An Autonomous Robot—The Ideal Design Project?

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Abstract

This paper describes a senior design project at Trinity University from the 1997-98 academic year. Senior design at Trinity is the culmination of four years of design courses and of integration of design into undergraduate laboratories and into engineering science courses. The autonomous robot designed by four seniors (advised by two faculty) is a four wheel vehicle, powered and steered by two DC motors, controlled by an MIT "Handy Board," with optical encoders and IR sensors as inputs. Starting from a fixed position, the robot finds its way to a given destination coordinate while avoiding randomly placed obstacles along the path. The project is an excellent teaching and learning experience due to the multiple disciplines involved: logic, electronics, control, programming and mechanics. In addition, the project provides the students with a relatively realistic professional experience involving financial and time budgeting, management, meeting of deadlines, making presentations and writing reports.

Introduction

Probably due to the interdisciplinary nature of the program, design has been an integral part of the undergraduate curriculum in Trinity's Engineering Science program since its inception in the 1960s. From those early beginnings, courses in engineering design have been in the engineering science core—courses with group-oriented projects beginning with the first semester and culminating in the senior year with a full year project that builds upon the entire curriculum.

The nature of the design element in the engineering science curriculum has evolved considerably in the thirty years since its inception. In the early 1990s, the Department reviewed the design components of the curriculum and redirected the emphasis on design to the entire engineering core [1] [2]. Rather than treating design as a separate component of engineering, the approach adopted by the Department tries to incorporate and integrate engineering science and design wherever possible in all courses and laboratories.

Along with philosophical changes, the availability of new tools to support design (e.g. personal computers, microprocessors and simulation tools such as Spice, MATLAB® and LabView®) have changed the curriculum and the students' ability to engage in and complete more difficult and realistic projects. The 1980s saw the first integration of computers into senior design projects and the advent of projects based on robotics and microprocessors. Besides the obvious benefits of these tools in enhancing the capabilities of students to successfully attack "real-world" problems, these technological advances also promote interdisciplinary projects.

Background

The design curriculum (in terms of specific courses) begins in the first year, which contains two three-hour courses that include topics in graphical analysis and communication, an introduction to the processes of engineering design, analysis techniques and two competitive design projects (i.e. groups in each semester pursue designs that meet a common set of specifications). First year projects are typically truss or bridge designs (in the first semester) and a "water balloon launcher" in the second. The second year contains two one-hour courses that address design of experiments, engineering economics, optimization and a competitive mechanics-oriented project in the second semester. The third year follow in the same (as the second year) format, addressing management of design activities, reliability, two competitive projects (electrical in the first semester and thermo/fluids [3] in the second) and initial preparation for the senior project.

The fourth year consists of two three-hour courses, each dedicated to a single, small group-oriented, year-long project. Group sizes range from three to six members—groups usually are formed by following student preferences for the initial project description developed in the third year. Each group is assigned a faculty advisor and the two courses have a faculty member who oversees the entire course and who is responsible for overall coordination, presentation of specific topics and grading. As part of their execution of a design, students are expected to demonstrate the establishment of design specifications and criteria, analysis and synthesis techniques, aesthetics, safety, construction, testing and evaluation. The courses also provide some exposure to mathematical modeling, the use of chemical, mechanical and electrical analogs, optimization, ethics, robust design, life cycle analysis, reliability and other current topics in engineering design.

The background that students have prior to embarking on a fourth-year project involving robotics includes physics, chemistry, six semesters of mathematics, statics and dynamics, electric networks and electronics, and controls. Most electives are taken in the third and fourth years, with many electives taught once every other year. Elective courses that are pertinent to this project are modern control systems, a second electronics course, digital logic and microprocessors.

The description of the project and the robot that follows is largely derived from the student group's final report [4]—it reflects their progress through the design process and the final decisions they made in implementing their robot.

Project description and constraints

The objective of this project is to design and build a microprocessor controlled land vehicle which will autonomously find its way from an initial starting position to a final destination coordinate while avoiding a set of randomly placed obstacles in its path. Up to five static obstacles could be placed at least three feet apart from each other along the robot's path on a 30'x30' playing field. The obstacles are opaque and they are of cubic shape. The vehicle must complete the course in less than fifteen minutes and reach its destination within three-foot radius. The robot must fit in a two-foot cubic box and must weight less than twenty pounds. The total cost for the project cannot exceed $500. To accomplish the project objectives within the above constraints, the students had to research the available types of micro-controllers, motors, obstacle avoidance sensors, navigation techniques, and the materials to use for the robot's platform.

