Autonomous Mobile Robot Operation: Playing Paper Football

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ABSTRACT
The designed robot, "Tim TeBOT", plays paper football against a human opponent. It operates with the function of hitting a yellow paper football to score a touchdown, then allowing the human opponent to take their turn. All components are interfaced with an ATmega 128 processor. A CMU Cam 2+ is used for vision sensing of a yellow paper football on the field. A custom stadium was designed for the robot to play which allowed for a more desirable and consistent autonomous operation. Ultrasonic sensors are used to determine distances and robot location on the field. The robot was able to play the game as desired with only minor issues in actual execution.

Keywords
Paper Football, Robotics, Vision Sensing, Color Tracking

1. INTRODUCTION
The autonomous robot, named "Tim TeBOT", was designed as a project for the Intelligent Machine Design Laboratory course at the University of Florida. His intended objective is to play a game of paper football against a human opponent autonomously. The robot will have the ability to identify the football on the playing field, approach it at a proper angle to hit the ball so that it stays in the playing field, and hit it with a variable force depending on the robot's location on the field.

A background of the rules and objectives of paper football will be given, after which the designs, both mechanical and electrical, will be discussed of the robot and environment. Finally a discussion of experimentation and results will be given to evaluate the performance of the autonomous robot.

The robot will begin behind his end zone and progress through a routine to search the field from right to left beginning at his goal line. If the football is found TeBOT will proceed at a right angle to hit the football and align itself with the opposing end zone wall to hit the football. If no football is found, TeBOT will move forward up the field and repeat its search until it has reached the end of the field, in which case it should have found the football otherwise resulting in a failure of operation.

2. PAPER FOOTBALL RULES
The rules used in the robot's adaptation of paper football were heavily influenced by the standard rules of paper football [1]. The overall objective of the game is to score touchdowns and 2 point conversions by sliding the football across the playing field in a single fluid motion. (Humans usually use a single finger to flick the "ball.") If the ball stops before the opposing player's goal line, the opposing player has a turn to hit the football from its current location. If the ball is slid past the back of the end zone, the ball is placed at the 20 yard line in the middle of the field and play resumes with the other player's turn. The robot will be unable to retrieve a football hit beyond the back of the end zone, this must be done by the human to recover and reposition the football at the 20 yard line. The robot assumes that it is his turn to play 20 seconds after his previous play. A touchdown is scored when a football stops with part of it on the goal line. The adapted rules are listed below:

1. How to Win: Score points with "Touchdowns" (6 points), "2-Point Conversions" (2 points)
2. Game Length: Players decide beforehand that either: a) the first player who scores a pre-determined number of points wins, or b) the game is timed and the player with the most points when the clock runs down is the winner. Begin by flipping a coin to determine which player will choose to kick or receive the football.
3. Touchdowns are easily determined by observing if any part of the football passes finishes on the opposing player's goal line (prior to hitting the endzone wall).
4. The kickoff is played by placing the ball at the 20 yard line in the center of the field.
5. Opponents take turns sliding the football back and forth across a table top using your fingers in either a "flicking motion" with the index/middle finger or with a single "bump" with two fingers, once per turn. In the robot's case this is done by spinning its wheel. An extended pushing of the ball is against the rules, the football is placed back to its original location and the offending player loses his turn.
6. Touchdowns, which are worth 6 points, count when after flicking or kicking off the football it stops with any part of it hanging over the edge of the goal line.
7. If a touchdown is scored the scoring player must attempt a "2-Point Conversion."
8. 2 Point Conversion: The football is placed in the middle of the table (this approximates the 50 yard line on the field) and is given only one flick or bump to try to have the ball stop with part of it hanging over the goal line as in a touchdown. If part of the football is hanging over the goal line then 2 points are scored; if not, then no 2-point conversion points are scored. Either way, the game then continues with a kick off from the player who scored the touchdown.
9. An "Out-of-Bounds" occurs when the football is flicked or kicked off and touches the "out of bounds" territory identified by the side lines of the field. Then the human

simply judges which "yard line" the ball left the field and places the ball as they wish back onto the playing field at that point, and the ball is in play again.

10. A "touchback" occurs when the football is flicked or kicked off and goes out of the end-zone. Then the person defending simply places the football at the 20 yard line taking possession at the 20; the ball is in play again.

