after_path)

    # Convert images to grayscale
    base_gray = cv2.cvtColor(base_img, cv2.COLOR_BGR2GRAY)
    before_gray = cv2.cvtColor(before_img, cv2.COLOR_BGR2GRAY)
    after_gray = cv2.cvtColor(after_img, cv2.COLOR_BGR2GRAY)

    # Apply Gaussian blur if selected
    if apply_blur:
        base_gray = cv2.GaussianBlur(base_gray, blur_kernel, 0)
        before_gray = cv2.GaussianBlur(before_gray, blur_kernel, 0)
        after_gray = cv2.GaussianBlur(after_gray, blur_kernel, 0)

    # Threshold the images to identify dirt (adjust the threshold value)
    _, base_thresh = cv2.threshold(base_gray, threshold_value, 255, cv2.THRESH_BINARY)
    _, before_thresh = cv2.threshold(before_gray, threshold_value, 255, cv2.THRESH_BINARY)
    _, after_thresh = cv2.threshold(after_gray, threshold_value, 255, cv2.THRESH_BINARY)

    # Calculate the percentage of dirt
    before_dirt_percentage = 100 - np.sum(before_thresh == 255) / np.sum(base_thresh == 255) * 100
    after_dirt_percentage = 100 - np.sum(after_thresh == 255) / np.sum(base_thresh == 255) * 100

    cleaning_efficiency = before_dirt_percentage - after_dirt_percentage

    # Display the images with dirt percentage
    fig, axes = plt.subplots(1, 2, figsize=(10, 5))
    axes[0].imshow(before_thresh, cmap="gray")
    axes[0].set_title(f"Before Cleaning\nDirt: {before_dirt_percentage:.2f}%")
    axes[0].axis("off")

    axes[1].imshow(after_thresh, cmap="gray")
    axes[1].set_title(f"After Cleaning\nDirt: {after_dirt_percentage:.2f}%")
    axes[1].axis("off")

    plt.show()