Microcontroller

The microcontroller is the most important component of this project. It monitors the inputs, performs computations, makes decisions, and drives the outputs in the manner desired by the designer. After evaluating some of the most popular microcontrollers such as the Motorola 68HC11, the Intel 8051, Microchip PICs, and the Parallax Basic Stamps, the design team decided to use Handy Board from the Media Laboratory at MIT [5]. The Handy Board uses the Motorola 68HC11 microcontroller with 2 MHZ system clock. It has the means of driving up to four separate DC motors. It contains power header inputs for 9 digital sensors and 7 analog sensors, 32k of battery-backed CMOS static RAM, 16x2 character LCD screen, internal 9.6 Volt Nicad battery with recharging circuitry, an IR input and output, and many other features. The Handy Board has an RS-232 port for easy interfacing with an IBM-PC or compatible computer. It also includes a bundled Interactive C programming language. In short, the Handy Board is ideal for robotic applications since it includes the microcontroller and all the necessary hardware to interface it with the target system.

Platform, motors, and wheels:

To build the platform of the autonomous vehicle, the design team decided to use model airplane wood because of its light weight, low cost, and wide availability. Model airplane wood is lighter and easier to machine than plastic, metal, or normal plywood. The base of the platform is circular with an 8-inch radius and ¼ inch thickness. The circular platform was chosen in order to improve maneuverability around obstacles. Two permanent magnet DC motors are used to power the vehicle. Each motor has independent speed and direction controls, allowing the vehicle to move forward, backward, or turn in any direction. The Handy Board independently drives each DC motor. The front and the back caster wheels enable the robot to perform sharp turns around its central axis. A diagram of the robot platform with the relative positions of the wheels and motors is shown in Figure 1.

Navigation Method

Various techniques for guiding the autonomous vehicle from its initial position to its destination have been analyzed based on their associated cost, accuracy, speed, and ease of implementation. After a careful evaluation, the design team opted for the Dead Reckoning navigation technique because of its low implementation cost, speed, and simplicity. Dead Reckoning is defined as finding the vehicle's position based on the starting coordinate and the distance traveled. When the distance traveled relative to the starting position is known, the remaining distance to the destination can be computed. The main disadvantage of the Dead Reckoning navigation method is its low accuracy due to wheel slipage and slightly unequal wheel diameters. The cumulative error can be reduced by deriving empirical "corrective equations" through experimentation and implementing them in software [6]. Dead Reckoning navigation method will perform reasonably well for the distances to be traveled by the autonomous vehicle in this project. Dead Reckoning navigation is certainly not recommended for long distances beyond 100 feet without some additional error correction technique.

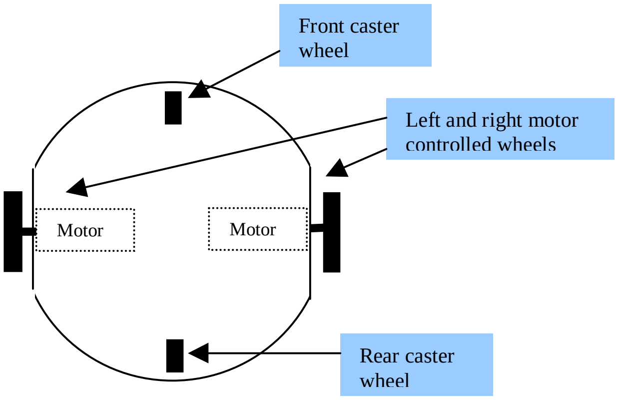

Fig.1. Top view of the platform.

Measuring the distance traveled

The distance traveled by the robot is determined by counting the number of wheel revolutions. This can be achieved by using either reflectance or a breakbeam sensors which are commonly implemented as optical encoders. The group chose the second sensor as described below:

The breakbeam method works by detecting interruptions in transmitted light instead of reflected light. The light source is placed on one side of a wheel and a photosensor is positioned on the other side to detect the passage of the incident light as it shines through the equally spaced transparent segments of the rotating wheel. Each time the light beam shines through the wheel, the photosensor detects it. The number of wheel revolutions is computed from the number of times the light beam passes through the transparent sections of the wheel, i.e. via shaft encoding. An illustration of the shaft encoder with the breakbeam sensor is shown in Figure 2a.

