AC 2008-237: TEACHING OPTIMAL ENERGY EXPENDITURE USING ROBOTIC PLATFORMS AND MICROCONTROLLERS

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Teaching Optimal Energy Expenditure Using Robotic Platforms and Microcontrollers

Abstract

In this paper we describe an example of a project-centered approach to teaching optimal (i.e. minimal) electric energy expenditure while navigating through a set of coordinate waypoionts in a mobile vehicle. The platform used is an in-house ruggedized robot design based on a commercially available robotic chassis design, commercially available parts and a simple sensor suite incorporating a multi-channel Global Positioning System (GPS) receiver module for navigation, a voltage sensor and a current sensor for measuring electric power. The choice of rugged chassis design enables flexibility in the use of the GPS receiver for navigation over multiple types of terrain outdoors. The vehicle is used as a platform to integrate sensor data processing and a microcontroller-based control system. This approach to teaching concepts using robotic platforms is not revolutionary, but the use of robotics in introducing navigation concepts as well as methodologies of optimization was found to encourage the students to consider real world design challenges condensed in just a few weeks out of one semester. A description of the evolution of the topics is provided along with the content of the project tasks. In addition, a description of the hardware and software implementation completed to provide a usable robot chassis for the students is provided.

Introduction

The use of robotic platforms as a teaching mechanism for mechatronics, artificial intelligence, motion planning and multiple degree of freedom actuators is fairly common in academia. A robotic platform provides students with ample opportunity to explore the non-ideal conditions of imperfect sensor accuracy, sensor noise, differences in actuator performance and other challenging design issues in an embedded system. Robotics, in general, is well suited for exploring integrated system designs combining aspects of multiple engineering specialty areas. For these and other reasons, robot motion and sensing was chosen as a core topic in the senior level undergraduate embedded systems course assigned as an elective as part of the electronic and computer engineering technology degree programs within the department. The embedded systems course was designed as a way to introduce topics of microcontroller interfacing with external peripherals, digital and analog component interfacing with low voltage microcontrollers, serial communication protocols, real-time operation and multi-threading, subsumption concepts and motor control. The course includes a lecture and weekly laboratory content. Microcontroller boards capable of supporting multiple peripheral functions and having general purpose I/O capability are available to the students during the laboratory sessions. The laboratory sessions are utilized to focus on completion of course group projects. The projects are intended to combine concepts from the class lectures into practical examples which have some plausible utility in an industry application. Examples include an automated logic circuit tester, a two player game, a multi-threading data processor, a portable audio data storage design interfaced via the Serial Peripheral Interface (SPI) protocol, etc. Projects make up 30% of the grade for the course. The evaluation for each project consists of a demonstration of all tasks for the group's project hardware and software and a written report.

In an effort to integrate concepts from other areas of electronic engineering technology including power electronics, power systems and serial digital data communication, a project was designed to provide students with an opportunity to not only interface devices enabling navigation data-based planning, but to provide an opportunity to experience the real unknowns associated with mobile robotic control. For the robotic project, the students choose a navigation scheme, are given latitude and longitude coordinates in an open area on campus and are tasked to program a microcontroller to interface with a GPS receiver and robot drive system. The goal of the project is to navigate the robot through the coordinates autonomously. In preparation for this project, the course material covers simple navigation concepts, an energy expenditure model for the robot drive system and a conceptual introduction to optimization. This paper discusses the concepts, hardware and software associated with incorporating an autonomous robotic platform project involving the polling and processing of serial navigation data, the use of that data to command a mobile robot through an outdoor ground course having multiple way points and the introduction of optimization and its usage in reducing energy expenditure. The paper is organized as follows. The second section describes a model for energy expenditure in a robot drive train and an overview of the optimization concepts discussed in the embedded systems course which relate to the robot navigation project. The third section describes the GPS navigation concepts introduced and the structure and format of the data received by the robotic platform. The fourth section details the robot project goals and the robotic platform including the integration of the main components required to enable completion of the project tasks. The fifth section discusses the incorporation of the project into the laboratory setting and the final section provides concluding remarks.

Energy and Optimization Concepts

The robotic platform discussed in this paper is an in-house design having strong design cues, purchased wheels and electric geared motors from existing products available through SuperDroid Robots Inc. (www.superdroidrobots.com). The platforms are 4-wheeled robots having one geared DC electric motor per wheel. Additional information pertaining to the procurement and construction of the robot platforms will be provided in later sections of the paper.