    return cleaning_efficiency
```

Fig. 37: Cleanness Evaluation Code

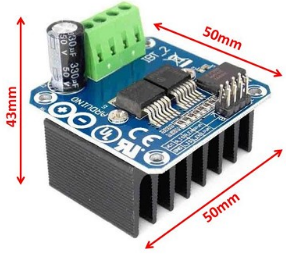



Fig. 38: Motor Driver

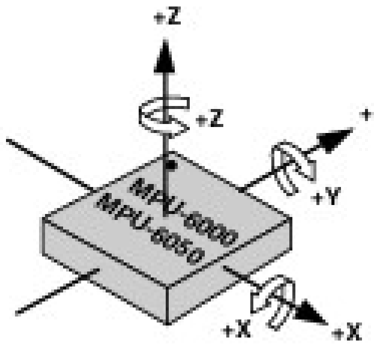



Fig. 39: IMU orientation

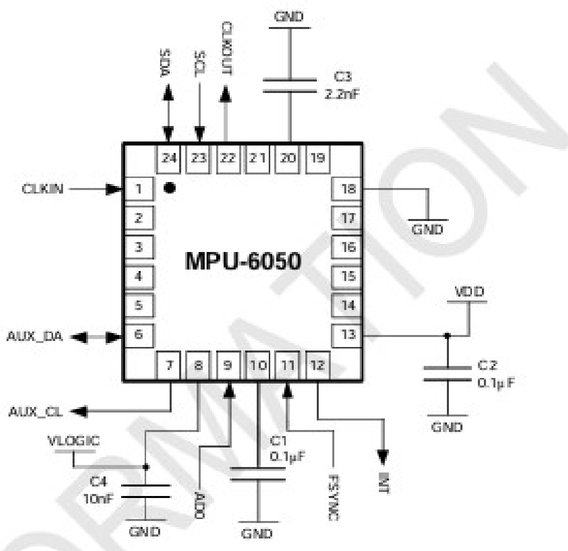



Fig. 40: IMU Schematic

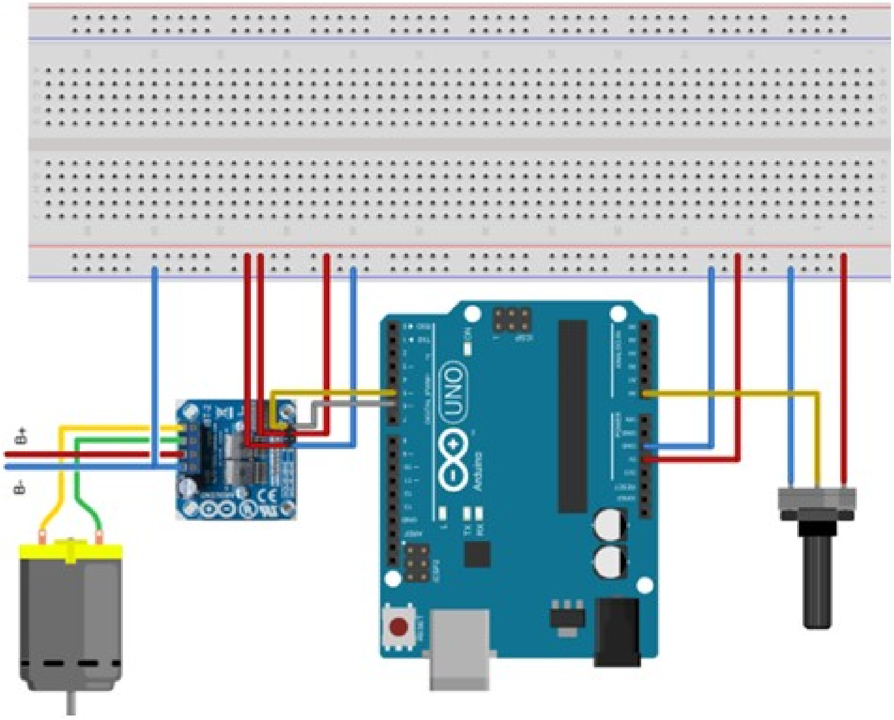



Fig. 41: Motor Driver Circuit

Fig. 42: Motor Encoder

What is your current method of ball collection ?
- What are the pros of this method?
- What are the cons of this method?

What is your current method of ball cleaning?
- What are the pros of this method?
- What are the cons of this method?
- Common alternatives you’re aware of and why do you use this method?

What is the average volume of golfers at the range per day (guesses is fine) ?

What is the average volume of balls hit per golfer (guesses are fine)?

