Autonomous Vehicle Tennis Ball Collector

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Abstract—In this paper an autonomous robot is introduced. Its goal is to collect and return tennis balls from a standard tennis court. Using off the shelf parts (OSPs) to rapidly develop a working prototype capable of finding and picking up a tennis ball. Because these OSPs were not intended to fit together, some modifications were made to a few parts to accommodate the addition of the other parts.

Key Terms—Autonomous Vehicle Tennis Ball Collector (AVTBC), Smart Vision Sensor, Ball Acquisition System (BAS), Ball Detection System (BDS), Vehicle Programmable Logic Control System (VPLCS)

I. Introduction

The Autonomous Vehicle Tennis Ball Collector (AVTBC) is an academic project sponsored by California State University, Northridge to buy ECE 492 and 493 students. The project began in November of 2019 and is advised by Dr. Shahnam Mirzaei of the Electrical and Computer Engineering Department at CSUN.

This paper discusses the project scope, design, prototype implementation, and assessment for the spring semester of 2020. In Section II. Project Description, the basic functionality of the AVTBC robotic car are elaborated and the general scope of the project is discussed and the teams formulated requirements are enumerated and analyzed to specify the detailed aspects of how the AVTBC will function. In Section III. Design Methodologies the project's design decisions, constraints and other limiting factors are elaborated.

To meet the task burden of the requirements, the major project systems and subsystems that were formulated are discussed in detail. In Section IV. Prototype Testing, considerations and results of the prototype robotic car constructed from the previous design are examined in respect to each major project system and requirement. Section V. Conclusion discusses how each subsystem met or did not meet requirements as well as prospective additions to the project which may improve future prototypes.

II. Project Description

A. General Function

The goal of an autonomous device is to be able to have it perform a task with minimal input. In this case, the robot will turn on and start its patrol looking for tennis balls on the ground. To do this it takes on two major roles, finding the tennis balls, and retrieving the tennis balls. These two roles require dramatically different hardware.

First, patrolling requires the robot to be mobile and able to observe the environment to identify tennis balls. Once it finds one, it must drive toward it, remembering what it did to get there, and stop at the ball. If at any time, there is an obstacle in the way, the robot must be able to drive around it and continue.

Once it is at the tennis ball, the robot must pick the ball up. This can be done in two ways: By driving the car to the correct spot in relation to the ball. Or with sensors on board to detect the balls' location relative to the robot using that data to coordinate grabbing the ball. In either case, the ball must be stored until the robot can finish its sweep of the court and transfers any tennis balls to the collection receptacle.

A. High Level Requirements

- ○ The AVTBC shall collect and store tennis balls at rest on the court floor.
- ○ The AVTBC must avoid any collision with all court obstacles including tennis balls.
- ○ The AVTBC shall perform all tasks unassisted by an operator.
- ○ The AVTBC shall extract all tennis balls from a court in a single court sweep.
- ○ The AVTBC will have battery capacity to continuously operate for at least one court sweep.

B. Lower Level Requirements

- The AVTBC shall collect tennis balls at rest on the court floor.
  - The AVTBC will detect at rest tennis balls.
  - The AVTBC will possess a mechanism to physically manipulate at rest tennis balls and load them into an onboard receptacle.
  - The AVTBC shall be able to traverse a flat hard tennis court.
- The AVTBC must avoid any collision with all court obstacles including tennis balls.
  - The AVTBC can detect obstacles including at rest tennis balls that are yet to be retrieved.
  - The AVTBC avoids any detected obstacles by

computing a path around the obstacle towards the next point of travel.
  - The AVTBC can detect collisions and obstacle proximity.
- The AVTBC shall perform all tasks unassisted by an operator.
  - The AVTBC must have sufficient computational and logical capabilities to execute all decisions related to gathering tennis balls, storing tennis balls, collision avoidance, and object detection.
  - court
  - The AVTBC will cease operation if any critical function is impeded or all balls are found.
- The AVTBC shall extract all tennis balls from a court in a single court sweep.
  - The AVTBC shall patrol the court for the presence of a variable number of at least two tennis balls.
  - The AVTBC shall provide detection for the entire area of the court during its patrol routine operation.
  - The AVTBC will conclude a sweep once all of the court area has been explored and all detected balls have been retrieved.
- The AVTBC will have power capacity to continuously operate for at least one court sweep without any auxiliary power source.
  - The AVTBC will be powered by batteries.
  - The AVTBC batteries will have sufficient output to power all components during any operational routine execution.
  - The AVTBC will have sufficient charge capacity to power vehicle operation greater than the worst case operational conditions with respect to the number of balls retrieved and distance traveled during patrol