3. INTEGRATED SYSTEM

The robotic system consists of the following components which are visually depicted in a block diagram in Figure 1.

The components comprising the Tim TeBOT system and their purposes are listed below:

- ATmega 128 [2]– This is the central processing unit for the entire system. All code executes on this device and interfaces with all of the components on the platform except the camera servo which is managed by the CMU Cam 2+.
- LEDs – Visual indicators of the state of the robot.
- Debug LCD –Used to display data for debugging purposes.
- Servo Motors –Used for motion of the robot.
- Servo Motor –Used to move the DC-motor into a docked (no hitting) and undocked (hitting) state.
- DC Motor - Used to spin the hitting wheel to a calculated speed in order to hit the football the desired distance.
- Ultrasonic Sensors (F) –Used to determine the robot's distance from the end zone and to align itself with the wall in front of it.
- Ultrasonic Sensors (B) –Used to determine a distance behind the robot when backing up.
- CMU Cam 2+ - This vision sensing device performs all of the image processing in order to identify a color (the yellow football) and to track the football when the robot is in motion. Since all of the image processing is performed on this device, the CMU Cam's processor on is considered a coprocessor to the ATmega.

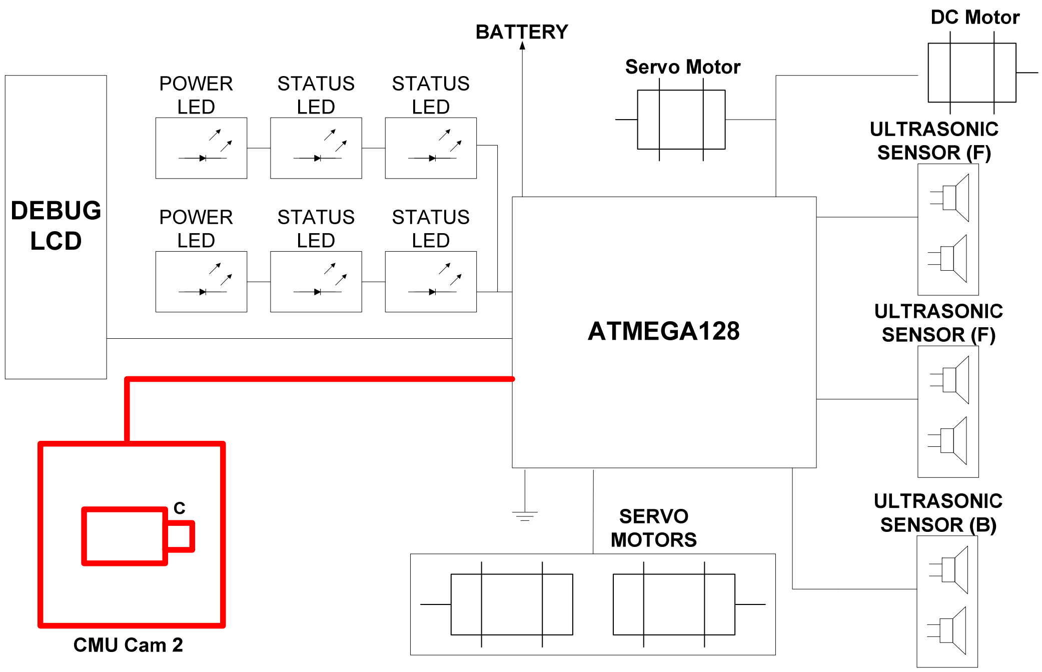

Figure 1. Integrated system design for the autonomous mobile robot Tim TeBOT.

4. MOBILE PLATFORM

4.1 Design

The platform underwent two revisions during its development. The second revision maintained all of the functionality of the first platform while adding other functions such as a spinning wheel mechanism to hit the football down the field.

The platform is approximately 9" wide by 10" long by 7.5" in height. The robot structure has two rear wheels driven by two standard hobby servos (hacked for continuous rotation), with two front weight supporting pegs that do not guide in robot movement. The servos and pegs are mounted to an enclosed box that contains all of the electrical components. Refer to Figure 2 for a CAD image of Tim TeBOT. The CMU Cam 2+ (omitted from the CAD drawing) was mounted atop the robot on the front in order to have an over head view of the front of the robot. There is third un-hacked servo (between the two rear wheel hacked servos) that controls the hitting wheel's location by being in the docked (up) or undocked (down) position. See Figure 3.