To introduce instantaneous power and energy expenditure and aspects of optimization in the context of a mobile robotic platform, the students require a familiarization with mobile robot dynamics modeling as well as energy storage system modeling. Starting from the underlying physics of an electromechanical system, the mobile robot drive motors can be modeled with the following time domain dynamics,

$$v_a(t) = R_a i_a(t) + L_a \frac{di_a}{dt}(t) + v_c(t), \quad (1)$$

$$c_m(t) = B\omega(t) + J\frac{d\omega}{dt}(t) + c_r(t), \quad (2)$$

where v_a is the applied voltage, R_a and L_a are the armature resistance and inductance, i_a and v_a the applied armature current and counter emf voltage, c_m and c_r the motor torque and load torque and B and J the viscous friction and inertia. Two additional relations also hold,

$$v_c(t) = K_1\omega(t), \quad (3)$$

$$c_m(t) = K_2 i_a(t), \quad (4)$$

where K_1 and K_2 are constant coefficients indicating linear relationships between voltage and motor shaft rotational speed and between current and motor torque. If the applied current and voltage are assumed constant over a finite interval, say Δt, and equations (1) and (2) are discretized over k steps where $t = k \cdot \Delta t$ we have

$$v_a(k) = R_a i_a(k) + K_1\omega(k), \quad (5)$$

$$i_a(k) = \frac{B}{K_2}\omega(t) + \frac{c_r(k)}{K_2}. \quad (6)$$

Combining these two equations yields $v_a(k) = R_a \cdot \left\{\frac{B}{K_2}\omega(t) + \frac{c_r(k)}{K_2}\right\} + K_1\omega(k) = \alpha_1 \cdot \omega(k) + \alpha_2(k)$ for coefficients α_1 and α_2. We will also assume that the load torque is constant on level ground. Under these conditions, the motor shaft rotational speed can be written as an affine function of the applied voltage. In other words, the motor speed can be controlled by varying the applied motor armature voltage. One additional relationship is required. The discretized speed of the robot, $\nu(k)$, is directly proportional to the motor shaft speed using the following equation,

$$\nu(k) = r_w \cdot \frac{1}{r_g} \cdot \omega(k), \tag{7}$$

where r_w is the wheel radius and r_g is the motor gear ratio. Note that a differential drive robot will have speed components, $\nu_l(k)$ and $\nu_r(k)$, for the left and right side. With this model we see that the applied armature voltage can be varied to modulate robot vehicle speed. The mobile robots have on board battery packs for electrical energy storage. Energy expenditure at time t, $E(t)$, is based on the voltage and current applied to the load, in this case the robot drive motors. Here,

$$E(t) = \int_0^t \frac{1}{\eta_b} \cdot i_a(\tau) \cdot v_a(\tau) \; d\tau, \tag{8}$$

where η_b is the lumped efficiency of the battery pack discharge and motor efficiency. If the current is assumed constant (constant motor torque conditions) and the voltage is assumed constant over finite Δt intervals we have

$$E(k) = \sum_{l=0}^{k} \frac{1}{\eta_b} \cdot i_a \cdot v_a(l) \cdot \Delta t \tag{9}$$

In an effort to link navigation concepts (discussed in the next section) to the dynamics of the robot, we mathematically describe the robot motion using discrete steps along latitude, or x-axis, and longitude, or y-axis, coordinate lines where

$$x(k) = x(k-1) + \left(\frac{\nu_l(k-1) + \nu_r(k-1)}{2}\right) \cdot \cos(\theta(k-1)), \tag{10}$$

$$y(k) = y(k-1) + \left(\frac{\nu_l(k-1) + \nu_r(k-1)}{2}\right) \cdot \sin(\theta(k-1)), \tag{11}$$

and where θ is the rotation of the robot with respect to the x-axis. At this point, the optimization problem can be formulated. We wish to control the motion of the robot, through the application of drive motor voltage, to autonomously navigate the robot through n coordinates, $C_1(x,y), C_2(x,y), \ldots, C_n(x,y)$. The optimization problem that is introduced is essentially a minimum energy expenditure problem through a course where the course path is not specified. To simplify the problem structure, the robot is required to reach the coordinate points in a specified order. In addition, constant motor current is assumed. The optimization problem can be cast as a constrained "cost" minimization with "cost", J,

$$J = \sum_{k=0}^{N-1} i_a \cdot v_a(k) \cdot \Delta t = \sum_{k=0}^{N-1} J_k \tag{12}$$