III. Design Methodologies

A. Design Overview

The biggest constraint for this project has been time. We wanted to get the project out as fast as possible. To aid in this endeavor, we used more off the shelf parts to expedite the process. The initial goal of the project included having a working robot that retrieves and stores tennis balls. While that can be achieved with a shovel attached to a moving robot, efficiency was not considered in the design process. The team wanted to develop a creative working solution that implements and connects various modules together and utilized image processing capabilities.

B. Systems

a. Drivetrain System

The two biggest components of this project include the drivetrain and the arm. At the early stages of the design we decided the most important aspect of the drivetrain was to be able to carry all the components while not expensive. The chassis must be able to have room to attach our sensors as well as allow modifications such as 3D-printed attachments.

The initial model of the car that was chosen had 2 motors for the back wheels and a ball bearing wheel for the front. A pair of infrared sensors was originally used as object detection which were then attached to the bottom floor of the car. After adding the car to the second layer of the car and implementing a two battery pack system we quickly learned the weight was too much for this design and had to pivot our idea.

In the next stage of the design we used an osoyoo chassis pictured below. With 4 motors the car was able to handle the load out upon it. The plastic allowed the team to drill and modify the frame to fit the arm as well as have room to 3d print an extra layer if needed.

Figure 1:Osoyoo Robot Car

With slight modifications to the power bank and arduino placements the completed chassis featured below gives us the final design. The pixy2 camera is mounted at the front so it is able to detect any balls ahead of it. The arm is centered in the middle allowing it to pick up the ball at any angle and easily deposit it into the basket.

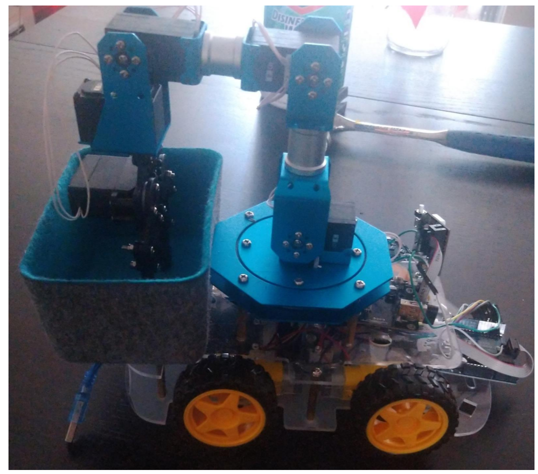

Figure 2:Final Car Design

b. Ball Acquisition System (BAS)

Once in proximity of the ball, the arm will reach, grab, lift, and deposit the ball into the on-board receptacle.

The arm has its own controller board that supplies data and power to each servo. We elected to keep this rather than make our own to speed up the development of the robot. Initially, the protocol for communicating with the arm was elusive. We opted to explore incorporating the arm's controller PCB itself into the design. Because this approach was crude, took up valuable space, and had no guarantee of working consistently, even if implemented ideally, when the arm's protocol was found, we shifted to using that to control the arm.

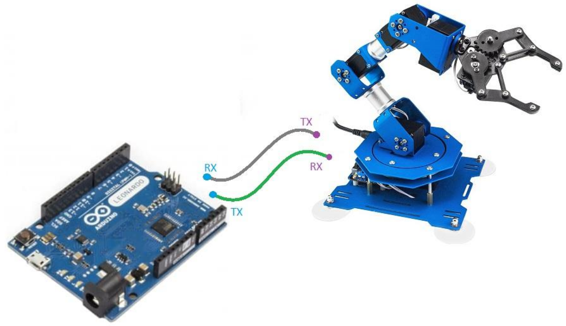

Figure 3: Two Wire Connection Between Arm and Arduino

The arduino and arm communicate using the serial tx and rx pins. Although the arm has the capability of reading the angle it is at, we found no short term benefit to including that ability in an arduino function. This means that the rx pin and the tx pin of the arduino and arm respectively do not need to be connected but are incase there is desire to have the arm read back information. Functions were developed to move one motor, or six motors at a time. These functions include a header, command, and command data. Command data consists of the number of servos involved, the time to move, and angles for each servo moved. These functions are used for all the arm's routines. Each routine has a set of parameters for each servo angle. The time the arm has to the servos to the desired position was decided to be 1 second. This is not the fastest it can go but it limits the risks of damage to both humans and the arm. How quickly the bot picks up balls is not a priority as long as it does it in a reasonable amount of time (~4 sec.). The arm has its own controller board that supplies data and power to each servo. We elected to keep this rather than make our own to speed up the development of the robot.

	id	header	length	command	parameters
Bytes	1	2	1	1	0 or more
Comments	Any number.	Always 0x5555.	Here to end.	See *commands*.	See *commands*.