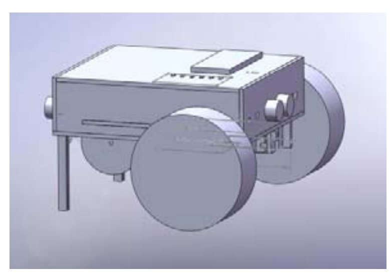

Figure 2. Mobile platform CAD drawing made in Solid Works.

Figure 3. Docked hitting wheel in center of the platform.

Figure 4 shows the robot. The platform top has cutouts for a 16x2 character LCD screen and 6 LEDs. Four holes were created in the front to mount two ultrasonic sensors (SRF04) [3,4]; the rear has a single ultrasonic sensor mounted in the middle. A JTAG port penetrates the robot body to in order to facilitate easy reprogramming and debugging of the microprocessor on the enclosed electronics board.

Below the robot platform (see Figure 3) is an servo-driven arm that moves a DC motor attached to the hitting wheel. The servo is used to keep it out of the way when not in use (docked). When undocked position, the hitting wheel is enabled to hit the ball.

Movement of the robot is performed by spinning the hacked servos either in the same direction (forward or backward) or in opposite directions (to turn left and right). Spinning both the servos for turning allows the robot to pivot about a point closer to the center of the robot; spinning only a single wheel causes wide turns and slipping of the other motor, and should generally be avoided.

The CMU Cam 2+ was used for image detection and image processing to track the football. This piece of hardware (omitted from Figure 1) was placed atop the platform (see Figure 4). A hobby servo was used to allow the CMU Cam 2+ to tilt when tracking an object. This servo was the only servo not directly controlled by the system microprocessor; instead the CMU Cam 2+ coprocessor controlled the servo movement (which would ultimately get movement commands issued from the main ATmega 128 processor). Figure 4 shows to is an image of Tim TeBOT upon final completion which includes the CMU Cam 2+.

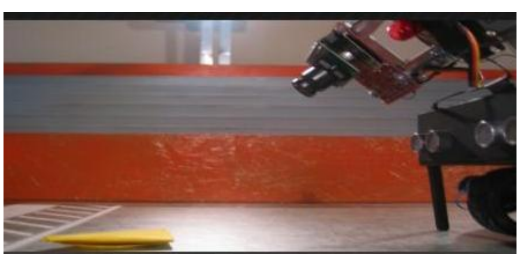

Figure 4. CMU Cam 2+ in tracking (top) and non-tracking (bottom) configurations

4.2 Turning Delays

Approaching the football at a right angle is crucial to hitting the football and keeping it in bounds. As an example, if the robot is in the middle of the field and the football is to the right of the robot, TeBOT must approach the ball at a right angle to hit it straight down the field. Otherwise, if TeBOT approached the football straight on, the ball would be hit out of bounds to the right sideline.

To ensure proper turn values when searching for and approaching the football, measurements were taken to observe how long to keep turning the servos when turning the robot in a certain direction. (The longer the delay, the farther the larger the turn.) Measurements were taken to determine the proper delays for turns of 90°, 45°, 0°, -45°, and -90°. These values were then extrapolated to a linear function to estimate the turning delays for other turning angles. The calculated delays are shown in Table 1.

Table 1. Turning Delays

Angle		Measured Delay (ms)	Calculated Delay(ms)
-1	1		10
-2	2		21
-3	3		31
-4	4		41
-5	5		52
-10	10		104
-15	15		157
-20	20		211
-30	30		317
-40	40		425
-45	45	480	480
-50	50		536
-60	60		645
-70	70		756
-80	80		868
-90	90	910	910

5. OPERATING ENVIRONMENT

Four inch tall walls were required to be constructed around the field to allow the ultrasonic sensors on the robot to determine the distance from the walls. This gave rise for the need of a dedicated playing environment for the robot to operate in. Although pieces of wood around the perimeter of the field may have sufficed for proper operation of the robot, a more controlled environment was desired that had a known playing floor friction/smoothness for proper ball sliding, floor color, lighting, goal lines side lines, robot movement area, robot waiting area, and human playing area. Refer to Figure 5 for a conceptual design of the field and Figure 6 for a picture of the constructed environment.

