

A New Curriculum on Planning and Cooperative Control of Autonomous Mobile Robots*

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This paper presents the robotics curriculum that was developed and is currently offered in the Department of Electrical and Computer Engineering (ECE) at the University of Central Florida (UCF). The curriculum retains many features of typical robotics curricula, such as being multidisciplinary, hands-on, and integrated. It also has several unique features, including a contemporary focus and a means of updating its contents and teaching a variety of topics. It represents one way of developing a curriculum on autonomous and intelligent robotic systems. As measured by the reactions from students and local industry, its implementation has been successful.

Keywords: curriculum development; course offerings; laboratory components; autonomous vehicles; intelligent systems

INTRODUCTION

ROBOTS ARE electrical-mechanical devices designed to perform certain tasks. As computing power has increased and technology (such as new sensors and materials) advanced, robots have become more functional and versatile, and can even be autonomous and intelligent. In fact, autonomous and intelligent robotics are increasingly desirable and are even in demand for many military and civilian applications. Because of this potential, the interest in education, research, and development of robotics is now stronger than ever.

There are a wide spectrum of robotics curricula, and they all have the common features of being multidisciplinary [1], of requiring hands-on experience through laboratory experimentation [2], and emphasizing system integration (of hardware and software) by means of projects of adequate depth and breadth [3]. Recent developments have also included a virtual robotics laboratory [4] and an online software-and-hardware system [5] for robotics education. All these features reinforce student learning in the classroom and enhance their skills and knowledge in the broad field of robotics. To advance robotics education, the contents and emphases of our curricula must be continually updated to address contemporary issues in the field.

This paper presents the robotics curriculum developed at the University of Central Florida (UCF). While traditional topics in robotics are also covered, the focus of this robotics program is on real-time trajectory planning, tracking control, and cooperative control of a group of

heterogeneous robotic vehicles operating in a dynamically changing and uncertain environment. Through undertaking multidisciplinary offerings, laboratory experiments and course projects, students can build a solid understanding of robotics, learn the state-of-the-art in the field, and begin their pursuit of providing innovative solutions to current problems and/or applications. Pedagogically, the spirally progressive learning paradigm is used not only as the teaching methodology for the curriculum but also as the means of updating the curriculum by incorporating new research results.

This paper is organized as follows. The next section outlines the core curriculum of a three-course robotics sequence, followed by multi-departmental offerings that support the core courses. The following section illustrates the key features and teaching methodology using three robotics topics covered in the core course. This is followed by an outline of the evolution of the robotics program and its evaluation. The next section discusses laboratory facilities and sample projects, followed by a section on the software platforms used in the laboratory and developed for instruction. Implementation and dissemination issues are then summarized and conclusions are drawn in the final section.

AN OVERVIEW OF THE ROBOTICS CURRICULUM AT UCF

The robotics curriculum at UCF consists of a three-core course sequence: an undergraduate senior elective, and two graduate courses. Their descriptions are as follows:

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- EEL4932 Introduction to Intelligent and Autonomous Robotics Systems
Kinematics, dynamics, vehicle dynamics, state space stability concepts, control design methods, trajectory planning, regulation and tracking, formation, cooperative rules and behaviors.
- EEL6662 Design of Robot Control Systems
Kinematics, inverse kinematics, dynamics, stability of nonlinear differential equations, trajectory planning, classical controls, and advanced controls.
- EEL6667 Planning and Control for Mobile Robotic Systems
Nonholonomic systems, kinematics and dynamics, trajectory planning and obstacle avoidance, canonical forms, control design, stability, performance, optimality and robustness.

As the first introductory course, EEL4932, is designed to develop basic understanding of such fundamental topics as kinematics, dynamics, trajectory planning, stability of tracking and regulation, control design, formation and cooperative algorithms toward the design of autonomous robotic systems, it begins with derivations of kinematic and dynamic equations for typical robotic vehicles, such as a unicycle and wheeled robots. Properties of these nonlinear models of robotic vehicles are illustrated using Matlab simulations. Then, by employing one of the standard linearization techniques (either pointwise linearization or feedback linearization), linearized models of robotic vehicles along a desired trajectory are obtained so that the standard framework of linear state space model can be used to study stability, tracking, formation and cooperative control. While the linearized model does not capture the nonholonomic nature of a vehicle's kinematics (which results in the loss of linear controllability for regulation and feedback linearization), such simplification makes it possible for students to move quickly into topics of current interest. In short, the goal of this course is to arouse students' interests in the field of robotics and autonomous systems and to provide a solid background for their applications and for more advanced topics, such as the ones covered in EEL6662 and EEL6667.

At graduate level, EEL6662 is a typical course for students who want to learn about traditional materials in robotics. It begins with homogeneous transformation and the Denavit-Hartenberg convention and deals with all the standard topics regarding manipulation of fixed-base robots. Emphasis is placed on forward and inverse kinematics, derivation of robot dynamics, Cartesian and joint space trajectory planning, position and tracking controls, and force control.

