Autonomous Mobile Robot Operation: Playing Paper Football

John Kurien
University of Florida, Gainesville, FL

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.*

Index Terms — Paper Football, Robotics, Vision Sensing, Color Tracking

I. 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.

II. 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 (by hand with a human) across the playing field in a single fluid motion. 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 slide 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 on 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 it to the 20 yard line. Additionally the robot understands its turn to play by waiting 20 seconds after its turn to hit and then proceeding to attempt to hit the football again. 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 the opposing player's goal line.
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.

III. Integrated System

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

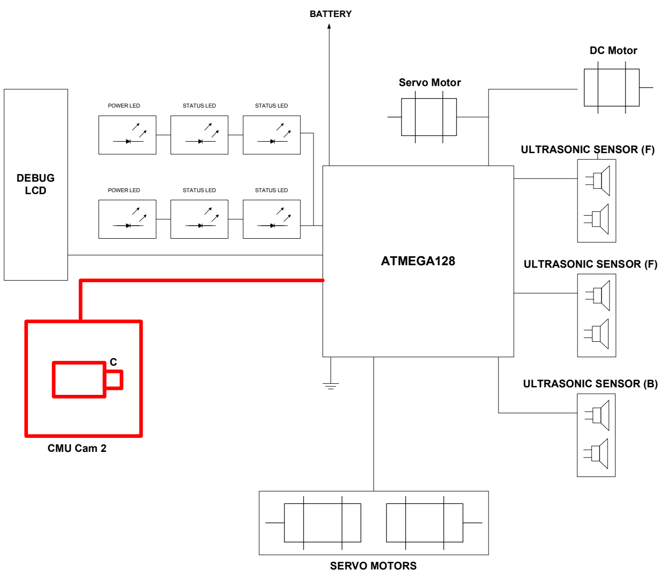

Fig. 1. Integrated system design for the autonomous mobile robot Tim TeBOT.

The components in the robotic system and their purposes are listed below:

- Atmega 128 – 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 as to what state the robot is in during execution. Each color corresponds to a different indicator.
- Debug LCD –Used to display data values from the processor 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 to either grip the football when above it or not touch it at all.
- DC Motor - Used to spin the hitting wheel to a desired speed to hit the football a variable distance.
- Ultrasonic Sensors (F) –Used to determine the robots distance on the field 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 the system to identify a color (the yellow football) and track it when the robot is in motion. The processor on this sensor is considered a coprocessor to the Atmega since all of the image processing is performed on this device.

IV. Mobile Platform

Design

During development the platform underwent two revisions. 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 structure of the robot is 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 electrical components without the hitting DC motor. Refer to Fig. 2 for a visual image of TeBOT.

There are cut outs for a 16x2 character LCD screen on the top with 6 LED holes cutout of the top. Four holes were created in the front to mount two ultrasonic sensors (SRF04); likewise the rear has a single ultrasonic sensor mounted in the middle. A JTAG port was externally created to connect to the electrical board containing the microprocessor.

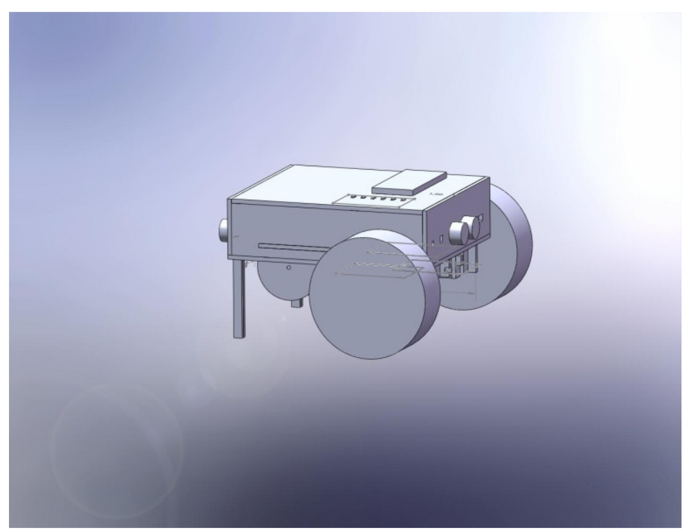

Fig. 2. Mobile Platform CAD design made in Solid Works. CMU Cam 2+ (omitted from design) was mounted atop the robot on the front so it has an over head view of the front of the robot. Additionally between the two rear wheel hacked servos is a third servo that controls the hitting wheel’s location by being in the docked (up) or undocked (down) position.