What is the average volume of balls used per day?

How are your targets marked (flags, baskets, holes) ?

What would you hope for out of a robotic, automated solution for ball collection?

What is your opinion on building an integrated ball-collecting and cleaning robot?

How often would you want this robot to collect balls? To clean them?

Where would you want the robot to deposit the balls?

How often would you want to charge this robot?

Describe the level of interaction between current C&C methods with golfers themselves.

Rank the issues of experiencing a lack of balls, dirty balls, or damaged balls at the ball dispenser from highest to lowest importance.

Fig. 43: Survey Questions

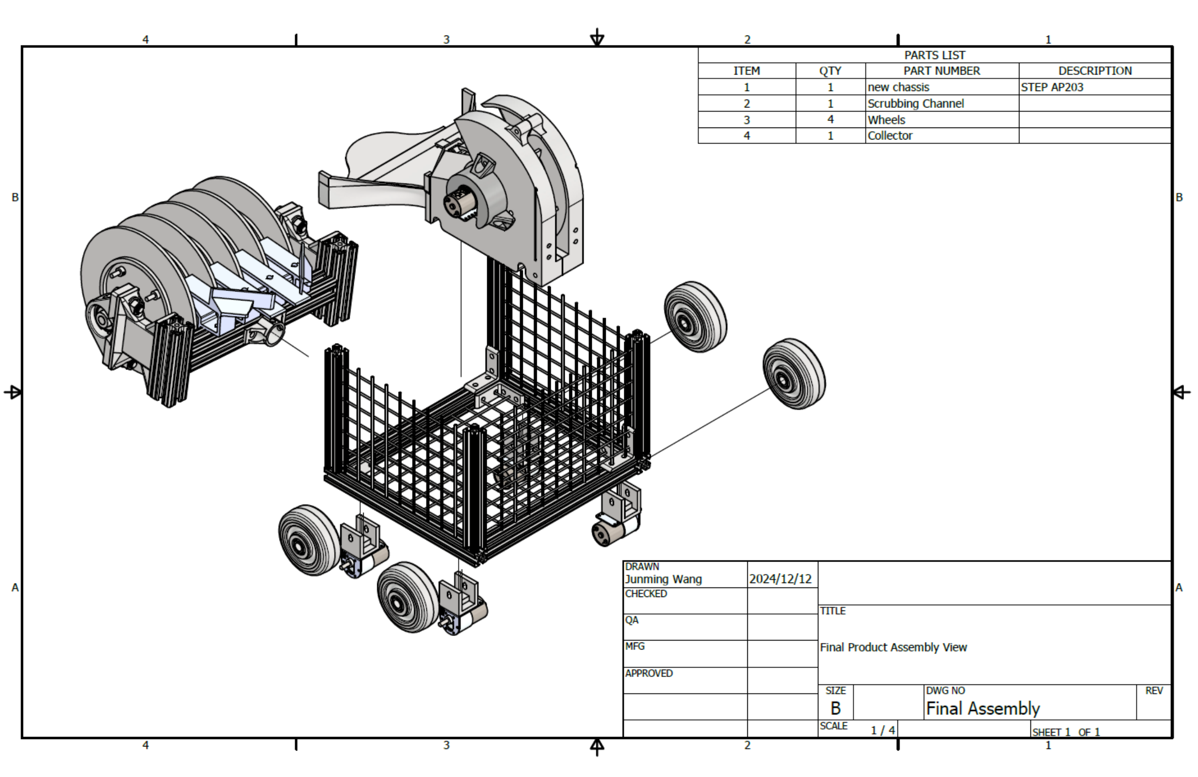



Fig. 44: Overall Structure Exploded view

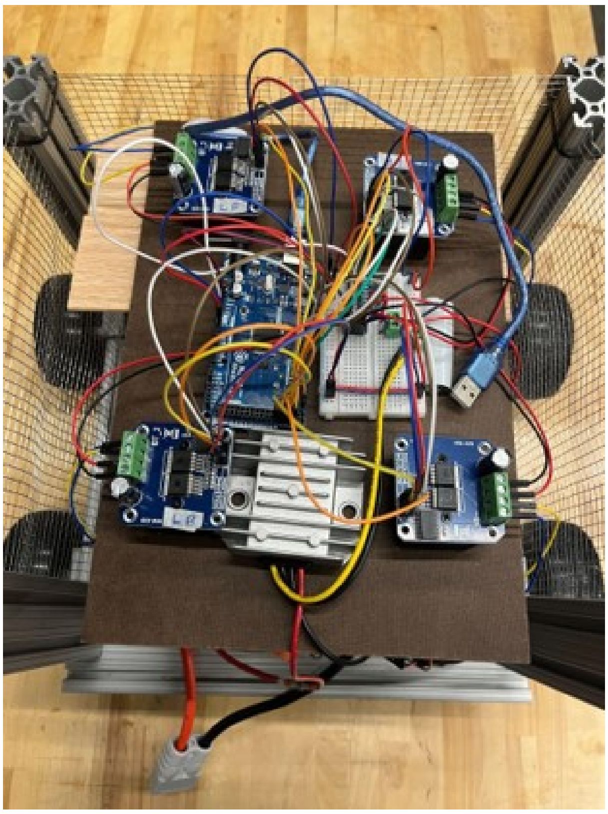


Fig. 45: Circuit on Robot Base