As a follow-up to EEL6662, EEL6667 is designed to develop fundamental understanding of systems and control issues for unmanned ground vehicles and unmanned aerial vehicles and to expose students to current and on-going research issues in the area. In particular, differen-

tial geometry methods and nonlinear system tools are used to analyze controllability of nonholonomic systems and to develop a chained form as the canonical form. Open-loop steering controls such as sinusoidal and polynomial steering controls are studied and then used to develop real-time trajectory planning algorithms for robotic vehicles operating in a dynamic and uncertain environment in which multiple moving obstacles emerge into and disappear from a robot's sensing range. Various feedback control designs are covered, including discontinuous control for stabilization and smooth time-varying controls for both tracking and regulation. Higher than the controls developed for an individual vehicle in the control hierarchy, formation and cooperative controls are devised for a team of vehicles. The stability, performance/optimality, and robustness of all these controls are investigated in detail.

The materials covered in this course provide a natural progression for students to first learn a selection of robotics topics without the need for advanced mathematical tools, then to proceed with traditional robotics materials and finally to study state-of-the-art advances in order to build an autonomous system of multiple vehicles. The spiral teaching method is used to organize the course contents both in terms of sequence and within the same course (this is discussed below).

The robotics curriculum at UCF is supported by comprehensive curricula in the following fields, with relevant courses listed:

- Systems & Controls
EEL4612 Introduction to Modern and Robust Control, EEL5173 Linear System Theory, EEL5630 Digital Control Systems, EEL6621 Nonlinear Control Systems, EEL6616 Adaptive Control, EEL6619 Nonlinear Robust Control, EEL6617 Fundamentals of Modern Multivariable Control, EEL6671 Modern and Optimal Control Systems, and EEL6674 Optimal Estimation for Control.
- Dynamics, Mechanical Control, & Mechatronics
EAS 5407 Mechatronic Systems, EAS 5535 Engineering Design for Aerospace Vehicles, EAS 6405 Advanced Flight Dynamics, EAS 6415 Guidance, Navigation and Control, EML 5290 Introduction to MEMS and Micromachining, EML 6295 Sensors and Actuators for Micro Mechanical Systems, EML 6296 MEMS Mechanism and Design, and EML 6808 Analysis and Control of Robot Manipulators.
- Signal/Image Processing & Computer Vision
EEL 5513 Digital Signal Processing Applications, EEL 5820 Image Processing, EEL 5825 Pattern Recognition, EEL 6502 Adaptive Digital Signal Processing, EEL 6505 Multidimensional Digital Processing, EEL 6823 Image Processing II, CAP 5415 Computer Vision, CAP 6411 Computer Vision Systems, and CAP 6412 Advanced Computer Vision.

- Intelligent Systems & Machine Learning
EEL 5874 Expert Systems and Knowledge Engineering, EEL 6769 Parallel Knowledge Processing Systems, EEL 6812 Introduction to Neural Networks, EEL 6843 Machine Perception, EEL 6845 Intelligent Control, EEL 6875 Engineering of Artificial Intelligence Systems, CAP 5512 Evolutionary Computation, CAP 5610 Machine Learning, CAP 5636 Advanced Artificial Intelligence, CAP 6637 Affective Computing with Artificial Intelligence, and CAP 6671 Intelligent Systems.
- Networked Systems
EEL 5780 Wireless Networks, CDA 5532 Network-Centric Computing, and COP 5537 Network Optimization.

These courses, together with the three robotics courses, are all of three semester credit hours. They are offered by courses in Electrical Engineering (EE), Computer Engineering (CpE), Mechanical and Aerospace Engineering, and Computer Science (CS).

For a typical M.Sc. degree program in robotics, the student is advised to take the three-course robotics sequence, two fundamental systems/control courses (Linear System Theory and Digital Control Systems), a minimum of one course from each of two additional fields mentioned above, plus six thesis hours for a total of 30 credit hours. Coursework beyond the M.Sc. degree depends upon the student's research focus and dissertation topic. A Ph.D. program currently consists of a minimum of 72 credit hours.

The curriculum is also supported by two laboratories in EE: the Robotics Laboratory, and the Controls and Autonomous Systems Laboratory. The former is a teaching laboratory, where several robotic manipulators are housed. The latter is a research laboratory, where two sets of mobile robotic platforms are available for course projects and research. In addition, simulation packages have been developed using Matlab for use in classroom instruction and course projects in trajectory planning and control.

CURRICULUM FEATURES AND TEACHING METHODOLOGY

The robotics curriculum at UCF has several features, some of which reflect the nature of the robotics field. Firstly, by its nature, the robotics curriculum is *multidisciplinary*, and so are the contents of the courses. Specifically, the three courses cover such issues as multi-body dynamics, controls, signal processing, automation and intelligence; and the course sequence is supported by many relevant courses in the programs of several departments (as discussed above). As such, the course sequence has attracted students from many degree programs in engineering and science, such as Aerospace Engineering, Computer Engin-

ering, Computer Science, Electrical Engineering, Mechanical Engineering and, hopefully in the near future, Biomedical Engineering. The fusion of interests and skills from these programs enriches the robotics curriculum and thus ensures its success. Secondly, *lab experiments, classroom demonstration, computer simulation, and course projects* are all integral parts of the curriculum. These components enable students to better understand the basic concepts, to see how course materials are related to real-world applications, to gain valuable hands-on experience, and to experiment with and apply what they have learned. Examples of these components will be outlined below.

