The Electronic Ball Boy: A Reactive Visually Guided Mobile Robot For the Tennis Court.

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ABSTRACT

In the modern world mobile robots are being utilized for many tasks that are either hazardous or unpleasant for human beings. The potential of robots to assume such tasks hinges on their ability to intelligently, efficiently, and reliably locate and interact with objects in their environment. This work focuses on the combination of intelligent sensor placement and a unique vision strategy (which itself combines several techniques) with reactive system theory to create the Electronic Ball Boy (EBB). This system is highly successful at performing the task of capture and retrieval of tennis balls, a task that is repetitious yet lacking in well-defined locations and motions for the objects of interest.

1. INTRODUCTION

There are a number of very interesting and difficult problems associated with enabling a mobile robot to both see and interact with its environment. First, a robot must be able to locate all objects near it and to determine what they are. However, even if this is done, the robot is unable to make intelligent use of the information unless it is able to calculate its own position. Because of this, self localization of mobile robots is an active research area, and many different techniques have been applied to this problem. Examples include laser range finders [1,2], ultrasonic sensors [3,4], dead reckoning [5], and GPS [6]. Vision sensors have also been used with success. For example, the National Conference On Artificial Intelligence sponsored a mobile robot competition called Clean Up the Tennis Court [7] where teams attempted to capture both moving and stationary tennis balls using onboard vision systems. Robot soccer competitions have also made use of vision sensors, and by removing the sensors from the robots themselves, have been able not only to locate the robots, but also to simultaneously classify other objects near the robot [8-11].

In this paper we apply modern visual targeting techniques, a unique vision algorithm incorporating color, and reactive system theory to the task of the former (capturing tennis balls) using the setup of the latter (overhead sensor placement). Overhead cameras have also been used with success in many other systems besides robot soccer. For example, they have been used to guide robots in office environments [12]. It is a strategy well suited to visual targeting because the target position is constantly in view. Also, a convenient method of robot self localization is provided because the robot also resides within the camera images.

While there is a good deal of research currently being done in guiding robots with cameras, the idea itself is not a new one. As early as 1973 researchers were beginning to see the utility of using cameras for robot guidance [13]. Between these beginnings and today, visual guidance has grown into a pervasive component of mobile robotics.

While visual targeting can determine the destination position for a mobile robot, it must work hand in hand with some method of object recognition in order to intelligently select this target. Many researchers are currently finding that color information is of great aid when designing such recognition schemes for a wide variety of objects. See for example [14-17]. In our application it is necessary to identify tennis balls on a tennis court. Since a requirement of this environment is that the balls contrast with the background (so that the tennis players can easily see them), and since both have strong color properties, the use of color information is a logical and important component of our system.

Another important component of the EBB is its reactive nature. There is a relatively distinct divide in the mobile robotics world between reactive and planned navigation systems. In planned navigation, some type of environment model must be created within the robot.

This model is used by the robot to calculate a desired path to the target. In contrast, a reactive system requires no internal model. Data retrieved from sensors is directly converted to motor commands [18]. This allows a robotic system to make a series of progressively corrected steps toward its target. The EBB uses this type of reactive navigation with corrections made in real time to reach its goal of capturing tennis balls.

This paper is organized in the following manner: Section 2 discusses the motivation behind sensor type and position and the contribution of these factors to the overall reactive system. Section 3 describes our unique image analysis algorithm which provides the mobile robot with the information it maps to its servo motors. Section 4 discusses the reactive vs. planned paradigms within the world of mobile robotics and explains why we favor the reactive system for applications where it is feasible. Section 5 discusses the physical components we used to implement the EBB and explains how we configured them to test our theory.

2. SENSOR TYPE AND POSITION

The sensor we chose was a color CCD video camera. This choice was made because video, especially color video, provides a great deal of information to a robot. This wealth of information allowed us to construct our system using one sensor only, eliminating the inherent difficulties associated with coordinating multiple sensors.

We placed the camera above the playing surface of the tennis court, with its optical axis perpendicular to the plane of the ground (Figure 1).

This overhead camera placement was a key element of our overall reactive strategy. While many applications require retaining the camera onboard the robot (space exploration, for example), we hold the position that overhead camera placement is superior in situations where it is feasible. Dissociating the camera and robot and placing the camera above the court infuses the camera images with valuable information that would otherwise not exist in them. With overhead camera placement the robot is able to maintain a holistic view of the workspace, rather than viewing only the portion directly in front of it. The robot can thus keep track of its own position and the position of every obstacle and target at all times, regardless of where these objects are in relation to the robot.

