A RESEARCH-DRIVEN APPROACH TO UNDERGRADUATE ROBOTICS EDUCATION

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Abstract

Robotics is a rapidly-progressing and applied subject. This paper advocates for a research-driven model for modern robotics course design that, based on a principled approach, prepares students to consider and adopt recent results in their mechatronics applications. This view provides a rubric for defining a sufficient set of topics that give a broad overview of robotic technologies and provides a foundation for later (undergraduate) research experience. To address the inherently multidisciplinary nature of robotics, a modular co-teaching model is adopted in which separate sections are taught by different lecturers, who potentially span various academic departments. Evidence supporting this approach is illustrated from case studies of student projects in The University of Sydney's Experimental Robotics course, MTRX 4700. By providing an engaging topic, a research approach, extensive mentorship, and an open-ended problem, the course not only meets learning objectives, but also promotes a research foundation supporting later undergraduate research opportunities.

Introduction

Robotics is an inherently fascinating subject that captivates the imagination. From US FIRST [1] to lunar rovers [2] to new doctoral programs in robotics, interest in the subject has increased both popularly and academically. This, in turn, has renewed interest in introductory and experimental robotics courses, particularly at the senior undergraduate (or mezzanine) level.

From a learning perspective such courses offer an opportunity to introduce systems engineering concepts and to integrate knowledge across multiple disciplines and topics. From a teaching perspective, these courses attract highly motive and engaged students due to the general enthusiasm for the subject. While such excitement is helpful, the applied nature and general expectation of robotics often implies interest in new material and "modern" results. This is directly addressed by a research-focus that enables students to navigate robotics research results and to apply these codes and methods.

Compared to the significant attention paid to curriculum and learning development within particular subdisciplines, the design and emphasis for introductory robotics courses has received little direct attention [3]. In part, this is attributable to the interdisciplinary and expanding nature of robotics, which has grown from articulated serial kinematics chains to mobile systems with integrated sensing and control. Both the breadth of material and the (relatively) short course periods suggest the need for a careful structuring of such courses.

The educational focus seems to vary widely from broad research [4] and technical skills [5] to student retention [6]. Course structure is also similarly varied. Using introductory textbooks as a guide, most courses either focus on autonomous manipulation [7], [8], [9] or basic mobile robot systems [10], [11]. Both of these implicitly assume operation in a structured, quasi-static, and rigid environment. This focus is in contrast to many trends in robotics research, which consider statistical methods, dynamics, compliance, and nonlinear operation.

A research-driven approach addresses several of these concerns [12]. It bridges the gap in course material by putting research ideas into the forefront. It gives the instruction a clear research focus. It provides a strong (peer-reviewed and vetted) structure for organizing and selecting course material. Finally, it provides a group research mentoring process by which students are exposed to open-ended problems, but in a more structured and less resource intensive way than one-on-one mentoring typical of research experience for undergraduate (REU) programs.

Illustrated in the context of The University of Sydney's Experimental Robotics course (MTRX 4700), this paper presents a research-driven template for course development and provides a rubric for defining a sufficient set of reference topics. By separating robotics into technical and application streams, it is possible to better balance and integrate elements from mechatronics, kinematics, signal processing, vision, and motion planning. It also facilitates a modular structure allowing for input by different lecturers or domain experts. While motivated and developed in the context of a modern introductory robotics program, it is envisioned that a research-driven template could well serve interdisciplinary course efforts in general. As evidenced by the popularity of double-degree programs and recent research trends, there is a clear demand for such courses. However, these courses tend to be specialized and without traditional teaching materials. By connecting students to recent results and by providing a template for structuring classes, this approach not only provides techniques by which to structure and adapt newer courses, but also allows students to appreciate and improve research methods, which aids future undergraduate (thesis) research efforts.

The remainder of this paper is structured as follows. The paper begins by examining the objectives of a research driven robotics course and illustrates and supports this approach in the context of MTRX 4700. Then presents two case studies of student projects and concludes with some generalizations based on the outcomes of the course.

Course Objectives

A tenet of the research-driven approach is that, because robotics is a rapidly developing field, students must possess the necessary skills to understand and apply results from the research literature. As a benchmark, students should be able to understand the digest of a major robotics conference (e.g., International Conference on Robotics and Automation (ICRA) or Robotics: Science and Systems (RSS)). In part, it is because of the diversity and rapid development in robotics that a research approach is necessary.

The curriculum structure of a research-driven course is based on the major science themes as identified in the area and technical committee divisions that are used as part of the editorial process at major conferences such as ICRA and RSS. For example, RSS divides robotics into 12 areas [13] and ICRA 22 technical areas [14]. However, both conferences separate robotics into technical ("science") areas (e.g., control, perception, learning, and planning) and application ("system") domains (e.g., medical and life sciences, industrial robotics and automation, field robotics, etc.).

While learning objectives are central to course design, they are often taken for granted in robotics and laboratory courses [15]. Even when objectives are explicitly defined, they tend to be abstract. In the proposed approach, the objectives are to foster a principled understanding of robotics, to introduce students to research, and to direct students' enthusiasm for the subject towards a more general discovery process.