The curriculum also has several other distinct features, in particular those related to how the paradigm of spirally progressive learning is applied. The curriculum has a unique focus on trajectory planning and cooperative control of autonomous mobile robots. This is implemented by exposing students to these key concepts in the first introductory course (EEL4932), followed by reinforcement and in-depth coverage in the subsequent courses. While the second class (EEL6662) ensures that the students learn the classical materials in robotics, the aim of the other two courses is to produce a series of heterogeneous robotic vehicles which feature autonomy and intelligence. Examples are given below to show how some of the key concepts are taught progressively but spirally at different levels and depths in the course.

To keep the focus of the curriculum contemporary, recent research results have been and will continue to be incorporated into the course contents. For example, the results in [6–8] are now a part of standard offerings. Once again, the paradigm of spirally progressive learning is used to introduce these concepts and examples and to determine the adequacy of their entry point and level of coverage. The process is illustrated by the diagram in Fig. 1.

Pedagogically, the spirally progressive learning paradigm has been widely used in most typical engineering degree programs so that students can enhance their understanding and gain perspectives by encountering a specific concept or principle several times but in different contexts. What distinguishes the curriculum at UCF from others is twofold: its focus on autonomous and intelligent vehicles, and updating the curriculum through integrating research outcomes and evaluating students' learning and interests. By exposing students to state-of-the-art research, they become aware of any problems in the area, which nourishes their curiosity and provides openings for their own research interests. There have been several M.Sc. and Ph.D. graduates at UCF whose theses and dissertations originated from the work they did when they took the robotics courses.

Three subjects are used in the following to illustrate both the spirally progressive learning method and integration of research in the curriculum. Recent research results introduced into the

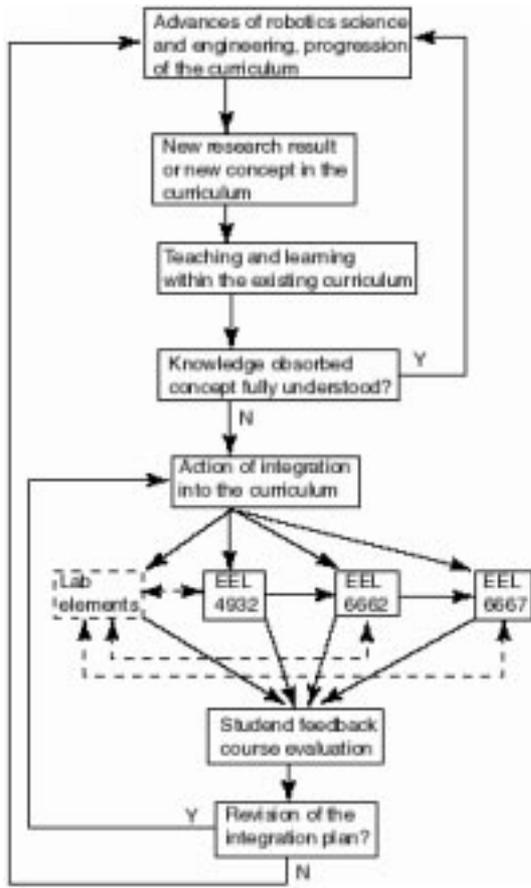


Fig. 1. The process of introducing new concepts into the course sequence.

curriculum include those on trajectory planning, modeling and control, optimal control, formation control, and cooperative control [6, 9, 7, 8, 10, 11, 12, 13, 14]. Implementation of the paradigm keeps the curriculum continually updated while maintaining its natural progression.

Modeling and analysis of robotic systems

As shown in standard robotics texts [15, 16, 17, 18, 19], robot dynamics can be described in general, for the i th robot, by:

$$M_i(q_i)\ddot{q}_i + N_i(q_i, \dot{q}_i) = A_i(q_i)\lambda_i + B_i(q_i)\tau_i, \quad (1)$$

$$A_i^T(q_i)\dot{q}_i = 0, \quad (2)$$

where q_i is the generalized coordinate vector, $M_i(q_i)$ is the inertia matrix, $U_i(q_i)$ is the potential energy, $N_i(q_i, \dot{q}_i) = \dot{M}_i(q_i)\dot{q}_i - 0.5\partial[\dot{q}_i^T M_i(q_i)\dot{q}_i]/\partial q_i + \partial U_i(q_i)/\partial q_i$, $B_i(q_i)$ is the matrix mapping the external input vector τ_i into forces/torques, λ_i is the vector of Lagrange multipliers which represent constraint forces, and matrix $A_i(\cdot)$ and its corresponding equation (2) characterize motion constraints (either holonomic or nonholonomic, if any). For instance, if the robot (or vehicle) is nonholonomic, matrix A_i is a nontrivial tall matrix. In this case, one can find matrix $G_i(q_i)$ such that $G_i^T(q_i)A_i(q_i) = 0$. Pre-multiplying (1) by