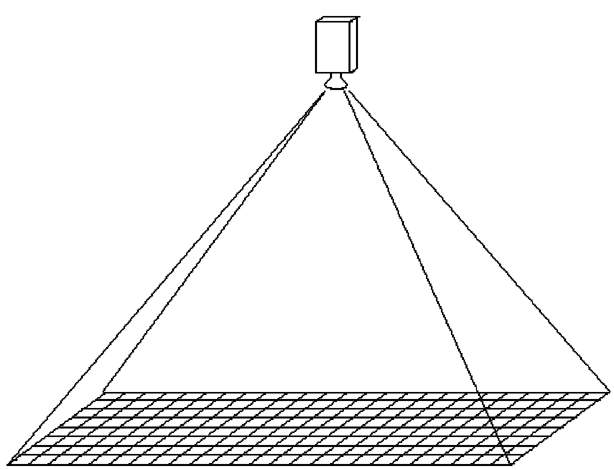

Figure 1: An overhead fixed camera causes pixels to correspond to physical Cartesian coordinates

Two additional advantages of using an overhead camera mounted with its optical axis perpendicular to the court surface are noted in [19]. First, it can eliminate the errors in measurements which must be compensated for in onboard camera systems where the camera reference frame is moving as the robot moves. Second, and most importantly, the overhead camera has the advantage of matching pixels directly to physical coordinates. This is a very important advantage in a reactive system such as ours because it simplifies the calculations necessary to map targets to motor commands.

Overhead camera placement provides images which contain the robot, tennis balls, and obstacles present on the court. The task of the vision algorithm, then, is to determine all relevant information about these objects and to package this information in a form that is useable by the mobile robot.

3. THE COLOR VISION METHOD

Our analysis of the captured video stream has several objectives. It must identify the following parameters in real time from each image captured:

- The location of the mobile robot.
- The orientation of the robot (the direction it faces).
- The location of tennis ball(s).
- The location of any obstacle(s) present.
- The size of an area fully encompassing each obstacle.

It must then combine the final three parameters into a single target position and transmit this along with the first two parameters to the mobile robot.

At the end of processing, each of the transmitted parameters is expressed in terms of physical coordinates on the tennis court. This task is not difficult, given camera position, because pixel coordinates are directly related to their physical counterparts, as noted in Section 2.

To enable the required information to be extracted from the image, it is necessary to place an identifying marking on the robot. We selected the shape shown in Figure 2 (next page).

Figure 2:
This shape, placed on top of the robot, allows robot identification by both its bright blue color and its directionality.

This shape is ideal because it is both directional and uniform in diameter with respect to any cutting plane that passes through its center. This shape, combined with fixed camera position provides us with a predefined size, color, and shape for the robot object. With the objects it is looking for now well specified, the image processing algorithm can begin processing the raw data.

The algorithm is composed of three sections or modules, which process each frame in sequence.

Figure 3:
An example image recorded by the overhead camera containing the robot, two tennis balls, and an obstacle.

The first module addresses processing the vast quantity of information gathered by the CCD camera sensor (see Figure 3) in real time. For this task we used a preprocessing module called the Color Filter. This module contains an RGB filter which removes extraneous information and classifies each pixel as belonging to one of four categories: robot, ball, obstacle, or background. For viewing purposes each of these categories is given a color, as shown in Figure 4.

The second phase in our algorithm is a module that scans the now pixel-wise classified image for groups of similar pixels and encloses each with a green box.

The third phase of our algorithm is a module that calculates all necessary coordinates based on the green box locations and sizes. The direction in which the robot is facing is determined by performing a circular search pattern about the center of the group of pixels of type robot, looking for the cutout. Target position is normally the same as tennis ball location. However, if an obstacle lies between the robot and the ball, an alternate target is chosen with the goal of bypassing the obstacle. (This is currently done simplistically by causing the robot to drive to the right until the obstacle is no longer in its way. Obviously, many more elegant solutions exist, and adding one is a logical extension of this algorithm. However, the topic of this paper is obstacle location, not avoidance.)

Choosing a target position here in image processing allows the same three parameters to be transmitted to the mobile robot regardless of whether the robot is heading directly toward a tennis ball or toward an intermediary position. This is an important aspect of our reactive system, as described in the next section.