with equations (10) and (11) and

$$\left.\begin{matrix} (x(l_1), y(l_1)) = C_1(x,y) \\ (x(l_2), y(l_2)) = C_2(x,y) \\ \vdots \\ (x(l_n), y(l_n)) = C_n(x,y) \end{matrix}\right\} \quad 0 < l_1 < l_2 < \cdots < l_n, \quad l_i \in \{1, 2, \ldots, N\} \tag{13}$$

as constraints where we seek optimal voltages $\{v_a^*(k) : \; k = 0, 1, \ldots, N-1\}$ which minimize J. The principle of optimality [5] holds that this optimization problem can be solved by looking at the "tail subproblem". In other words, the optimal voltage minimizing J_{N-1} is equal to $v_a^*(N-1)$, the same voltage at time $(N-1) \cdot \Delta t$ which minimizes J. Therefore, we can consider minimizing the energy expenditure between any two coordinate points separately. Since the energy expenditure is directly proportional to the robot velocity which, with fixed Δt, is proportional to distance, the optimization reduces to a distance minimizing problem and clearly the optimal path between two coordinate points is a straight line. Note: Here we can introduce Pontryagin's Minimum Principle to prove the shortest distance result if desired. See [5] or other similar texts for details.

This is an intuitive result as well as one arrived at through theory which hopefully resonates well with engineering technology students. One additional component of this derivation is the modeling of the energy storage device, the battery pack. The pack used in the robotic vehicles is composed of Ni-MH (Nickel Metal-Hydride) secondary battery cells. The discharge characteristics are of particular concern. These characteristics include limitations on discharge current, operating temperature limitations and the discharge curves (i.e. the voltage of the battery pack versus percent capacity utilized under different constant current loading conditions). Percent capacity of the battery pack utilized is also known as the percent State Of Discharge (SOD) of the pack. Typically these characteristics can either be derived from constant current discharge testing or directly from manufacturer data. For either case, given discharge function $F(\%SOD)$, if the discharge current is known and the starting percent SOD ($\%SOD_i$) is also known, a single voltage measurement, v_m, can yield the present percent SOD. From this, the energy expenditure can be computed with

$$E = \int_{\%SOD_i}^{F^{-1}(v_m)} i_a \cdot F(\tau)\ d\tau \tag{14}$$

Given these models of the robot dynamics and energy utilization, the students can consider applying them to calculate energy consumption over the robot path. In the next section the concepts associated with latitude and longitude coordinate navigation are introduced. This is necessary for the students, who are traditionally used to a two-axis cartesian coordinate system, to put into context the format of the data received serially through the GPS receiver. In essence, the students must recall the calculation of distance between two points in 2-d space, the component vectors of the direction vector from one point to the next and coordinate system rotations. Using these, the students can develop equations to maneuver a robot toward any given point in 2-d space.

Navigation Concepts

The mobile robot destinations (way points) are predetermined as a set of coordinates specified as latitude and longitude data. This is only a subset of the data available from even the most inexpensive GPS receivers which can be purchased commercially. Along with the actual coordinates, computed velocity, altitude, time and other parameters are available on many GPS devices. The key data for navigation are the coordinates. All other necessary information for navigation can be derived from the coordinates. Latitude coordinates describe coordinate points along lines parallel to the equator which are separated by fixed distances. The units are in degrees and/or minutes north or south of the equator. One degree of latitude is equivalent to 60 nautical miles (or 111 km). One minute is equivalent to one nautical mile. Points along the equator are considered to have zero degrees latitude. Longitude coordinates describe coordinate points along lines connecting the north and south poles. The units are in degrees and/or minutes west or east of the line running through Greenwich, England also called the prime meridian. This coordinate system yields unique positions across the surface of the entire planet Earth. Using information from three or more satellites in the network of orbiting GPS satellites, latitude and longitude coordinates can be derived accurate to within a bounded measure of uncertainty. Additional information such as altitude and improvements in position accuracy can be achieved through data from additional satellites.