$G_i^T(q_i)$ eliminates λ_i and, together with the variable substitution in (4), yields the following model:

$$M_i'(q_i)\dot{v}_i + N_i'(q_i, v_i) = G_i^T(q_i)B_i(q_i)\tau_i, \quad (3)$$

$$\dot{q}_i = G_i(q_i)v_i, \quad (4)$$

where v_i contains the free variables under constraint (2), $M_i'(q_i) = G_i^T(q_i)M_i(q_i)G_i(q_i)$, $N_i'(q_i, v_i) = G_i^T(q_i)M_i(q_i)G_i(q_i)v_i + G_i^T(q_i)N_i(q_i, G_i(q_i)v_i)$. Furthermore, under certain conditions [18], driftless equation of (4) can be transformed into the so-called chained form, for instance, the (2,4) chained form is given by:

$$\dot{z}_{i1} = u_{i1}, \quad \dot{z}_{i2} = u_{i2}, \quad \dot{z}_{i3} = u_{i1}z_{i2}, \quad \dot{z}_{i4} = u_{i1}z_{i3}. \quad (5)$$

In summary, given a general nonholonomic robotic system, equation (5) characterizes kinematically constrained motion while equation (3) describes dynamic motion.

The model derivations outlined above and the corresponding analysis are carried out spirally in the robotics curriculum at UCF. Specifically, the coverage of each course in modeling and analysis is as follows:

- In EEL4932, simple vehicles such as wheeled robots are used to illustrate the nonholonomic constraints given by (2) and their corresponding chained form in (5). Rather than undertaking nonlinear modeling and analysis, the approach of point-mass modeling and the methods of pointwise linearization and feedback linearization along a given desired trajectory are then used to yield a model that consists of a linear state model from input u_i to output y_i and a nonlinear internal model, i.e.:

$$\dot{x}_i = A_i x_i + B_i u_i, \quad y_i = C_i x_i \quad (6)$$

$$\dot{\eta}_i = h_i(\eta_i, x_i). \quad (7)$$
- In EEL6662, kinematics, inverse kinematics, Jacobian, force and acceleration mappings are systematically presented. Upon having the expressions of kinetic and potential energy, dynamic equation (1) is then explicitly derived using the Lagrange formulation, and its properties are explored. The stability of nonlinear systems and tools of analysis are covered.
- In EEL6667, the nonholonomic constraints outlined in the first course are studied in detail. Using differential geometry tools, the conditions to transform (4) into the chained form (5) are developed, and the controllability of the chained form (5) is proven. Finally, by employing feedback linearization and dynamic feedback linearization methods, conditions are derived under which the nonlinear model of (3) and (5) can be transformed into the model of (6) and (7). The

stability of the nonlinear internal dynamics in (7) is investigated.

Trajectory planning and real-time replanning

For robotic manipulation, trajectory planning is normally done using interpolation methods to satisfy such constraints as working space, motion range, and smoothness, and this can be done in either the Cartesian space or joint space. In EEL6662, the traditional setup of motion planning is covered.

On the other hand, the motion of mobile robots needs to be replanned in real-time to avoid any emerging obstacle. By incorporating recent research results, the framework in Fig. 2 is introduced to model a dynamic and uncertain environment in which terrestrial robotic vehicles of limited sensor range operate. In the framework, piecewise-constant polynomial functions are used to represent arbitrary time functions in the motion plane; that is, within the time interval $t \in [t_0 + kT_s, t_0 + (k+1)T_s)$ (where T_s is often small), the i th object of radius r_i has constant velocity denoted by v_i^k , only the objects in the range of sensors are considered, and trajectory and control of a given robot (of radius r_0) are chosen to be polynomial functions with piecewise-constant parameters. As time passes, k increases, and the trajectory is replanned (if the environment has changed) real-time while the robot is in motion, and the final composite trajectory will be a smooth collision-free trajectory from any initial position (x_0, y_0) to a final position (x_f, y_f) .

In EEL4932, trajectory planning is solved using polynomial parameterization but without considering nonholonomic kinematic constraints. In

particular, the family of trajectories in the $x - y$ plane are denoted, during the k th update, by:

$$y = [a_0(k) \quad a_1(k) \quad \cdots \quad a_p(k)] \begin{bmatrix} 1 \\ x \\ \vdots \\ x^p \end{bmatrix} \equiv \bar{a}(k)\bar{x},$$

where the coefficient vector $\bar{a}(k)$ is solved using appropriate boundary conditions: initial and terminal conditions. Terminal conditions are always given by the final position, final orientation, and final curvature as

$$(x_f, y_f), \left. \frac{\partial y}{\partial x} \right|_{x=x_f}, \quad \text{and} \quad \left. \frac{\partial^2 y}{\partial x^2} \right|_{x=x_f}.$$

At $k = 0$, initial conditions are given by the initial position, initial orientation, and initial curvature as

$$(x_0, y_0), \left. \frac{\partial y}{\partial x} \right|_{x=x_0}, \quad \text{and} \quad \left. \frac{\partial^2 y}{\partial x^2} \right|_{x=x_0}.$$