Below the robot platform is an arm attached to a servo on one side with a DC motor mounted with a third wheel on the other side to allow for the hitting mechanism to dock and undock when a hit is going to be performed.

Movement of the robot is performed by spinning the hacked servos either in the same direction (forward and backward) or in opposite directions (to turn left and right). Spinning both the servos for turns allows the robot to pivot about a point closer to the center of the robot rather than around a single when (when only one wheel spins) which would cause wide turns.

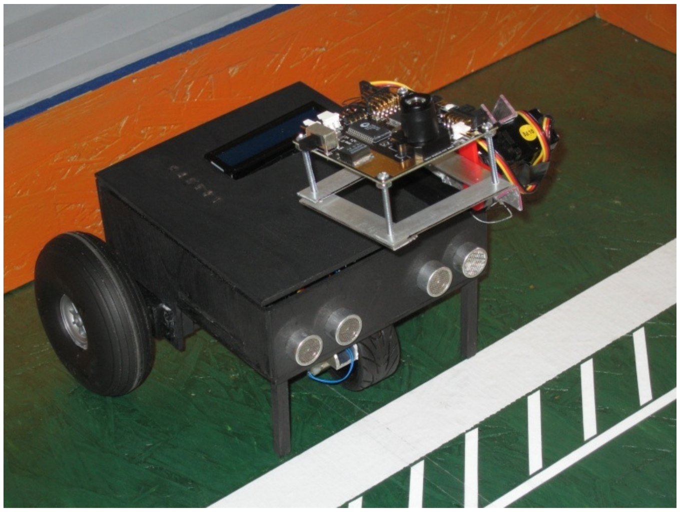

Fig. 3. Mobile Platform in fully constructed state

The CMU Cam 2+ was used for image detection and image processing to track the football. This piece of hardware (omitted from Fig 1) was placed atop the platform connected by a metal rod connected to a hobby servo which allowed the CMU Cam 2+ to perform tilting when tracking an object. This servo was the only servo not controlled by the microprocessor of the system; instead the CMU Cam 2+ coprocessor controlled the servo movement (which would ultimately get movement commands issued from the main Atmega 128 processor). Fig 3 is an image of Tim TeBOT upon final completion which includes the CMU Cam 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 the football and when approaching it, 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 turn will go.) Measurements were taken for how to delay for a 90°, 45°, 0°, -45°, and -90° turn. 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 I
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

V. 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 Fig 4 for a conceptual design of the field and Fig 5 for the actual environment that was constructed.

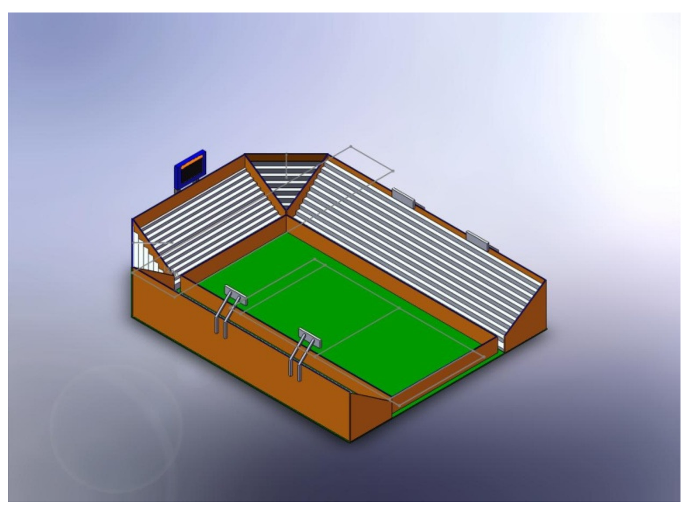

Fig. 4. Conceptual CAD design created in Solid Works.