Navigating a mobile robot from point to point requires two pieces of data, the present position coordinates and the destination coordinates. From this data, a path can be generated between the two coordinates, the simplest (and optimal in the sense discussed previously) being a straight line. A straight line path is defined by a single direction vector pointing toward the destination coordinate. At this point, many different path following methodologies could be applied. Two straightforward and more common methodologies, namely *follow-the-carrot* and *pure pursuit*, will be described. First, periodically repeating the process of finding a direction vector to the next coordinate based on present coordinate information, turning toward the destination and moving along the direction vector yields the *follow-the-carrot* methodology. Although this method suffers from some disadvantages including the need to periodically completely decelerate and then accelerate the mobile robot motors for turning, it is simple and easily implemented. Second, periodically repeating the process of finding a direction vector to the next coordinate based on present coordinate information, computing the appropriate path curvature leading to the destination and modifying the mobile robot drive motor commands to follow the path curvature yields the *pure pursuit* methodology. This methodology requires additional computation including conversions between the global coordinate system and the mobile robot local coordinate system, however the robot does not require periodic decelerations to zero speed. See [1] for additional description of these methodologies. Implementation of these or other methodologies is possible given the periodic acquisition of coordinate data and processing of that data to determine the appropriate control stimuli for the mobile robot motors. The processing engine used is a Microchip 8-bit microcontroller having a serial communication peripheral capability as well as general purpose input/output pins capable of interfacing with other hardware. Specific hardware used as part of the student project will be discussed in the next section.

Mobile Platform for Navigation

The robotic platform was designed as a rugged chassis capable of traversing rough and uneven terrain. The chassis was constructed of thin aluminum with a raised platform to mount the GPS receiver. The GPS receiver is a Garmin GPS 18-LVC having serial EIA-232 compliant interfacing and 5V DC power requirements. The drive system of the robot consists of four motor driven wheels having independent control capable geared DC motors. Each motor is integrated with a custom encoder wheel providing low resolution wheel speed information. The motors are driven using three high capacity 7.2V NiMH battery packs in series and high current motor driver circuits. Battery pack voltage and current flow is measured on-board and is used to compute energy expenditure. The programmable microcontroller is housed inside the chassis along with the other support electronics as the robots will be operated outdoors. See Figure 1 for a picture of the platform.

Lab-based Experience

The goals of the project were to utilize the robotic platform, drive system and GPS receiver to navigate the robot autonomously through a given set of way points pre-determined by the instructor but not revealed to the student teams until the day of the demonstration. To give the students some idea of how they can expect the robot to operate with a properly implemented strategy programmed into the microcontroller, a couple of simulations of a robot following a path through a rectangular course were developed. Manufacturer data for the robot geared motors is available and to simplify the computation of energy utilized for the simulations, an equivalent model for energy usage was used which does not require a computation of voltage nor current. In discrete time the simulated energy expenditure, $E_s(k)$, is computed assuming constant motor torque and $\Delta t = 1$ as

$$E_s(k) = E_s(k-1) + c_m \cdot \frac{\nu_l(k-1) + \nu_r(k-1)}{2 \cdot r_w}, \tag{15}$$

where c_m and r_w were previously defined as the motor torque and wheel radius respectively. This equation follows from the relationship between instantaneous motor torque, instantaneous motor power and instantaneous motor rotational shaft speed,

$$c_m(t) = P_m(t) \cdot \omega(t),$$

where P_m is the motor power and ω the rotational speed in rad/sec. Figures 2 and 3 show the results of running two simulations. One implementing a *follow-the-carrot* strategy and