For $k > 0$, the initial conditions are given by the current position, orientation and curvature. It is clear that $p \geq 5$ is needed to satisfy all boundary conditions and hence $p \geq 6$ is needed in general for collision and obstacle avoidance. Trajectory planning is done at $k = 0$ by solving $\bar{a}(0)$ so that the trajectory at any given time instant will be at a distance of at least $(r_0 + r_i)$ from the trajectory of the i th obstacle, solvability of avoiding all static or moving obstacles is investigated using detailed analysis and reasoning, and a class of solutions with $p = 6$ is obtained analytically. The same

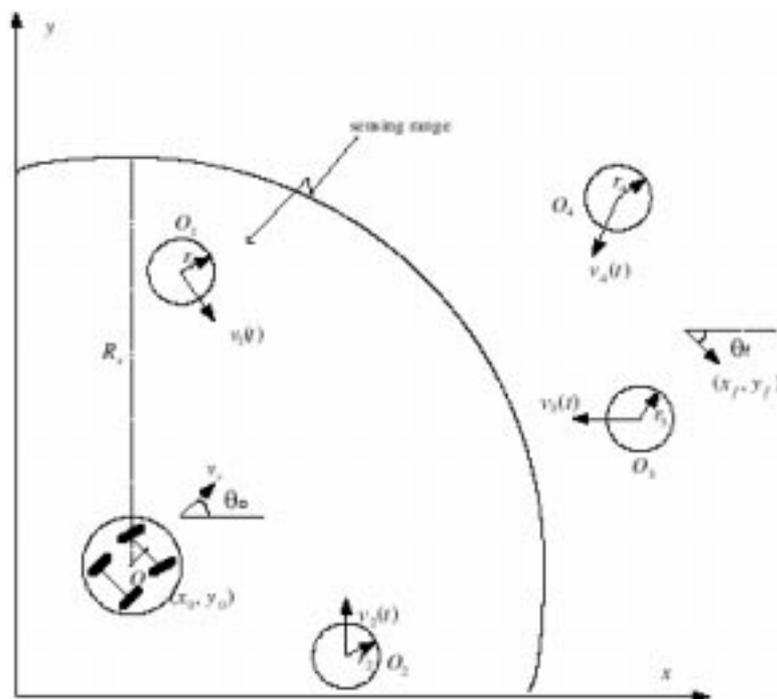


Fig. 2. A framework for real-time trajectory planning in a dynamic and uncertain environment.

analytical solution can be readily used for real-time replanning by resolving $\bar{a}(k)$ as k increases.

In EEL6667, the class of solutions obtained in EEL4932 are first revisited, and then *feasible* trajectories and the *optimized* trajectory among the class of $p = 6$ and $p = 7$ are obtained. A trajectory is said to be feasible if it satisfies both the boundary conditions imposed and the kinematic model (5). This is done by explicitly deriving expressions of open-loop steering control for the chained form (5) so that the planned polynomial trajectories can be realized. Constrained optimization is then applied to yield the best solution of $\bar{a}(k)$ by minimizing an appropriate performance index, and the solution represents the near-shortest path that is analytically solvable (while the shortest path of minimizing line integration is not analytically solvable). As a further step, the methodology developed is then extended to solve real-time three-dimensional trajectory planning for unmanned aerial vehicles (UAVs).

Individual robot control and cooperative control

In EEL4932, local feedback control design is first carried out for an individual system of the form (6) without considering nonlinear internal dynamics. It is then shown that, under an appropriate local control, the dynamics of an individual vehicle can be made to be (6) with $u_i \in \mathbb{R}^m$ being the cooperative control that needs to be designed,

$$A_i = J_{l_i} \otimes I_{m \times m} \in \mathbb{R}^{(l_i m) \times (l_i m)},$$

$$B_i = \begin{bmatrix} 0 \\ I_{m \times m} \end{bmatrix} \in \mathbb{R}^{(l_i m) \times m},$$

$$C_i = [I_{m \times m} \quad 0] \in \mathbb{R}^{m \times (l_i m)},$$

and

$$J_k = \begin{bmatrix} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & -1 & 1 & 0 \\ 0 & 0 & 0 & \cdots & -1 & 1 \\ 0 & 0 & 0 & \cdots & 0 & -1 \end{bmatrix} \in \mathbb{R}^{k \times k},$$

where \otimes denotes the Kronecker product, $I_{m \times m}$ is the m -dimensional identity matrix, and integer $l_i \geq 1$ is the relative degree of the i th vehicle. Then, it is proven that, given any constant row-stochastic matrix G^* (i.e. matrix with non-negative entries and with row sums all being equal to one), cooperative control

$$u_i = G^* [y_1^T \cdots y_q^T]^T \equiv G^* y \tag{8}$$

achieves cooperative behavior (i.e. all y_i have the same steady state). However, due to various constraints (such as communication, sensor, computation, security), it is either practically

impossible or undesirable to implement (8). Thus, the cooperative control is generally of the form

$$u_i = G(t)y, \tag{9}$$

where $G(t)$ is a piecewise-constant matrix, its changes occur at the time sequence $\{t_i, i = 0, 1, \dots\}$, and the sequence and the correspondent changes in $G(t)$ may not always be predictable. Thus, cooperative control design is to find the least restrictive condition on $G(t)$ so that all y_i have the same limit. In EEL4932, the analysis is narrowed down to find the condition(s) such that the matrix product, $\prod_{t_i} G(t_i)$, has an appropriate limit. It is shown that such a limit exists for the product if $G(t)$ has a lower triangular structure in which the diagonal blocks are irreducible and, in every block row of the lower triangular part, at least one matrix element is not vanishing as i approaches infinity (if i does; otherwise the matrix under study is that corresponding to the final finite value of i).