Figure 4: Template for Coding a Command for the Arm [1]

There was consideration of mounting a sensor to the claw to guide it to the tennis ball. This approach was dismissed with the philosophy that simpler is faster and required fewer parts to get the prototype built. Instead we rely on the sensors being mounted to the chassis and use the sensors in both positioning the car and guiding the claw. Next, ultrasonic sensors were chosen to locate the ball when the bot is close because the ultrasonic sensors were easier to calculate distance with. Only a rough location was needed for the claw to grab the ball, so using the PixyCam was not only overkill but also more work.

Finally, we needed a place to store the balls while patrolling. It would be ineffective to pick up and return one ball at time. After extensive dimensional and weight analysis of possible BAS containment solutions, a rudimentary approach was adopted to expedite prototype design and facilitate BAS testing. A felt and nylon bucket was attached to the rear chassis using screws and washers. The lightweight nature of the basket helped in keeping the car from slowing down or tilting backwards due to a heavy rear as we had seen with the battery pack.

c. Ball Detection System (BDS)

In the original design of the car the team used a set of IR sensors to help simple navigation and test the functionality of the car. While the IR sensors helped in the early stages of the project, to help us reach our goal of detecting tennis balls, we needed to incorporate object recognition as well as detection. The device will have to be able to detect objects several feet away, recognize using shape, color, or texture and be small enough to not add significant weight to the car.

After reviewing different sensors with various features the team decided upon using the Pixy2 Camera as well as Ultrasonic Sensors (HC-SR04) as shown below. With the pixy camera being used as the primary object locator and detector, it fulfills a majority of our previously mentioned requirements. The pixy 2 is very lightweight and small enough to be able to securely mount at the front of the car. With a 10 foot radius of detection, the camera uses a color based object detection algorithm that tracks on 60 frames per second. The main selling factor of the pixy is the compatibility with the arduino controller. As an arduino is also being used to control the car we save upon price and space. A feature not included with the pixy camera is the exact distance the ball is at within the 10 foot radius. To circumvent this, a simple ultrasonic module is attached to the side of the car. As it is a lightweight module completely compatible with the arduino, it was the perfect choice. With the pixy camera now coupled with ultrasonic sensors we now have object recognition and detection.

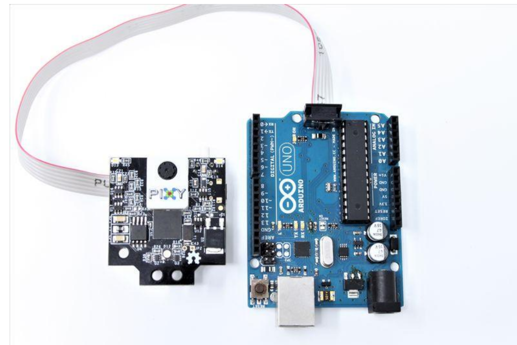

Figure 5:Pixy camera with Arduino Controller

Figure 6:HC-SR04 Ultrasonic Module

When first researching the appropriate camera to use, an initial contender was the RPLIDER laser scanner. This sensor would have been able to map a larger area of the tennis field and we wouldn't need to combine other sensors with it. The problem arises with the size and cost of the sensor. When compared to the pixy camera, the laser scanner doubles in price. With the increase of capabilities comes an increase of size and weight. At the initial phase of the project the original car with 2 motors couldn't handle the arm attachment so having a bigger and heftier camera was not feasible.