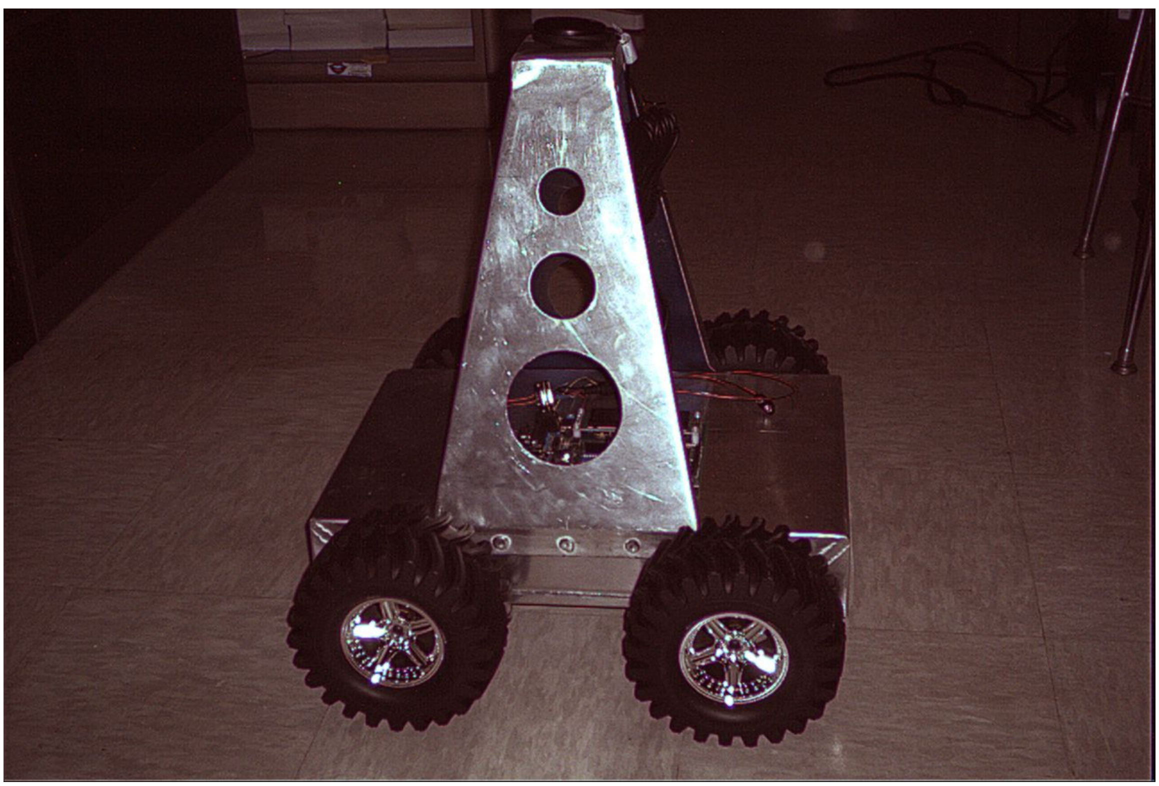

Figure 1: One of two developed robotic platforms.

the other implementing a *pure pursuit* strategy. Additional random error added to the reported navigation coordinates of the robot and independent random velocity error offsets added to ν_l and ν_r were included to account for GPS error and to account for wheel slip or uneven path surfaces. All simulations were conducted with $\Delta t = 1$. Average energy expenditure for both strategies over the same course were calculated as part of these simulations and as expected, the *follow-the-carrot* strategy was found to require less energy expenditure. This can be attributed to shorter path lengths between coordinate points.

The students work in teams of two and are required to integrate a microcontroller board and any additional necessary components (via external breadboard) with the robotic platform. Only two robotic platforms were constructed requiring the student teams to develop a simplified wiring harness interface which can be easily connected and disconnected to facilitate demonstrations in a timely manner. The student teams are given three weeks to develop their implementation and are provided with access to a robotic

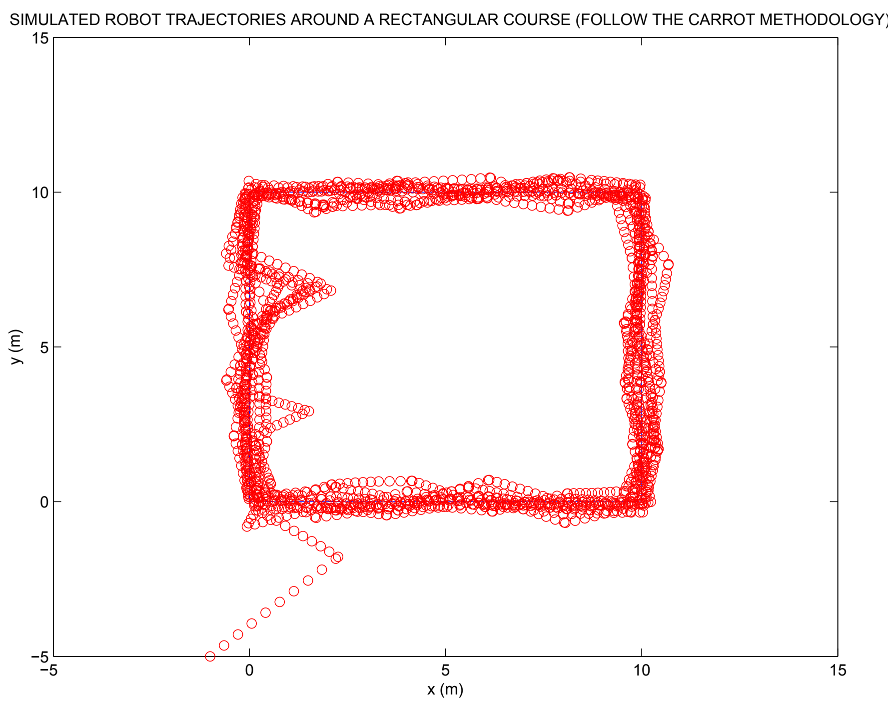

Figure 2: Overlapping plot of ten successive trips around the rectangular course using a follow-the-carrot pursuit strategy. The initial position of the robot is (x(0),y(0)) = (-1,-5), $c_m = 0.51$ (Nm) and $r_w = 0.025$ (m). The average energy expenditure per loop is 858.35 Joules.