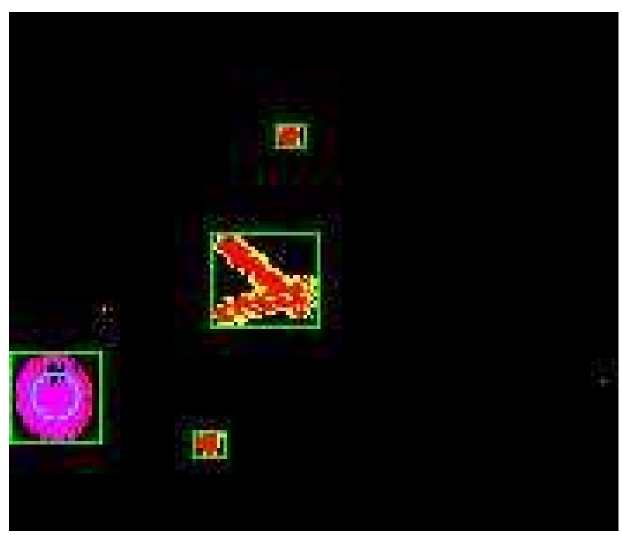

Figure 4:
A processed image. The robot is purple with blue illustrating the circular search. The tennis balls are red, and the obstacle is both yellow and red.* Each object is bounded by a green square.

As soon as all coordinates have been obtained, they are sent, on an image by image basis, to the mobile robot.

* Note: This is not a problem, because the obstacle is a different shape and size from the tennis balls. Only an obstacle very similar to a tennis ball in both size and color has the potential to be incorrectly identified as a tennis ball.

4. REACTIVE COMMAND GENERATION

An advantage of the Color Vision Method described in the previous section is that it is a closed loop technique. The EBB is able to keep track of the target and robot at all times, as well as their relationship to each other and to obstacles in the workspace. However, it is the manner in which the robot acts on the information generated from the vision algorithm which determines that our system is reactive.

The EBB lies firmly on the reactive side of the planned/reactive divide in mobile robotics in that it uses no internal model of the environment. We have found that the task of capturing tennis balls can be most efficiently accomplished without the creation such a model.

The information the mobile robot receives, which it then reacts to, is comprised of the X and Y coordinates specifying the location of the robot, the target position, and a point describing the direction the robot is facing. The mobile robot maneuvers toward the target by turning about its center to face the given target, and then rolling forward. In order to turn toward the target, the robot must calculate the shortest angle of turn (θ), and then roll one of its two wheels forward and one backward until it has achieved the angle. In order to calculate the magnitude of the angle the robot begins by defining vectors from the center of the robot to the direction coordinate (RD) and from the center of the robot to the target position (RT). Equation (1) shows how θ can be calculated using the cross product formula, where Tx and Ty are the respective x and y coordinates of the target and Dx and Dy are the respective x and y coordinates of the direction point.

$$\theta = \sin^{-1}\left(\frac{\begin{vmatrix} Dx & Dy \\ Tx & Ty \end{vmatrix}}{RT * RD} \right) \qquad (1)$$

However, Equation (1) alone does not give a unique solution for θ. This is because the sine function is not unique on [0,2π]. However this ambiguity is easily rectified using a similar application of the dot product, which selects the unique correct member of the two angles generated by the arcsine function.

Using the cross and dot product formulas thus specifies not only how far the robot must turn, but also the direction of turn that is the shortest. θ is then mapped directly to servomotor commands transmitted using pulse width modulated signals and the robot begins rolling forward while processing the next set of updated coordinate values.

5. IMPLEMENTATION

The algorithms we developed were experimentally tested using a mobile robot called a Sumo-robot. This platform was constructed for use in a sumo robot competition and features the Mitsubishi M30624FGLFP 16-bit Microcontroller on a development board. Servomotors provided locomotion, and the 3Com HomeConnect color CCD camera was used as the vision sensor. This camera provided the most features in its class in terms of scaleable resolution and many configurable image parameters, allowing easy manual calibration to suit our application. It was mounted above the tennis court and transmitted an Audio Video Interleave (AVI) file to a personal computer through the Universal Serial Bus. The PC, a 400 MHz Pentium II running Windows 98, utilized the object-oriented dynamic linking functionality of a program called Robot Vision Cad (RvCAD) to implement the Color Vision Method. RvCAD is freely available to anyone wishing to use it for research purposes [20].