The limiting factors that come into play when choosing an appropriate detection system is pricing, but also the car area. Since the arm will be mounted on the top the sensors will have to be small enough to be mounted on the edge of the frame. It would be possible to 3d print platforms and use standoffs to mount onto the car, but with the added weight we would have to either deal with a very slow moving car or transition to a pricier upgraded model.

d. Vehicle Programmable Logic Control System (VPLCS)

The original control design involves the use of a state machine. When the robot is placed on the tennis court the first thing it does is patrol the area in a straight line. While the robot is moving we will use a series of ultrasonic sensors to help map the area, avoid obstacles, and help save the last position on the patrol route. It will keep patrolling the area until we have finished the patrol area or until an object is detected in a 10 foot semicircle in front of the car

Once an object is detected, the pixy camera will confirm whether it's the tennis ball or another obstacle. After there is confirmation the car will head into the retrieval stage and the arm will assume its ready stage.

The car will drive towards the ball keeping it in the middle of its line of sight. The pixy documentation luckily helps us in this regard as it explains two methods we can use, "`pixy.ccc.blocks[i].m_x`" and "`pixy.ccc.blocks[i].m_y`". [2] Using these two methods we can pinpoint the exact location of the ball and should the car strafe a little too much onto one side then less power will be given to adjust and realign. The ultrasonic modules are then used for precise measurements and tells the car to stop a few centimeters in front of the ball. Once in position the arduino powers the arm and goes through its retrieval subroutine. Once the ball is securely placed in the basket it quickly sweeps its current area of any other balls. Should the car lose sight of the ball during its retrieval state the car will return to the previous patrol point and resume patrol.

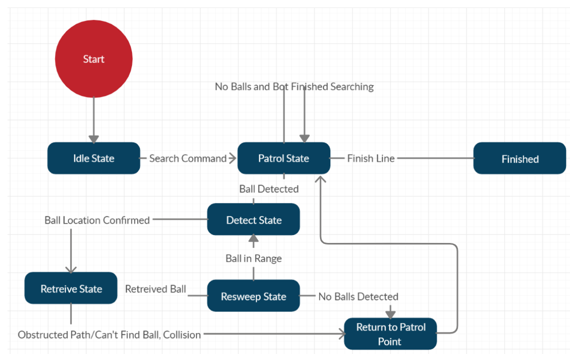

Figure 7:AVTBC Conditional State Diagram

e. Power System

The AVTBC has been designed in the early iterations to be battery powered. Initially, we designed our system to use one battery pack for two drive motors, motor control, six servos, and two Arduino boards. To power the hardware we chose a battery pack that held two high discharge 3.8V batteries. These two batteries can produce 7.4V output which must power the motor drive module, Arduino, six servos and their control board. Motor drive module uses an L298N chip which can operate from 5V to 35V with a current of up to 3A. The module takes input voltage and can power four motors and an arduino board. After testing the arm is connected to the same power supply realizing the single power supply design. By running a wire in parallel with the motor drive, we were able to power the arms control board which required a steady 1mA current to keep it ready.

One concern is the operational time. The arm alone can spike to more than 2 amps of draw. This will put a significant drain on the 2.2 A/hr battery pack. Another concern is the motors and servos cannot function at the same time. However, the arm only functions when the vehicle is fully stopped and therefore does not pose a problem of limited power. Although the reduction of power in servos and motors is noticeable slightly, it is adjusted appropriately in the arduino.

We have considered adding another battery pack to power systems individually, as well as adding mosfet switches and controlling them logically using arduino. We decided to forgo these designs because it would first add weight to the already heavy vehicle. Furthermore, switches would require additional design time as well as more components such as freewheeling diodes to block current from going back into the arduino, resistors to bias the mosfets, as well as capacitors for filtering the signal. The design cost is not very significant, but during the lockdown of CSUN campus and slow delivery from online marketplaces we were not able to realize these power designs.

IV. Prototype Testing

A. Prototypical Considerations

From the design methodologies imposed on the AVTBC project, numerous integral and unique considerations were recognized with regards to the first iterative prototype built this semester. The fundamental task of acquiring a tennis ball was reduced to its basic attributes and contrasted with the project requirements to determine what functionality the prototype would implement. The AVTBC's capability to pick up and travel to a single tennis ball were focal points of the first prototype, as such the prototype would satisfy the following broad capabilities synthesized from our requirements:

- The prototype can pick up a spherical object with equivalent density to a tennis ball.
- The prototype can store a spherical object with equivalent size to a tennis ball
- The prototype can ambulate unassisted by any auxiliary power source or piloted input.
- The prototype can identify and travel to a tennis ball or equivalent test object at rest no further than 10 feet away.