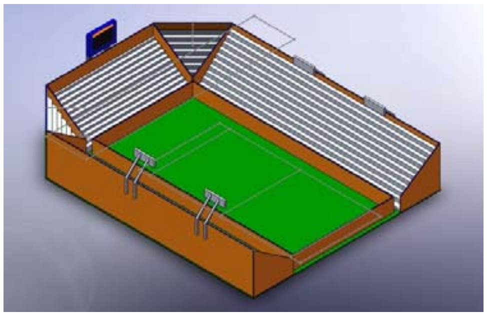

Figure 5. Conceptual CAD design created in Solid Works.

Figure 6. Constructed environment for robot operation.

The features of the stadium and purposes are listed below:

- Slick surface - Allows for consistent servo movement operation every time robot is used. For example, using different tables resulted in inaccurate 90° turns that are required for proper operation.
- Stadium lighting - Allows for consistent lighting conditions for the camera to operate properly and guarantee that it will be able to see the yellow football the same each time the robot is used. There are four stadium lights.
- Walls - This allows the robot to use its ultrasonic sensors to determine its distance to the goal line once it has approached the paper football. The walls also provide the robot with a means to align itself perpendicularly so that it can hit the ball in a line perpendicular with the goal line.
- Goal line - This provides a consistent goal line distance for the robot. It is also aesthetically pleasing.
- Centerfield "F" - This was intended to be a stumbling block for the design to ensure that the robot can properly distinguish the yellow football from the orange 'F' in the field. (The "F" stands for the Florida of the University of Florida.)
- Horseshoe "U" stadium design - This gives an open end for the human user to easily play against the robot without having to reach over the stands.
- Green field - This provides a good background to give a contrast between the yellow paper football and the field.
- Looks like a stadium - It was initially understood early on in the design process that a playing environment was necessary. The look of a stadium is purely for aesthetic purposes.
- Jumbotron – This fully functional LCD panel (digital picture frame) had no purpose other that to provide an aesthetic addition to the project. The Jumbotron played prerecorded credits and Gator videos during game.

6. ACTUATION

The actuation mechanisms of the robot consist of four total servos, two hacked for locomotion, one for camera tilt, and one for docking and undocking the hitting mechanism. The final piece of actuation is the DC motor used to spin the hitting wheel that hit the football.

The operation and functionality of the locomotion, camera, and dock/undock servos were discussed previously. The DC motor operates by receiving a PWM signal, just as the servos do. The PWM signal allows for varied motor spinning speeds while operating on a constant 5V supply [5]. The switching of the PWM to operate the DC motor is done by using an H-bridge circuit to enable or disable the motor. The larger the duty cycle of the PWM signal to the H-bridge the faster the DC motor spins.

Measurements were taken at various PWM speed values. Ten measurements were taken for each speed value (900, 1050, 1200, 1350, and 1500) and an average of the corresponding hit distances were determined. These values were then extrapolated to an exponential, linear, and 3rd order polynomial approximations shown in Figure 7 and Figure 8, and in Table 2.

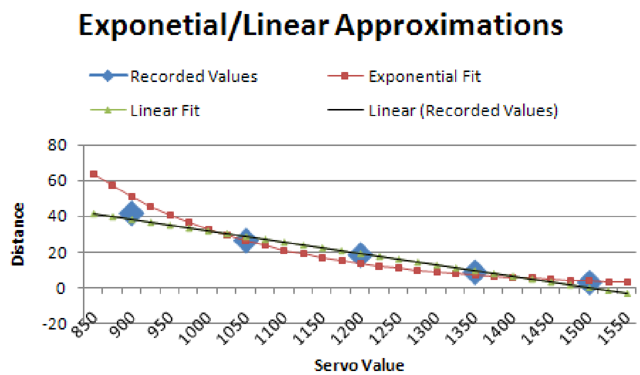

Figure 7. Servo values versus estimated distances for an exponential and a linear approximation.