Fig. 5. 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, switching from table to table will not allow for the same 90° turn required by the robot to approach the paper football.
- 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.
- 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. Additionally it allows the robot to use the walls to align itself perpendicularly to hit the ball in a straight line.
- Goal line - This provides a consistent goal line distance for the robot the hit the paper football to. 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.
- Horseshoe "U" 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 backdrop 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 – Aesthetics to play prerecorded videos during game.

VI. Actuation

The actuation mechanisms of the robot consist of four total servos (two hacked for movement), 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 up the hitting wheel to hit the football.

The operation and functionality of the movement, camera, and dock/undock servos have previously been discussed leaving the operation of the DC motor to be explained. The DC motor works by receiving a PWM signal just as the servos do for operation. The PWM signal allows for varied motor spinning speeds while operating on a constant 5V supply.[2] The switching of the PWM to operate the DC motor is done by using an H bridge 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.

TABLE II
Hitting Strengths and Distances

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

Table II. The servo value units are unit less and are a scalar value used to set the duty cycle value of the 50 Hz PWM signal in software.

Measurements were taken at various PWM speed values. Ten measurements were taken for each speed value (900, 1050, 1200, 1350, and 1500) and a mean average of the distances hit were taken. These values were then extrapolated to an exponential, linear, and 3rd order polynomial approximation. Refer to Tables 2, Fig 6, and Fig 7.

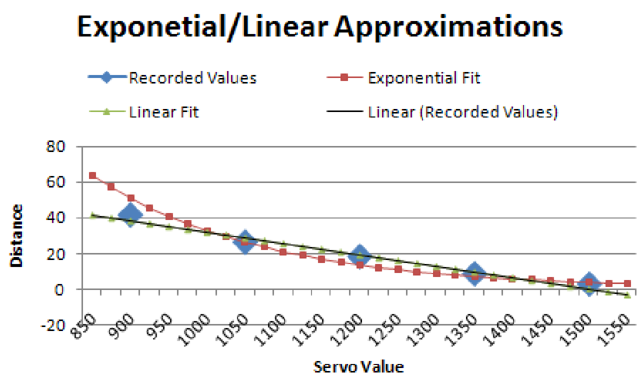

Fig. 6. Servo Values vs. Estimated Distances for an Exponential and Linear Approximation.

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,

$$y = 1.25x^2 - 17.50x + 56.67$$

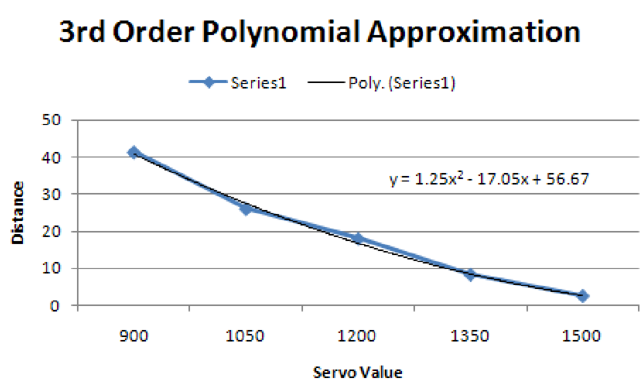

Fig. 7. Best case approximation using a 3rd Order Polynomial function.

The 3rd order polynomial approximation was the lowest order approximation that accurately to 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 go. It is hypothesized that this occurs because of the orientation of the football when being hit, but remains to be validated. If the wheel lines up with the ball to cover more of the football when it glides over it for the hit, then the football will get more grip and go further than if less of the football made contact with the wheel. This issue can be overcome in future version by analyzing the orientation of the football first and aligning with it so that the same amount of football is gripped on each hit.

VII. Sensors

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. Additionally these sensors are 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, likewise if the left sensor is larger than the right, the robot is turned too far to the left. By continuously taking these measurements it is possible for the robot to align itself with any wall on the field so long as the ultrasonic sensors are detecting the same wall (and not a corner). This alignment function helps to correct any errors when turning with the servos. 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 reversing, primarily for when it returns to its starting position and when it backs up slightly to approach the football.