To explore testing the initial prototype capabilities, each system's potential burden of proof with respect to the requirements was considered and a system specific testing strategy was formulated.

B. Testing Strategies

a. Drivetrain System

In the first model of the car, the team created an object detection algorithm using the infrared sensors so test the speed and range of motion capable of the car without any external modules. Once satisfied with the car's functionality, the infrared sensors were taken out for the pixy camera. After setting the tennis ball signature in the pixy camera the drivetrain now moves under the influence of the pixy camera.

When adding the arm component however, the team ran into the car stalling or moving very slowly. The added weight that came with the second battery pack and arm was too much for the drivetrain and so a new 4 motor chassis was used. With the new model and wiring the arm to the drivetrain battery pack the car was complete. A test drive of scanning and moving proved to be working without any weight issues.

b. Ball Acquisition System (BAS)

Since the arm is an off the shelf part, it was trivial to verify it worked appropriately. However, developing the arduino functions to reliably produce the desired actions without the user necessarily having intimate knowledge of the arm's protocols was more intensive. This testing process required experimentation and verifying arduino functions as well as recording the positions for the minimum and maximum rotation of the servos. For initial testing, a battery pack separate from the drivetrain was used. After the arm was verified, it was connected to the drivetrain power supply.

The basket was confirmed to be able to contain the dropped tennis ball and ample capacity to hold additional tennis balls.

c. Ball Detection System (BDS)

Testing of the sensors yielded several problems concerning the pixy camera. With the original settings in place the pixy camera has a high tendency to produce false positives and sometimes ignore the ball completely.. Due to the camera using a color detection algorithm, when testing inside a classroom with less ambient light than a tennis court, shadows caused the camera to pick up the wrong signature in corners or other objects. This wouldn't be a problem in an outdoor tennis court as we assume the field will be sunny and well lit, but even so, only after allowing the pixy camera to focus on one signature at a time and adjusting the settings, there have been no more false positives.

d. Vehicle Programmable Logic Control System (VPLCS)

A simple model of the state diagram was made to test out the functionality of the system as a whole. The elementary solution has the car spin in a 360 degree motion while scanning for a tennis ball using the pixy camera. Once the object is detected the car then drives towards the ball, and the ball is then retrieved with the arm.

Hypothetically, instead of simply spinning in place the car traverses a straight pre-designated path. The ultrasonic sensors can then be used to map the area around the car if the tests are being run in a foreign court, or using the pixy camera color detection, a line with various checkpoints can be demarcated on the court's floor. This will give the car a sense of location and be able to return to it's patrol point easily after retrieving the ball. We assume the field to be empty except for tennis balls, but in the later stages of the project the ultrasonic sensors will also be used as object collision preventers to help avoid various rocks, feet, and the net.

e. Power System

To check our power system we used multimeters and bench power supply to check if our hardware was up to specifications. To see if the motor driver module would power correctly in parallel with the robotic arm, we first checked how much voltage and current they draw separately while idle. After simultaneously powering both and inspecting the AVTBC's behavior when moving, a significant reduction in speed of the motors and arm servos was observed. Then, by updating software parameters we were able to achieve the necessary speeds. For future peripherals it is strongly recommended to update the code and check connections for proper voltages.

V. Conclusion

The AVTBC provided a wide variety of real-world challenges. The initial power to weight ratio of the vehicle was insufficient. The solution to meet our weight requirement was to upgrade from a two motor chassis to a four motor chassis. This gave the team a few advantages. It not only gave us more power to move about the court but also added stability for when the arm moved and increased the capacity for peripherals.

Unifying the arm and the car to use the same resources took careful consideration. Finding the information on the arm protocol allowed the car and arm to operate without sharing any pins on the single on-board arduino.

Image processing was a new field of exploration to the team. However, after learning techniques and carefully tuning the shape and color criterion, false positives were eliminated. This was critical as a false positive would lead the car to drive full speed into a wall. The restriction currently is that the car must stop and scan for the ball. This is due to lowering the framerate to reduce false positives from noise artifacts in the camera feed. The frame rate reduction results in causing the car to stop moving when reacquiring the ball.

In conclusion, the project provided lessons in constraints. The power and size constraint was insufficient at the start. We redesigned. The car and arm both needed to use the arduino. We researched. The image processing was giving false positives. We refined. The design developed as constraints were found, a real life affair.