In EEL6662, control designs are pursued for an individual robot whose dynamics are given by equation (1). Specifically, the following classes of controls are investigated: classical controls such as proportional-derivative (PD) control and proportional-integral-derivative (PID) control, computed torque control to place closed-loop eigenvalues/poles of the tracking error system, adaptive control to handle unknown system parameters and load variations, and robust controls to overcome various uncertainties. For cases where two or more robots hold the common object, cooperative force/tracking controls are also designed.

In EEL6667, advanced designs are pursued for controls at both vehicle and system levels. For the vehicle level, real-time near-optimal smooth controls are designed for both tracking and stabilization of systems described by the general nonlinear model of (3) and (4). For formation control and cooperative control, the properties of non-negative matrices and their sequence are thoroughly discussed to show that the conditions developed in $G_i(t)$ and in EEL4932 render a cooperative behavior for dynamic systems of any relative degree. In particular, for systems in the chained form (5), the cooperative control law naturally leads to the solution of the tracking and formation control of multiple vehicles. Then the results are extended, such that multiple cooperative behaviors can be achieved and that specific values of these behaviors can be accomplished adaptively.

EVOLUTION AND EVALUATION OF THE ROBOTICS PROGRAM

The aforementioned robotics program grew out of the strong Controls program established in Electrical Engineering at UCF back in 1990. Initially, robotic manipulators were used as physical exam-

ples to which advanced nonlinear controls are applied. As more students became interested in robotics over the years, EEL6662 was introduced and taught several times as the first stand-alone course in robotics in the 1990s. After 2000, EEL4932 and EEL6667 were introduced as research in autonomous and intelligent robotic vehicles gained popularity.

The robotics program and its contents have been and will be continually updated according to feedback, evaluations, and input from students and our sponsors in governmental agencies and industry. Courses are offered and new ones are introduced mainly to meet students' interests. In turn, their interests are driven by the needs and trends of research/development, the job market, and society at large. At UCF, graduate courses in robotics/controls are offered in two-year cycles, and their contents and schedules are decided based on polls of and requests from students. Formal teaching evaluations by students at the end of each course enable us to collect specific input on the course content, teaching effectiveness, and supporting materials/facilities. Our external partners provide their input through joint research, visits, and other interaction. Our experience running the robotics curriculum has been that students are enthusiastic about robotics and especially so about recent developments, that their research interests follow closely those of funding agencies, and that evolving the curriculum while maintaining its high standard requires both funding for and efforts to implement adequate software and hardware platforms in the laboratory (which is the subject of the next section).

LABORATORY FACILITY AND SAMPLE PROJECTS

The robotics curriculum at the University of Central Florida is supported by a 400-square-foot robotics laboratory and a 300-square-foot control and autonomous systems laboratory. The laboratories contains standard equipment such as workstations, personal computers, data acquisition systems from National Instruments, vision feedback systems, and real-time control systems from Integrated Systems and Texas Instruments. Traditional robotic systems available in the laboratories include a Puma 560 manipulator, an Adept arm, a SCARA direct-drive arm, and a 2000-kg 6-DOF electric motion platform.

Unfortunately, the traditional robotic manipulators are no longer adequate for instructional and project purposes. Among the main difficulties are proprietary software (and their user interfaces) being too obsolete to update and hardware being bulky/inefficient and outdated. A contemporary robotics curriculum needs to be supplemented by robotics platforms that are equipped with standard off-the-shelf components (actuators, sensors, electronics, computing units, communications and

networking), are run by open-source software packages and easy-to-use user interfaces, are lightweight and versatile, and that can be continually updated.

Three robotic platforms recently acquired or developed and their utilization in the curriculum are now described: an automation robotic testbed, an all-terrain mobile robot, and a team of six all-wheel-drive mini robotic vehicles. To students who want to implement their algorithms, these platforms are virtually transparent in terms of hardware (both electronically and mechanically) and are easily programmable with software.

Robotic platforms for the curriculum

Of the three platforms, the ATRV-Jr from *iRobot*TM is an all-terrain mobile robot, the only system purchased as a whole because it has been commercially designed for the purpose of research and development. The robot (Fig. 3) has an on-board computer, a suite of sensors (including a compass, a sonar array, a vision system with pan-tilt-zoom control, an inertial navigation system, a differential GPS system), a wireless/radio system (including a base station, a mobile station, and antennas), and safety devices (tactile bumpers, an emergency system, and backup units).

A cylindrical robotic manipulator was designed and assembled to simulate many applications in manufacturing automation. As shown in Fig. 4, it has three degrees of freedom (two translational and one rotational) and a gripper as the end-effector. It is controlled by a host computer with a PCI-7344 motion controller card from National Instruments. It is built using off-the-shelf components (Galil servo motors, PWM power amplifiers with torque-control mode, a Lintech manipulator, and a standard camera).