platform during the three week period. Student teams are encouraged to work outside the scheduled weekly two-hour laboratory sessions. Time management enters as a key aspect of the project efforts. During the demonstration, each team is provided with the way points for the robot to follow and given ten minutes to incorporate the way points into the embedded program of the microcontroller. Then the on-board battery pack voltage is measured and the demonstration is initiated. At the completion of the demonstration, the on-board energy usage computation based on voltage and current measurement is displayed to a Liquid Crystal Display (LCD) screen. Students are encouraged to use equation (9) for this computation. The total time to complete the course, traversing to within the radius of position error for the GPS receiver for all way points, is measured via stopwatch and the battery pack voltage is measured at the conclusion of the demonstration. The post demonstration battery voltage measurement provides a measure of energy usage during the demonstration and is used as an estimate to validate the on-board energy usage computations. Depending on the collection of waypoints, it may be more optimal (require

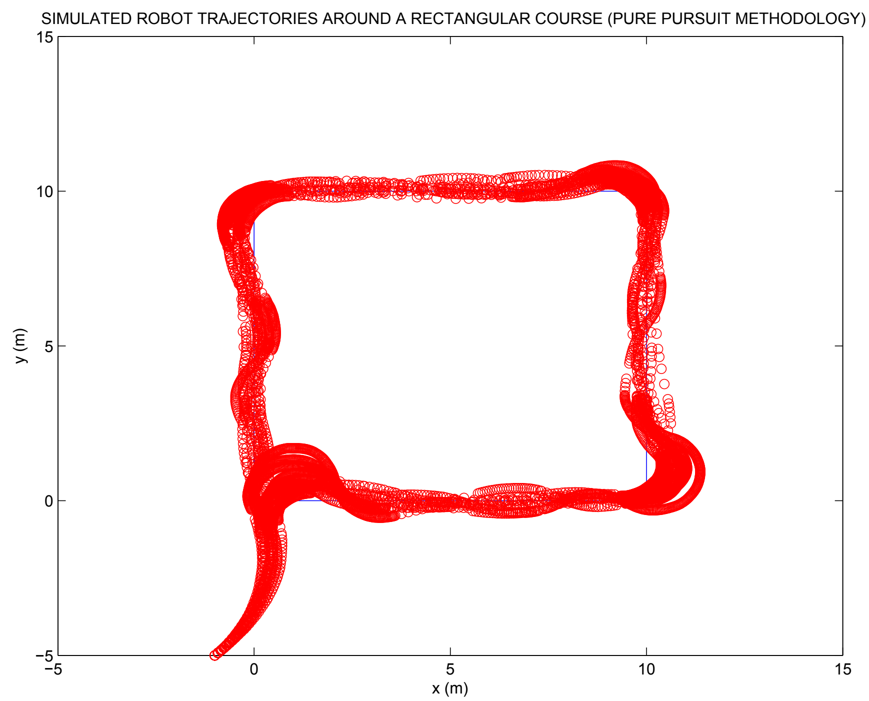

Figure 3: Overlapping plot of ten successive trips around the rectangular course using a pure pursuit strategy. Note the nonlinear path between way points. The initial position of the robot is (x(0),y(0)) = (-1,-5), c_m = 0.51 (Nm) and r_w = 0.025 (m). The average energy expenditure per loop is 973.48 Joules.

less time) to consider the solution to the well known ”traveling salesman” problem to determine the shortest path trajectory, however this was not considered to be within the scope of the course topics and the student teams were required to follow the way points in the order given. Teams which minimized accelerations/decelerations and considered look-ahead trajectory planning for minimal path turns were rewarded with shorter demonstration times and/or lower levels of energy expenditure.

Conclusions

Incorporation of this robotic project into the embedded systems course has been very positive. Not only do the students gain a greater appreciation for the complexities associated with the implementation of a practical mobile robot system operating with limited sensing capability in a partially unknown environment, the students were able to integrate aspects of wireless data communication and its limitations, motor drive systems and calculations related to physics driven optimization. In addition, given the variety of additional projects that could incorporate the robotic platform hardware and software, this is expected to provide a flexible and reconfigurable system for future courses.

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