A. System Functionality Not tested

a. Ball Acquisition System (BAS)

The biggest challenge with the arm was finding the protocol for controlling the arm. Finding the correct phrase in order to conduct an online search for the protocol, caused a significant delay in programming the arm. Second was creating easy to understand arduino functions. This wasn't difficult or overly technical, however, it was tedious to verify each function had full functionality.

b. Vehicle Programmable Logic Control System (VPLCS)

The VPLCS testing is very interdependent on the full functionality of other systems including the BAS, and drivetrain. Due to this testing burden, much of its functionality has not been formally tested in the field for the AVTBC. One component that remains untested is the static path computation which will be used to chart a route to a detected ball so that it can be traversed again, thereby returning to patroll from the same point if no other balls are detected.

c. Power System

The power system has not been tested in a prolonged use or with added loads. In the long term this rover would have to operate in a large open area with multiple objects that it will have to pick up and store. Theoretically there should be no problem with it working for at least an hour. From our limited testing batteries lost a quarter of their charge in half an hour of rover just turning and spinning in circles.

B. System Functionality Not Implemented

a. Ball Acquisition System (BAS)

The next step would be to have the arm take distance data from the ultrasonic sensors and use that to reach to the correct point to pick up the ball. This involves the arduino reading the sensors, and calculating the servo angles required to reach the ball and then writing the angles. In a perfect world, this step would be irrelevant because the car would drive to exactly the right location for the arm to grab the ball. The relationship between the ball and car will vary. This step will allow the robot to compensate for small differences in positioning.

b. Ball Detection System (BDS)

With the program currently, the ultrasonic sensors are not implemented and are only running off the input of the pixy camera. The team hopes to add the ultrasonic module to help with more precise object detection. After approaching the ball, ultrasonic sensors sense the distance and angle to the ball. This is then used to calculate the servo angles for the arm to grab the ball.

c. Vehicle Programmable Logic Control System (VPLCS)

Much of the control system also remains yet to be implemented. Some of the system capabilities absent from the current prototype includes using a pre-programmed routine to expedite path computation and pass the relative positioning of the vehicle to the BAS and BCS systems. In addition critical interfacing with proximity detecting ultrasonic sensors remains absent from current test vectors limiting the ability of the VPLCS to send meaningful control signals to the other systems.

d. Power System

There is enough power to meet the implementation needs of this project;

however, if there are more load requirements, another power bank would be necessary. A power bank is available to be fitted into the design if such requirements are needed in the future, but are not implemented currently.

C. Requirements Not Satisfied

a. Ball Acquisition System (BAS)

The arm does not currently react to the placement of the ball relative to the car. To implement, the ultrasonic sensors need to be mounted on the front of the car or on the arm itself. Then the sensor data must be analyzed and the location of the ball found and the servo angles calculated and set.

b. Vehicle Programmable Logic Control System (VPLCS)

In our implementation of the VPLCS a majority of the project requirements were not satisfied or only partially satisfied. This AVTBC prototype was not able to detect or avoid obstacles and had not implemented sufficient proximity detection to avoid obstacles. While the computational capabilities of the prototype Arduino board were not tested to the worst case in this prototype, the VPLCS had sufficient processing power to detect a ball and move to it. In this iteration, no dynamic routines such as the patrol routine were implemented as the only relevant function was to move toward a detected ball.

D. Future Additions

a. TSP Algorithm

To handle any cases when multiple tennis balls are detected by the sensors in a relatively short period of time, the AVTBC can optimize its performance by implementing a Traveling Salesman Problem to minimize the time and distance required to collect the balls. As the number of tennis balls to be collected increases and the static path computation for each ball will rapidly become a large sink of resources and time. Implementing a TSP type solution to this problem will allow for redistribution of resources to other systems during the patrol and detection routines.

b. Improved Ball Detection System (BDS)

Currently, the PixyCam is used to find and direct the car toward the ball. It must stop moving to locate the ball. With tweaking and the addition of ultrasonic sensors, the car should be able to locate a ball and drive to it without stopping. This will however, require a smooth transition from the PixyCam to the sensors when the ball is < 5 feet away.

c. Ball Capacity

A bigger bucket would allow the robot to collect more balls without having to travel back to unload. A 3d printed basket could be designed to have a higher carry capacity and not add much, if any, weight compared to the current container.

d. Additional Power Sources

There is still some speculation on whether or not the current power source will be sufficient. At some point a larger, more powerful source may need to be implemented.

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