In contrast to a traditional teaching style, aligning educational practice with research practice further provides a template for establishing more general learning objectives [16]. Learning objectives shift from mastering isolated concepts to discovery via the research process. In so doing, students appreciate the scope and challenges of various standard robotics problems. For example, Denavit-Hartenberg [7] can be presented as one of many algorithms for solving kinematic frame assignment problems.

A research-driven approach facilitates the addition of fresh course material without extensive revision of course structure. Further, an independent project component allows students to incorporate new materials sometimes faster than the course can as a whole. It also aligns the course with university-level research training goals by not merely asking the students to assist with research at a low level, but by training students to direct research by engaging their personal interests. That is, by inspiring in them a passion for discovery, students see that research is not limited to university laboratories, but is relevant in professional engineering tasks.

MTRX 4700: Experimental Robotics

The MTRX 4700 course at The University of Sydney is designed to provide students with the essential skills necessary to develop robotic systems for practical applications. It motivates and supports the aforementioned research-driven approach for introductory robotics courses.

The course covers a broad variety of topics related to robotics that build on prior courses in mechanical design, electronic systems, and software development. Students are provided with unparalleled access to resources with which to complete a major project of their own design. This project allows students to select a topic of interest and to engage deeply with the material in developing a robotic system of their choosing. They present their work to their peers as part of the assessment procedure, and they submit a report written in a journal or conference style that outlines the design of their system and results of their activities. They are also asked to relate their work to the current state of the art in the literature from which they have drawn inspiration, thereby extending their skills in research and inquiry. Case studies of example projects are presented later.

A. Background

As with many robotics courses, MTRX 4700 is targeted at fourth-year undergraduates and first-year masters students (i.e. a mezzanine-level course). MTRX 4700 provides a broad overview of the technologies associated with industrial and mobile robots in a research-grounded framework. Topics are presented along principal scientific lines in robotics with applications shown that connect the various aspects. In so doing links are made between the sciences (e.g., the rigid body transformations of manipulation are the same as those in computer vision).

Major topics covered include sensing, mapping, navigation and control of mobile robots and kinematics and control of industrial robots. The subject consists of a series of (didactic) lectures on robot fundamentals and case studies on practical robot systems with this material illustrated through experimental laboratory assignments and a self-selected group project.

B. Course Structure

The course consists of one two-hour lecture and three hours of laboratory time per week. A team of three lecturers present the scientific core. Invited experts present case studies and guest lectures to give the students a broad exposure to robotic systems both in research and industrial contexts.

Material covered in lectures is illustrated through experimental laboratory assignments. By applying the techniques they have learned, students are given the opportunity to contextualize their learning. Application of the concepts will encourage a deeper approach to their learning. Finally, students are asked to present a demonstration of their major project to other students and staff. This encourages them to produce a system of sufficient quality to demonstrate to their peers. This also provides the students with an opportunity to share their experiences with their classmates.

Collaborative learning is not only a central aspect of interdisciplinary research, but has been shown to produce learning gains [16]. An important distinction for this course is that the projects are defined by the group (typically 3 students). The scope of the projects is about half the size of an honors thesis project. While the available time is approximately one quarter that of a thesis, the task is performed as part of a team. The teams are provided a list of suggested topics/areas along with a list of laboratory robotic equipment available (e.g., iRobot Create). The teams also receive appropriate mentoring from all three course supervisors to aid them in scoping and understanding their selection. The students write their results using an IEEE template and present their results at the end of the course in a mini-symposium.

This project critically builds on research inquiry skills and allows the teams to go into new directions that would otherwise not be part of the larger course (e.g., SURF feature tracking on Roombas [17], model generation from picture collections using Bundler-SFM [18], and feedback motion planning for a student-built aircraft [19]). Working on current topics and accessing recently published results serves to engage students, motivate effort, and encourage learning. Finally, the mini-paper and presentation offer a demonstrable outcome that the students can add to their portfolio.

C. Modular Instruction

A principled scientific approach, fundamental to research, is notoriously difficult to teach. It is resource intensive and requires personal supervision. Adding an explicit research direction to the course adds to the initial mentorship requirements, but aids later in the degree program by improving the quality of later one-on-one mentoring in undergraduate thesis or research programs.

To logistically facilitate this approach, a modular team-teaching structure is adopted with three co-teachers each with different scientific areas of expertise. In the case of MTRX4700, all the instructors are part of the general robotics program, but each has research leadership in various areas including kinematics, motion planning, and navigation.

D. Laboratory Facilities

The course begins with an educational perspective to the laboratory and then adopts both development and finally research perspectives. The laboratories are designed progressively to focus students on first understanding concepts and then to challenge them to research parts of the problem. In the later project phase of the course, the laboratories are more open-ended with support given for getting experimental data to iterate and advance their designs.