The 3rd order polynomial's trend curve was given by the following equation where x is the servo value and y is the calculated distance,

$$\mathbf{y = 1.25\, x^2 - 17.50\, x + 56.67} \quad .$$

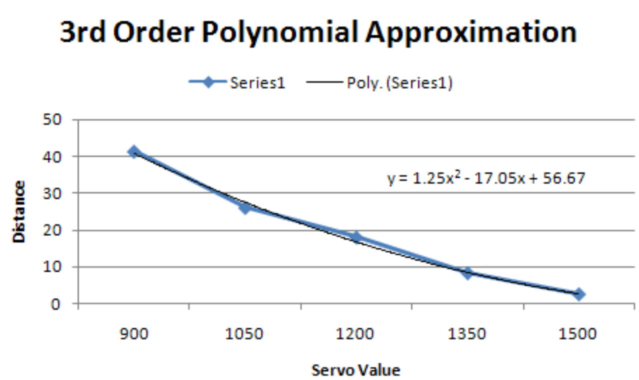

Figure 8. Best case approximation using a 3rd Order

Polynomial function.

The 3rd order polynomial approximation was the lowest order approximation that accurately determined the servo values for hitting strengths of the ball with the DC motor. These values were then hard coded into the behavior of the robot to determine hitting strengths based on distance from the end zone. Since the robot operates in a controlled environment, it would be expected that the hitting distances would remain consistent over multiple hit attempts, however it was observed that there was a large variation in the distances that the ball would travel upon being hit. It is hypothesized that this occurred because of the orientation of the football when being hit. It was theorized that if more of the football was covered when the hitting mechanism engages with the ball, then the football would travel further than if less was covered. This issue can be overcome in future versions by analyzing the orientation of the football first and aligning the robot in order to obtain a consistent hitting surface area.

Table 2: Hitting strengths and distances. The servo value are used to set the duty cycle of the 50 Hz PWM signal.

Servo Value	Exponential Distance (Inches)	Linear Distance (Inches)	Actual Values	Polynomial Distance (Inches)
850	64	42		46
875	57	40		43
900	51	38	41.4	41
925	45	37		38
950	41	35		36
975	36	34		34
1000	33	32		32
1025	29	30		30
1050	26	29	26.1	28
1075	23	27		26
1100	21	26		24
1125	19	24		22
1150	17	22		20
1175	15	21		18
1200	13	19	18	17
1225	12	18		15
1250	11	16		14
1275	9	14		12
1300	8	13		11
1325	8	11		10
1350	7	10	8.3	8
1375	6	8		7
1400	5	7		6
1425	5	5		5
1450	4	3		4
1475	4	2		3
1500	3	0	2.55	3
1525	3	-1		2
1550	3	-3		1

7. SENSORS

7.1 Ultrasonic Sensors

Two ultrasonic sensors in the front of the robot are used for distance measurements to determine how far away the robot is from the end zone. These sensors are also used for alignment with a perpendicular wall. By taking multiple measurements and averaging them on both sensors, an error value can be determined between the left and right side. If the right side is farther than the left, then the robot is turned too far to the right; similarly, if the left sensor is larger than the right, the robot is turned too far to the left. By continuously measurements, the robot was able to align itself with any wall on the field (as long as the ultrasonic sensors were detecting the same wall and not two adjacent walls). The re-alignment function helps to correct for errors when turning the robot with timing delays. This helps to approach the football at a right angle and for the robot to return to its starting position.

The third ultrasonic sensor on the back of the robot is used for distance detection when the robot is moving in reverse, primarily for when it returns to its starting position and when it backs up slightly to approach the football.

7.2 CMU Cam 2+

The CMU Cam 2+ [6] is connected directly to the Atmel ATmega 128 communicating through a through a serial port (UART). The power to the camera is supplied directly from the 8.5V voltage regulator.

Since there is a controlled environment for the robot, the color of the football is hardcoded into the robot, i.e., no color calibration is necessary. In most situations, when the environment is not well controlled, it is critical to calibrate the CUM Cam for every use. The camera is used to detect the paper football on the playing field. After detection, the robot approaches the paper football at the proper right angle to hit the ball straight down the field.

The "track color" command of the CMU Cam 2+ is used to identify the football and to keep the football in the image; the tilt servo attached to the camera (which is controlled by the CMU Cam 2+ and not the ATmega 128 processor) performs this function. This is done by sending 4-byte commands and receiving a standard packet of data via UART identifying where the ball is located in the camera's field of vision.

7.3 Football Color (CMU Cam 2+ Extension)

Five football colors were considered and tested: red, green, blue, purple, and yellow. A comparison can be seen between the five colors in Figure 9 (Red), Figure 10 (Green), Figure 11 (Blue), Figure 12 (Purple), and Figure 13 (Yellow).