Two shaft encoders, one for each of the two powered wheels, are used in this project. The selected shaft encoder is model E3 from US Digital. Each encoder consists of two main parts, the code wheel and the encoder module. The code wheel is a transparent plastic disk with 500 black marks around its edge and mounted to the motor shaft. This causes it to rotate at the same rate as the vehicle's wheel. The encoder module is attached to the robot's platform, positioned in such a way that the outer edge of the code wheel passes through the encoder module. A top view of the encoder assembly is shown in Figure 2b.

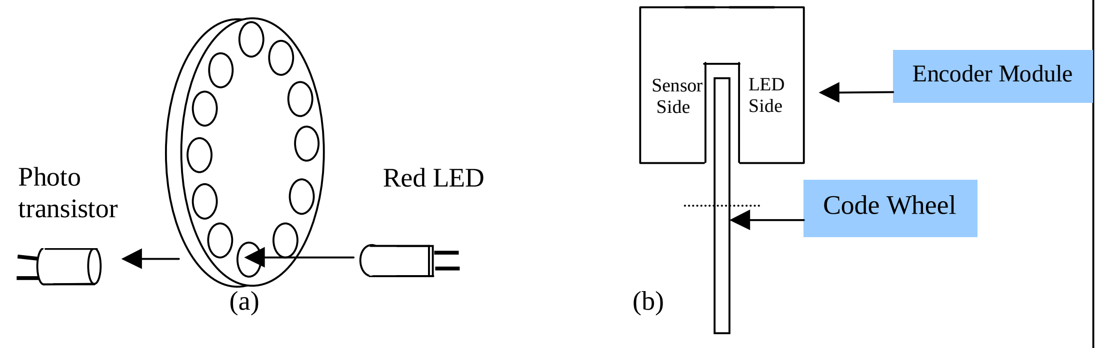

Fig. 2. a) Shaft encoding with breakbeam sensor. b) Top view of the shaft encoder assembly

When a mark on the code wheel passes through the encoder module, the output of the module changes from high to low logic state. In fact, the output of the encoder module generates a square wave as the motor shaft rotates. This output is connected to one of the Handy Board's analog input ports. It allows the microcontroller to count the number of black marks on the code wheel and consequently compute the distance traveled by the autonomous vehicle.

Obstacle detection

To detect obstacles along the vehicle's path, four infrared sensors were used; one sensor was placed in front of each of the two powered wheels and the other two were positioned on the front section of the vehicle. No IR sensors were placed on the back section of the vehicle since it never operates in reverse. The IR sensor (from Optek) used has two components: an IR emitter and a phototransistor. The phototransistor is capable of receiving IR signals up to six feet away. In this project, obstacles are to be detected at about one foot distance. Therefore, a potentiometer was placed in series with the phototransistor in order to adjust its sensitivity range. After testing, the potentiometer was replaced with a 610 kΩ resistor. The phototransistors were very sensitive to ambient lighting; therefore, it was necessary to put shielding around the sensors to avoid false readings.

Finally, an op amp was placed as a buffer between the IR sensor circuit to prevent interaction between the 610 kΩ resistor and the 47 kΩ pull-up of the Handy Board input. The IR sensor interface circuit is shown in Figure 3.

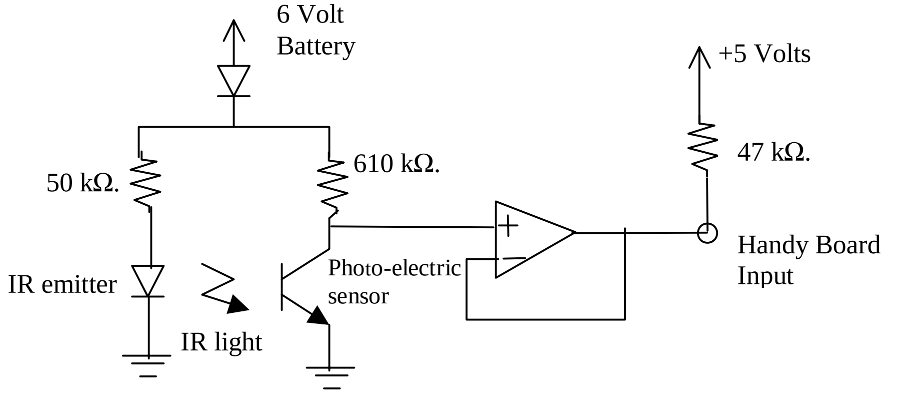

Fig.3. IR sensor interface to the Handy Board

Obstacle Avoidance

If an obstacle is detected, the vehicle executes a sequence of spin and move operations. If the obstacle is detected on the front-right direction, the vehicle will turn left 90 degrees, move forward three feet, turn right 90 degrees, and move forward three feet. A similar maneuver is executed when an obstacle is detected on the front-left direction of the vehicle.