Included with the manipulator is the guide segment of a convey belt commonly utilized in industry. In Fig. 5, a capacitor for commercial



Fig. 3. ATRV-Jr all-terrain mobile robot.



Fig. 4. A cylindrical manipulator.



Fig. 5. Capacitor on a conveyer belt.

AC compressors is used as the subject of an automated product inspection station. Vision-feedback control is applied to detect the presence, location and orientation of the capacitor and the end-effector is driven to pick up the capacitor, rotate it to the given orientation, and place it in a prescribed position.

The third robotic platform consists of six all-wheel-drive rovers shown in Figs. 6 and 7, a group shot and a close-up image. These mini rovers are equipped with a four-axis microcontroller, a fast wireless communication module unit, an optical encoder (consisting of a disk/scanner pair and being attached to some or all of the four wheel assemblies), a digital compass, and a micro inertia

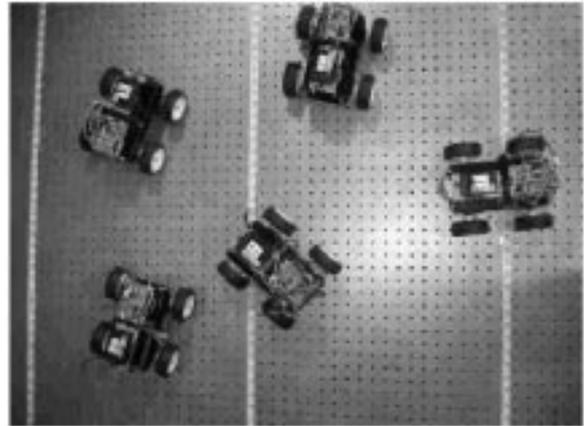


Fig. 6. A team of mini rovers.

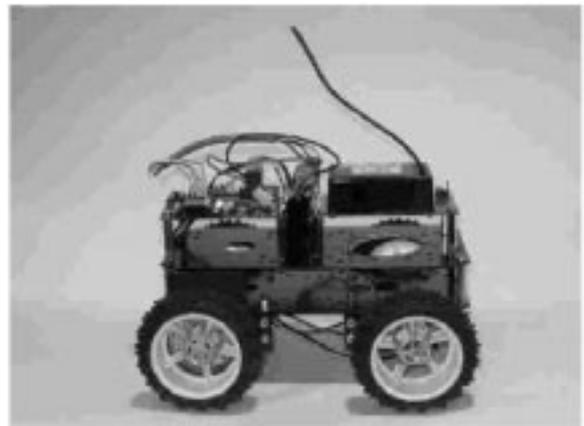


Fig. 7. A wireless controlled mini rover.

measurement unit (for three out of six rovers). A mini gripper can also be installed.

To reduce size, weight and cost and to increase flexibility, the rovers are not made to be truly autonomous; instead they are controlled wirelessly by a host computer. In the host computer, information about the individual rovers is shared according to their appropriate trajectory planning and control algorithms. For example, in simulating a dynamic and uncertain environment, a few of the rovers are designated to play the role of “moving obstacles,” and these “obstacles” are open-loop controlled according to any prescribed trajectories. The trajectories of the “obstacles” are not available to any robotic vehicles; the current position and velocity of an “obstacle” (or one rover) are passed to a specific rover only if it enters into the “sensing” range of the rover, and the rover replans its trajectory (and/or changes its control) to account for the “uncertainty.” By controlling the information sharing among the moving entities (vehicles and “obstacles”), the host computer can create whatever environment is desired, can simultaneously and independently undertake the planning and control functions of each rover, and can become the arbiter in quantifying the overall system performance.

Sample projects

The ATRV-Jr mobile robot, the team of mini rovers and their combinations provide the ideal platforms to conduct experiments in the following topics covered in EEL4932 and EEL6667:

1. Real-time trajectory planning for collision/obstacle avoidance.
2. Advanced control strategies for robotic vehicles (e.g. formation control, control of nonholonomic systems).
3. Cooperative control and behaviors.
4. Patrolling and coverage control.
5. Swarming, machine intelligence, evolutionary computing, and rule-based controls.

The cylindrical manipulator is used in EEL6662 to facilitate coverage of the following subjects:

1. Derivation and simulation of kinematic and dynamic equations.
2. Design, simulation, and implementation of rigid-body robot control methods (classical controls, computed torque control, adaptive control, robust control, and force control).
3. Visual servoing and vision-feedback control systems.

Similar to the implementations in [20–21], these platforms can be used to learn, test, and overcome many practical issues, such as calibration, unmodeled dynamics (e.g. sensor dynamics), quantization, saturation (of actuators), noise and interference, bandwidth (in communication and sensors), time delays, etc.

SOFTWARE PACKAGES AND SIMULATION PLATFORMS

In the laboratories, standard software packages of design, analysis and implementation such as Matlab, Labview, Labwindows, AutoCad, and C++ builder are installed.