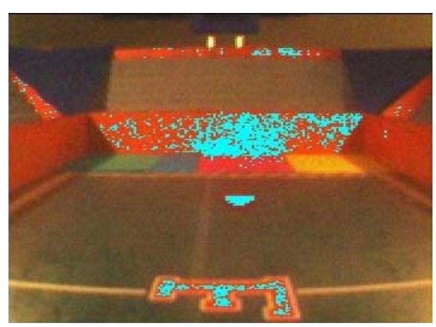

Figure 9. Red blends too easily with orange wall. (R 255 G 0 B 0)

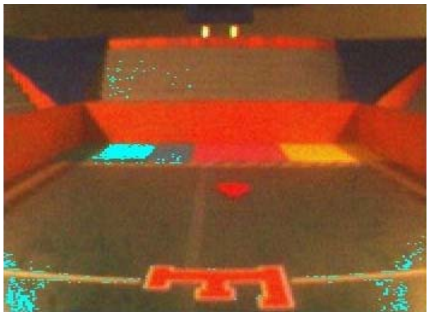

Figure 10. Green blends too well with green field. (R 0 G 255 B 0)

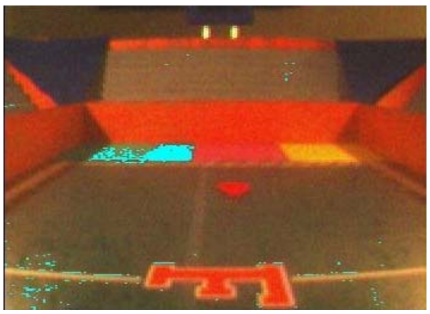

Figure 11. Light blue has slight confusion with field however remains relatively consistent. (R 173 G 216 B 230)

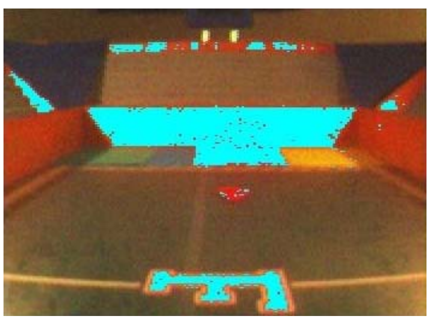

Figure 12. Purple blends intolerably with orange wall. (R 128 G 0 B 128)

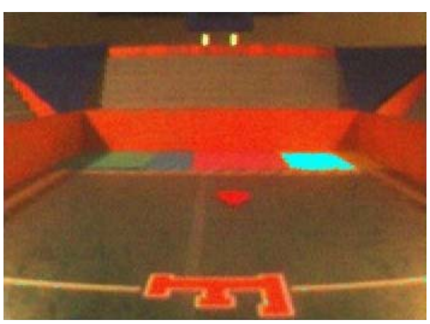

Figure 13. Yellow is extremely identifiable and does not get confused with any other colors in the image. (R 255 G 255 B 0)

8. FUNCTIONAL BEHAVIOR

The robot works by starting at the goal line in the center of the field and booting up with an initialization sequence that requires about 8 seconds (including the time for the camera to adjust to lighting conditions). The robot then proceeds to search for the yellow colored football directly in front of it, looking at three different angles of tilt with the camera (away, middle, and close). If nothing is found TeBOT will turn 45° to the right and perform the same three angle searches; if nothing is found again realign and then turn 45° to the left. If the football found, TeBOT will approach the football at a right angle by aligning to a wall to his right or left and then proceeding a calculated distance, depending on the angle of the robot with respect to the football position. He will then turn 90 degrees to face the football. This is what is meant by approaching at a right angle.

A simplified flow chart of the search algorithm is shown in Figure 14. For readability, the algorithm has been simplified for this figure. The 45° turns (executed 3 times) are actually 15 degree turns (executed 7 times). Additionally, the track color boxes are more complex in the actual software, since they have three angles for tilting when searching in a particular direction.