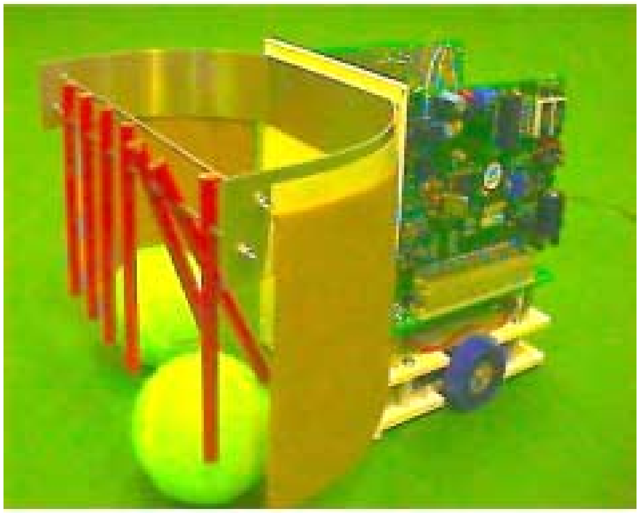

Figure 5: The EBB mobile robot.

RvCAD provides an environment that allows the robot developer to configure a system graphically. Code modules are represented by blocks, which can be wired together to create a pipeline for processing a series of images. Blocks implementing many standard image processing techniques are included (several edge detection algorithms, for instance). Custom blocks can also be created by writing Dynamic Link Library files from which RvCAD extracts necessary code.

The coordinates output by the PC are transmitted via RS232 to the mobile robot, where the Mitsubishi microcontroller reactively maps the coordinates into servo motor commands enabling the robot to navigate to the tennis ball position.

The mobile robot utilized a simple, reliable, and inexpensive device for capturing encountered tennis balls. The device was inspired by a similar sort of device developed at the University of Newcastle [21]. We made some modifications, notably in sizing and type of materials, which made the device simpler to construct and enhanced its strength. In final form our device is essentially a concave surface constructed of molded aluminum mounted on the front of the robot. A metal rod spanning the front of this device holds a row of lightweight teeth that form a one way gate at the entrance to the trap. These teeth are prevented from swinging outward and away from the robotic vehicle by a stop bar suspended just behind and above the bar on which the teeth hang (see Figure 6). The final system was very successful at capturing and carrying tennis balls.

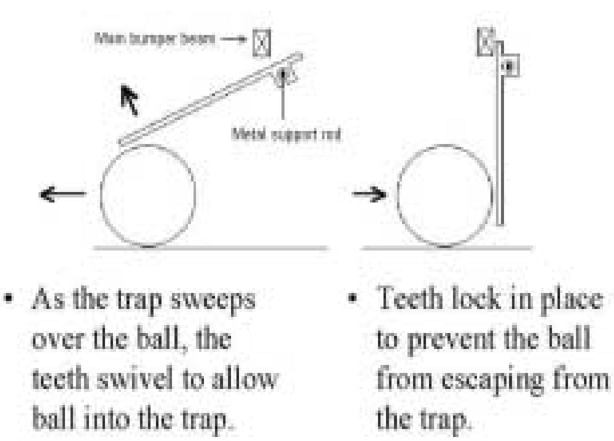

Figure 6: Ball trap mechanism.

6. RESULTS

The Electronic Ball Boy was implemented in the laboratory of the University of Newcastle in Australia. It was an extremely reliable system that was run through well over 50 trials with a wide variety of initial robot and tennis ball positions. Its task success rate (success defined as capturing the tennis ball and returning it to a specified location) was nearly 100%. This was made possible in part by the reactive nature of the robot, which allowed it to turn around and go back for any ball that it failed to capture on the first try (this happened approximately 5% of the time). If the tennis ball was moved (either by outside intervention or contact with the robot at a location other than the front of the ball trap), the robot would continue to adapt its motion to pursue the ball until it was captured. After the ball was captured it resided in the ball trap under the blue circle, and disappeared from the camera's view. At this point the robot could no longer see a tennis ball target, and the new target selected was home base. Video of the robot in motion can be found at [22].

7. CONCLUSION

This paper has described the visual guidance techniques and the reactive algorithms developed for the Electronic Ball Boy, a robot designed to capture and relocate tennis balls. The contributions of the EBB are twofold. First, a vision algorithm utilizing a unique combination of color and shape information for efficient mobile robot targeting. Second, the design of the EBB system presents an example of the successful application of many recently developed ideas and algorithms to a new and challenging task.

Importantly, the EBB setup is easily extendable to other applications through software modifications, and many of the strategies we use can be adapted by other researchers into their mobile robot laboratories.

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