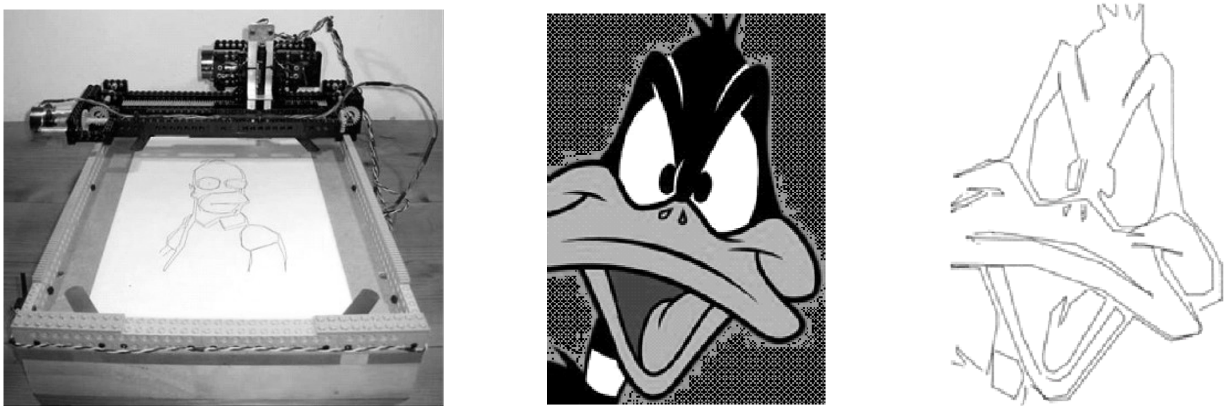
The course itself is typical in terms of the resources needed. Both the individual laboratory assignments and the student design project are conducted in a standard mechatronics laboratory room. This space (12 x 30 m) is equipped with terminals (oscilloscopes, computers, power supplies, etc.), an electronics cabinet (ICs, passive components, etc.), and a mechanics cabinet (motors, etc.). For the course, access is provided to four iRobot Create mobile robot platforms, a custom miniature robot arm, and four Logitech Sphere cameras. Students are provided open-access to the space outside of times when it is reserved for the class.

Case Studies

This section presents two examples of student projects demonstrating concepts and skills learned in the course. The first project uses computer vision and kinematics to generate an artistic robotic interpretation of a digital image. The second project illustrates knowledge of computer vision and robot motion planning.

A. Robot Artiste

The Robot Artiste project consists of an XY plotting table. A digital source image is input to the system and a line drawing interpretation is output via the XY plotter. Computer vision is used to analyze the source image and generate a line representation, and methods from kinematics are used to control the plotter in tracing the line representation on paper. The student report details design choices, high-level control processing, and the low-level control algorithms used. Sample images are shown in Fig. 1.

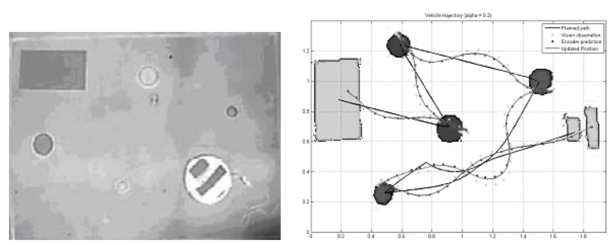


(a) (b) (c)

Figure 1: Robot Artiste project. (a) Prototype XY table that draws an image on paper. (b) Sample image input to system. (c) Resulting image drawn by system.

B. Ground-based Search and Retrieve using Aerial Localization

Cooperative ground vehicle/aerial vehicle pairs can potentially be utilized for search and retrieve applications in disaster scenarios. Students implemented a simplified setup using an iRobot Create mobile robot platform, colored retrieval targets and a ceiling-mounted camera for localization. Students documented the design of the entire system, with particular emphasis on perception, navigation, guidance and control subsystems. Preliminary vehicle test results were presented and discussed, and potential future improvements were suggested. Fig. 2 shows an overview of the system.



(a) (b)

Figure 2: Ground-based search and retrieve project. (a) Over-head view of robot, targets and calibration rectangle. (b) Sample path plan generated by system and resulting vehicle trajectory.

Conclusion

Driven by research ideas, MTRX 4700 presents a novel approach to robotics education. This is manifest in several strong initiatives, including:

- Guided, team selected project topics;
- Curriculum structure delineated by science trends in robotics (as identified by the IEEE Robotics and Automation Society and the RSS Area chairs);
- Multiple co-faculty (from across various domain areas); and,
- A low student/faculty ratio (giving strong support to the program and insuring quality mentoring).

The research-driven approach presents a template for a modular structure by which course instruction and mentorship can be shared across domain-experts, thus reducing the workload of teaching in such a broad and rapidly moving domain. This helps make such courses more approachable from a faculty perspective. Finally, the research-driven approach conveys the importance of interdisciplinary research skills. This helps reduce the level of one-to-one mentoring (which is particularly resource intensive) needed in later honors or other thesis-based courses.

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