Turning the vehicle

A differential steering method is used to turn the vehicle to the desired direction. It consists of spinning the two motors in opposite directions. The following formula is used to calculate the value of the turn angle:

$$\Theta_{abs} = \frac{\Pi}{2} - \arctan\frac{Y - Y_{dest}}{X - X_{dest}}$$

In the equation, θ_{abs} is the new heading angle with respect to the y-axis, X_{dest} and Y_{dest} are the destination coordinates, and X and Y are the current coordinates. The sign of θ_{abs} must be adjusted depending on the direction the vehicle is facing. If θ is the current heading angle, $(\theta - \theta_{abs})$ gives the angle value the vehicle is to rotate to head in the new direction. The program converts this angle into a number of encoder counts. The motors are then turned in opposite directions until the encoder counts match the calculated value.

Software Implementation

Most of the programming was done in Interactive C, a multitasking version of C programming language written for robotic applications using the Motorola 68HC11 microcontroller. A small portion of the code was written using assembly language routines for reading the shaft encoder values. This code uses Pulse Width Modulation routines written by Julian Skidmore [7]. These routines provide for more accurate feedback control than those provided with the Handy Board.

Initially, the robot receives coordinates of the starting position, the destination coordinates, and the heading angle. The origin and the axes of the coordinate system can be set up at an arbitrary position for flexibility. These initial parameters are defined in the program code and must be downloaded to the vehicle whenever they need to be changed. A simplified version of the software that controls the movements of the autonomous vehicle is outlined in the flowcharts given in Figures 4 and 5. More detail regarding the software can be found in the group report [4].

Results

The completed vehicle weighted 9 pounds and measured 19 inches wheel to wheel, 17 inches front to back, and 7 inches in hight. The weight and the size of the the robot are well below the maximum requirements. The autonomous vehicle was able to navigate from a fixed starting position to within an acceptable range of less than 3 feet from its destination, while detecting and avoiding multiple obstacles on its path. The robot completed its course way below the maximum requirement of 15 minutes. The results of three robot runs with varying number of obstacles are summarized in Table 1.

Table 1. Three robot runs with varying number of obstacles

Number of Obstacles	Distance to destination	Error
None	6 ft.	7 in.
1	12 ft.	2 in.
5	20 ft.	16 in.

It is worth mentioning that the project team has exceeded its initial $500 budget by $20. The cost would have been within budget if only 4 IR sensors were purchased instead of 14. The bulk of the money went to the purchase of the Handy Board ($284) and shaft encoders ($150). A summary of the project expenses is given in Table 2.

Table 2. Project expenses

Items	Price
Handy Board	284.00
2 Motors	20.00
Wheels	9.00
Caster Wheels	16.00
Platform	11.00
2 Shaft Encoders	150.00
14 IR Sensors	25.00
Operational Amplifiers	5.00

The autonomous vehicle described in this project has potential for expansion and improvement in future senior design projects. For example, it could serve as a platform for testing alternative robot navigation algorithms such as combined Dead Reconing and sonar ranging. Most likely, future senior design projects will spawn from this work to design and build more sophisticated autonomous robots at Trinity.

Conclusions

For an interdisciplinary program such as Trinity's, robotic projects are almost ideal. The mix of mechanical, electrical, electronic, control and software topics required by such projects fits the background of most seniors quite well. The nature of the project also permits some compartmentalization that helps students develop and employ management skills and to begin to appreciate the sometimes tenuous connections between theory and practice. Finally, the students gain facility in technical communications via multiple public presentations, reports, and in some cases, project web pages. [8]

Problems for students in such projects include learning the available technology, making optimal decisions based on limited and imperfect information, keeping within a limited budget and scheduling activities so that unforeseen problems can be addressed. Additionally, the offering of most electives every other year, rather than annually or in each semester, makes a complete background a somewhat fortuitous happening.