CMU Cam 2+

The CMU Cam 2+ is connected directly to the Atmel Atmega 128 communicating through UART. The power to the camera is supplied directly from the 8.5 V voltage regulator.

Since there is a controlled environment for the robot to play in, the color of the football is hardcoded into the robot. This will allow the robot to identify only the football and not require recalibration every time the robot is used. The camera allows the robot to detect the paper football on the playing field. The robot then 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 maintain looking at it using the tilt servo attached to the camera (which is controlled by the CMU Cam 2+ and not the Atmega 128 processor). 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.

Football Color (Extension of CMU Cam 2+)

Five colors were considered to use since the stadium had been saturated with orange and blue. These colors were red, green, blue, purple, and yellow. A comparison can be seen between the five colors in Fig 8 (Red), Fig 9 (Green), Fig 10 (Blue), Fig 11 (Purple), and Fig 12 (Yellow).

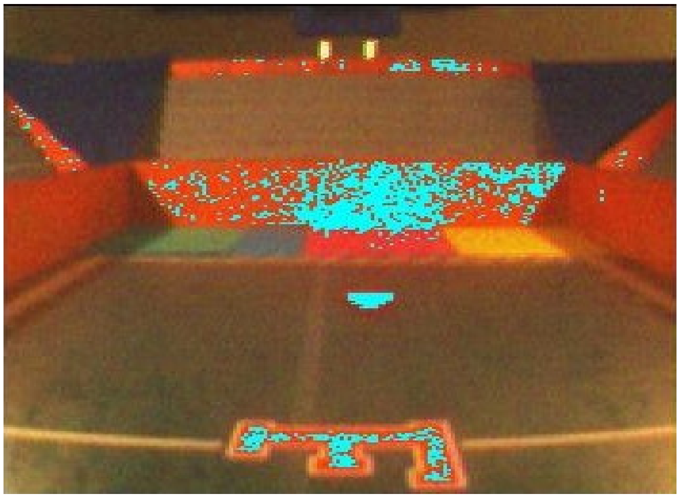

Fig. 8. Red blends too easily with orange wall. (R 255 G 0 B 0)

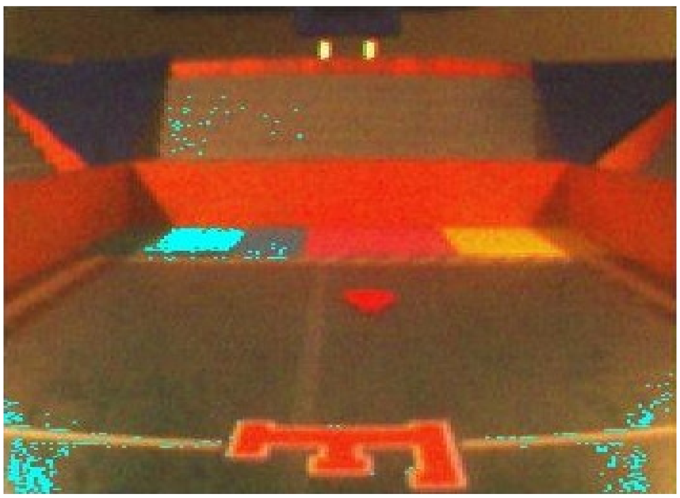

Fig. 9. Green blends too well with green field. (R 0 G 255 B 0)

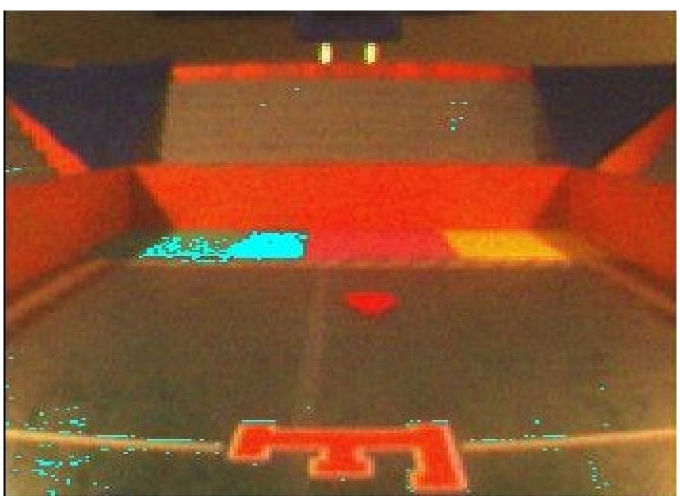

Fig. 10. Light blue has slight confusion with field however remains relatively consistent. (R 173 G 216 B 230)