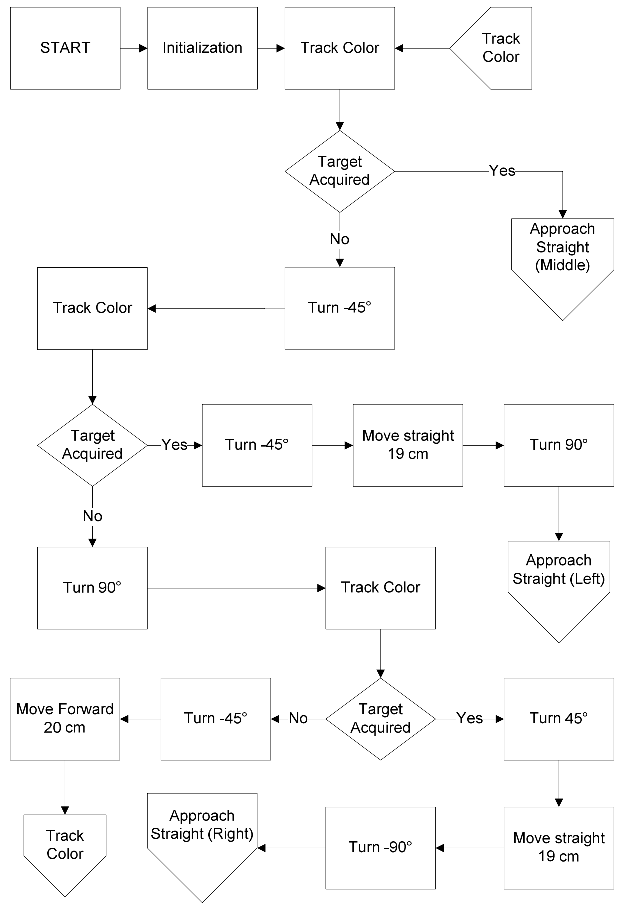

Figure 14. Simplified software flow of the search algorithm.

When Tim TeBOT is close enough to the football, he will stop at a fixed distance from the ball. After stopping, the robot will align itself with the football. The robot will then drive over the football, pass it, undock its hitting motor and start to spin it at a certain speed based on the distance of the robot from the end zone. Once spinning, the robot will drive backwards over the football to hit it towards the end zone. The robot will then return back to its starting position using its distance sensors and alignment algorithms.

9. RESULTS AND CONCLUSION

The robot functioned very closely to its desired behavior. He consistently and reliably located a football directly in front of him and hit it a reasonable distance toward the goal line. Similarly, for footballs at the side of the robot, the algorithm to identify balls to the left and the right worked properly and did not experience any false detections due to the lighting or other colors in the arena.

Upgrades that would make Tim TeBOT more successful in playing (and winning) the game include improvements in the distance measurements (for hitting strength), a more reliable turning algorithm, better lighting when the ball is close to the robot (when the robot's shadow blocks the stadium lighting), an edge detection algorithm to determine how to better align with the football, and a more reliable alignment algorithm.

Distance measurements taken with the SRF04 are only reliable with a resolution of 2-3 cm when approximately 100 cm (the length of the field). This caused slight variations in the hitting strength. Distance sensors with better resolution would allow for improvements in the alignment algorithm. The slight variations in the returned values lead to errors that were unavoidable with the present sensor resolution. This caused the robot to be several degrees off from its desired perpendicular line.

When the robot approaches the ball and the camera is directly on top of the ball, the camera can no longer track the object since the camera casts a shadow on the object reducing the lighting conditions. To alleviate this issue, lights could be placed on the camera board to allow for better light when close to the football.

As stated previously, an edge detection algorithm used by the CMU Cam 2+ would be ideal to determine the orientation of the football. Knowing the football orientation would allow the robot to achieve more reliable hits. However an edge detection algorithm for a color tracking does not exist in the CMU Cam 2+ hardware that was used. The CMU Cam 3 is an open source version of the CMU Cam 2+ and could be used to accomplish this task. The CMU Cam 3 is significantly more expensive than the 2+. Another very popular open source camera that could be used for this application is the AVRcam.

10. ACKNOWLEDGMENT

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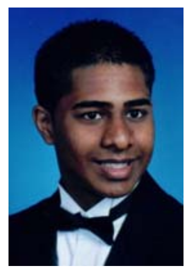

John Kurien earned his Master's of Science degree in Electrical Engineering in May 2009 from the University of Florida (UF). He previously earned a Bachelor of Science degree from UF. John has accepted a position with Raytheon Company's Integrated Defense System business division as a participant in the Rotational Engineering Leadership Development Program (RELDP) in Sudbury, Massachusetts. He will begin his employment at Raytheon in July 2009.

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