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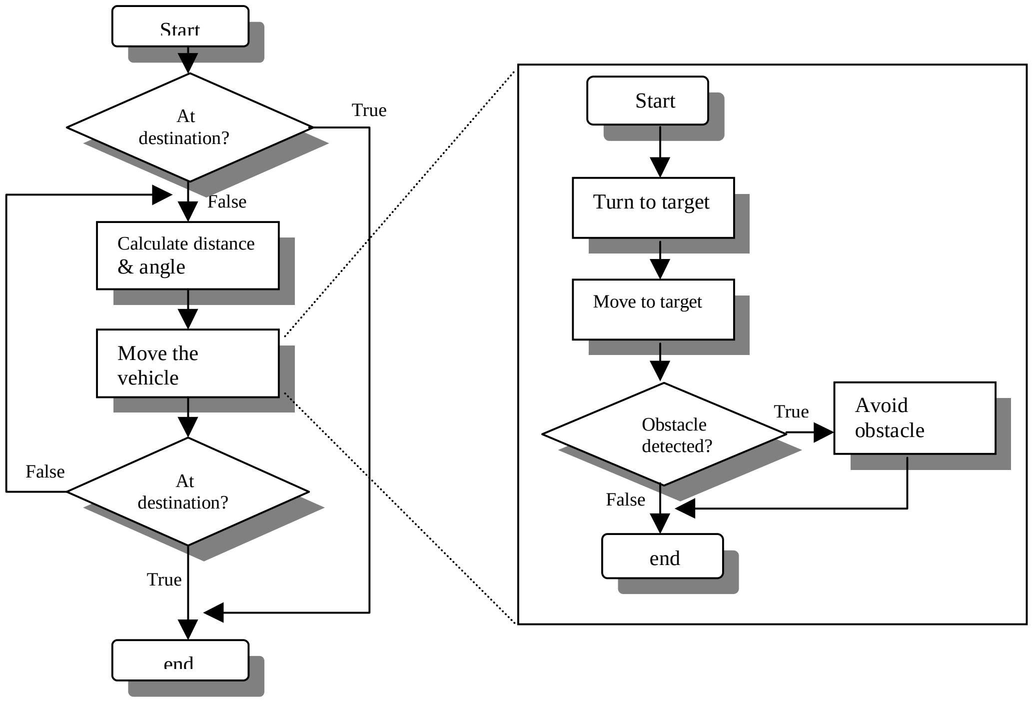

Fig. 4. Simplified flowchart of the robot movement control software

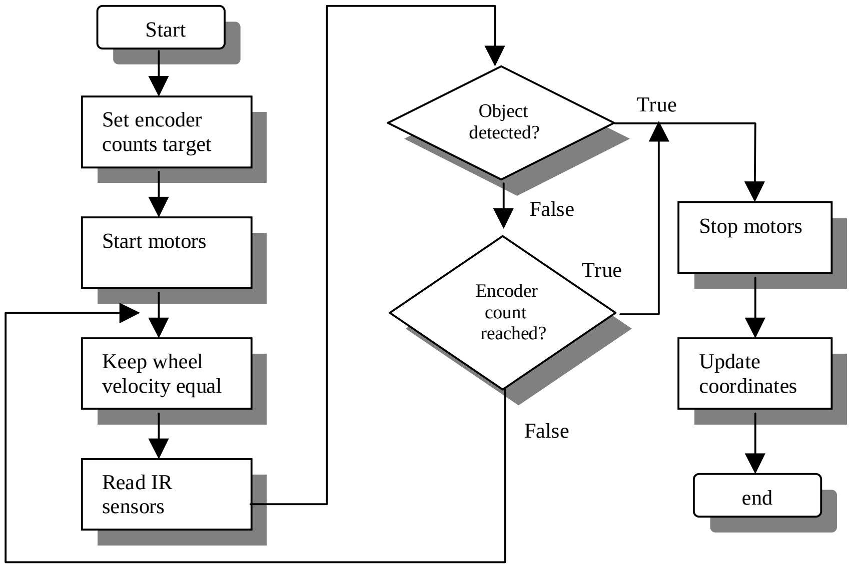

Fig. 5. Simplified flowchart of the “Move to Target” module

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