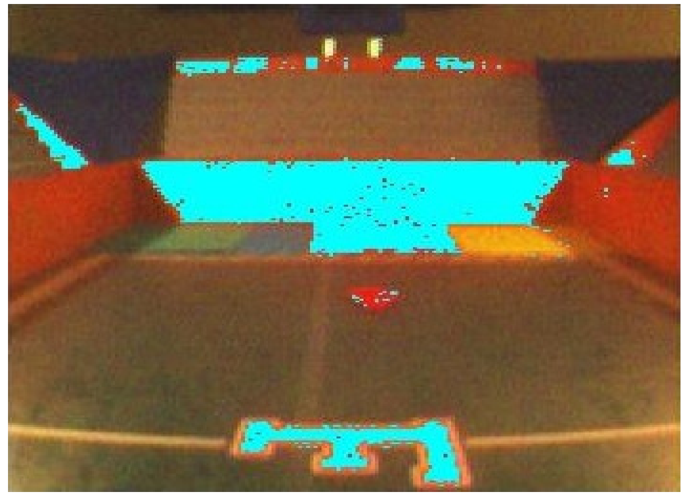

Fig. 11. Purple blends intolerably with orange wall. (R 128 G 0 B 128)

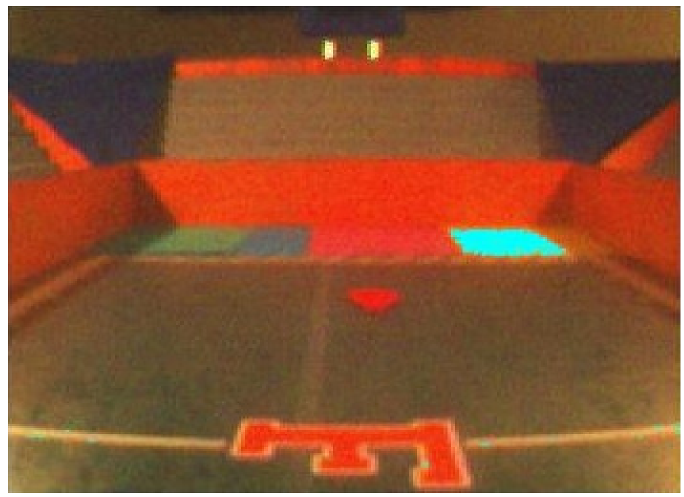

Fig. 12. Yellow is extremely identifiable and does not get confused with any other colors in the image. (R 255 G 255 B 0)

By visually interpreting the images (and through experimentation) it was determined that yellow provides the clearest identification of a color from the five available colors. It is for this reason that yellow was chosen for the football color.

VIII. Functional Behavior

The robot works by starting at the goal line in the center of the field and booting up with an initialization sequence (about 8 seconds including the time for the camera to adjust to lighting conditions). The robot then proceeds to track for the yellow color 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 to the right 60° and perform the same three angle search turning 15° to left if nothing is found on each three angle search. If the football found, depending on the angle that the robot is currently turned, TeBOT will approach the football at a right angle by aligning to a wall to his right or left and then proceeding a certain distance depending on what angle the robot was turn to. He will then turn 90 degrees to face the football. This is what is meant by approaching at a right angle.