The three robotic platforms are all equipped with reprogrammable software modules for implementing algorithms of trajectory planning, control, and cooperative behaviors. iRobot's ATRV-Jr robot comes with an on-board PC running Red Hat Linux [22], its mobility robot integration software installed by the vendor provides code reusability and top-to-bottom integration, and its software development environment provides easy interface with sensors, communication devices, and actuators. For the cylindrical manipulator, a human machine interface (HMI) system is developed using Borland C++ Builder 5.0, the software platform allows the user to select a number of standard control laws (such as PID and computed torque control), and human commands of position/velocity can be adjusted on-screen using the measurement and automation explorer (MAX) from National Instruments. For the team of mini rovers, a multi-vehicle control software has been developed, and its functionality is continuously being improved. As a result of these developments, students can focus on implementing their own ideas and algorithms without paying any significant amount of attention to software and hardware details.

Software has also been developed for classroom/project demonstration and visualization. Several general-purpose algorithms have been implemented using C++. For example, a graphic user interface

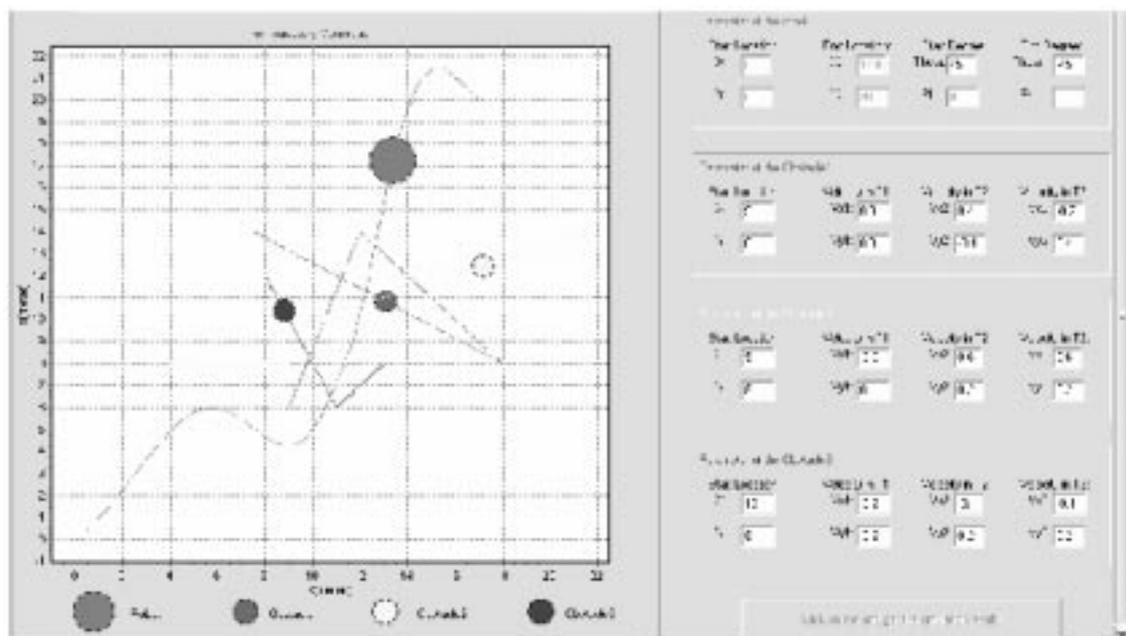


Fig. 8. GUI on real-time trajectory replanning for mobile robots operating amid moving obstacles.

(GUI) is available for students to simulate the obstacle avoidance algorithm in [9] and outlined in section 3.2. A snapshot of the GUI and a simulation result is shown in Fig. 8, in which the largest filled circle (of red color) represents the robot and the smaller filled discs (of yellow, green and blue) denote three moving obstacles. Boundary conditions (starting location/angle, ending location/angle, time interval) of the robot and changes of the obstacles' trajectories can simply be set through the on-screen windows of the GUI. The GUI has proved to be a very effective teaching tool.

IMPLEMENTATION, TRANSFER, AND DISSEMINATION

We believe that the robotics curriculum outlined in this paper can be implemented elsewhere and that, without too much effort, a new curriculum with a different focus can be developed.

The cost to acquire the necessary equipment is moderate. The ATRV-Jr mobile robot was purchased at a cost of \$33,000; the mini rovers (equipped with a four-axis controller, an optical encoder, a compass, a wireless communication module, and a gripper) are about \$700 each, its basic chassis can be ordered from www.totalrobots.com, and the compact inertia unit adds \$2,300 per vehicle; the cylindrical robotic manipulator was built using standard industrial components, and its parts have a total cost of \$11,000.

More detailed information on course materials and on robotic platforms is available on request.

CONCLUSION

A robotics curriculum with a contemporary focus on autonomous mobile robots is presented here. Its courses, main features, methodology, laboratory facilities, and projects are discussed and illustrated using examples. The curriculum has been and will be continually updated by incorporating new research results, by adopting the spiral learning paradigm, and by implementing feedback. Its evolution is driven by students' interests and their research needs. As a result, the proposed model of curriculum development is applicable to establishing similar or distinct robotics programs at other institutions. Requirements of space and supporting facilities are modest and feasible for most M.Sc. and Ph.D. programs.

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