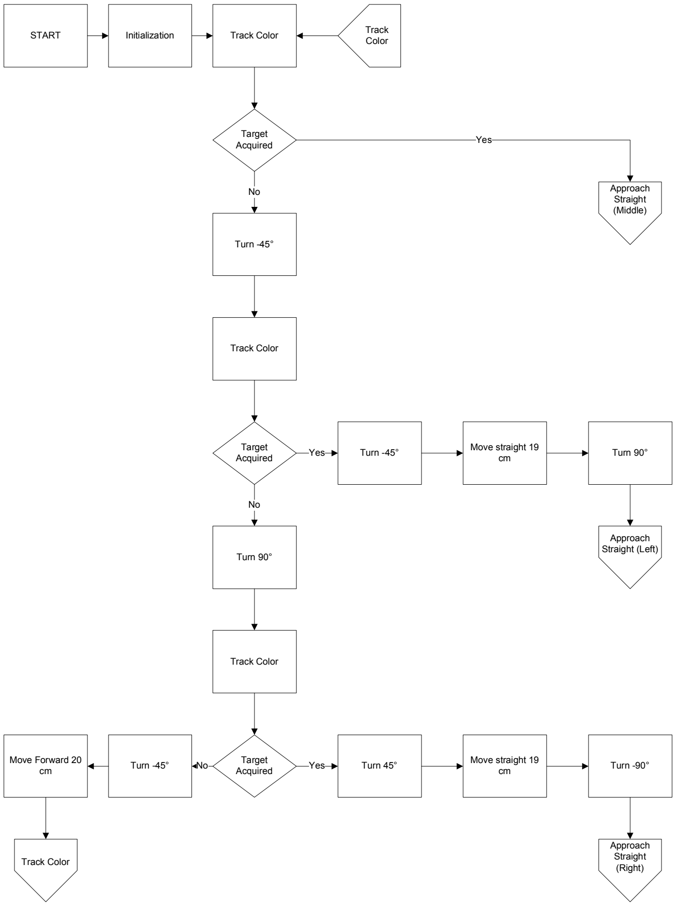

Fig. 13. Simplified software flow of the search algorithm. The algorithm has been simplified for this graph due to readability. The 45° turns are actually 15 degree turns which are executed 7 times instead of 3 as in the graph. Additionally the track color boxes are more complex in that they have three angles for tilting when searching in a particular direction.

Facing the football the robot will back up in reverse slightly to allow spacing between it and the football then proceeding closer towards the direction of the football. Once close enough, the camera will detect the football and stop when the football is a certain distance away. After stopping, the robot will start to align itself with the football to line up the hitting mechanism with the ball. 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.

IX. Experimental Results and Conclusion

The robot functioned very close to its desired behavior when tested. It would consistently and reliably track a football directly in front of it and hit it a reasonable distance. Likewise 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 detection due to the lighting or other colors in the arena.

The issues seen with the robot that could have improvement were the distance measurements (for hitting strength), a more reliable turning algorithm, better lighting when the ball is close to the robot, an edge detection algorithm to determine how to align with the football, and a more reliable alignment algorithm.

Distance measurements taken with the SRF04 can only reliably take measurements with resolutions of 2-3 cm when approximately 100 cm away as was the length of the field. This caused slight variations in the hitting strength. Distance sensors with a better resolution would lead to fixing the alignment algorithm since there are slight variations in the returned values, this leads to an error that the sensors do not have the resolution to account for. This leads to the robot being a few degrees acute 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 prior, an edge detection algorithm used by the CMU Cam 2+ would be ideal to determine the orientation of the football to know how to line up with it to get more reliable hits. However an edge detection algorithm for a color tracking does not exist in the CMU Cam 2+ hardware that was used and would have to be coded in the open source version of the CMU Cam 3. This would lead to much higher development time, and costs.

Acknowledgment

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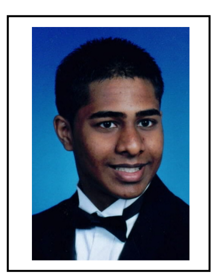

John Kurien is a Master's of Science Electrical Engineer from the University of Florida holding a Bachelor's of Science from the University of Florida. He will complete his degree at the end of May 2009 and will work with Raytheon Company's Integrated Defense System business division; participating in the Rotational Engineering Leadership Development Program (RELDP) in Sudbury, MA beginning July 2009. His current work has been conducted with the Intelligent Machine Design Laboratory at the University of Florida with Dr. Eric Schwartz, Dr. Antonio Arroyo, and Dr. Carl Crane.