An Interdisciplinary MIT Course: Designing Robots That Interact With the Physical World

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Abstract

The objective of this thesis was to help develop an interdisciplinary course in robotic design at MIT. The course is a comprehensive study of applied robotics that gives students the chance to put their theoretical knowledge to practical use. The course heavily emphasizes hands-on work, and lab work comprises most of the material in the class. This thesis discusses some of the work that goes in to planning and organizing such a class.

Contributions to the class detailed in this thesis include design of various hardware used by the students over the first term. Additionally, detailed responsibilities included fabrication of most of the parts used by the students, and various administrative tasks such as inventory.

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1 Introduction

There is a major effort among the faculty at MIT to bring more opportunities for practical, hands-on experience in robotics into the undergraduate curriculum. This class, hereafter referred to as RSS (Robotic Science and Systems), aims to fill that gap with a comprehensive year-long project course. RSS covers practical and theoretical techniques in many fields, including EECS, A/A, OE, and ME. In this project, I had a diverse set of responsibilities. Most of my work involved design and fabrication of many of the hardware components that students would be using. In addition to this, I ordered and kept track of the parts that we needed for the lab kits. Also, I worked with the rest of the staff to decide the scope and size of each lab.

2 Background

2.1 About the Class

The class is framed around a "Grand Challenge," a major issue on the cutting edge of robotics research. It involves designing and programming robots or embedded systems that interact effectively and autonomously with the real world. Students get hands-on experience with the entire design process behind solving real-world design problems.

In order to equip students with the knowledge and experience to tackle the challenge, the first portion of the class is be devoted to familiarizing the students with the motors, sensors, materials, and equipment at their disposal. Later labs incorporate a fully functioning robot, and challenge students to tackle problems such as navigation.

The Grand Challenge that this class builds up to incorporates two main problems in autonomous robotics today: localization and object manipulation. Both are discussed below.

The localization problem considers the situation where the robot is given a priori knowledge of the surrounding environment, and must use visual (or other) cues to localize itself within this map. The maze fiducials discussed in the design subsection of the discussion are intended to aid the robot in this goal.

The other main problem in this Grand Challenge is object manipulation. This problem is a classic robotics problem because it requires you to combine two separate issues into one control scheme: locating an object, and manipulating the object. Also, the applicable control scheme for a robotic arm depends largely on whether or not the arm is *in contact with* the object.

Because this class is spread over two terms, there is enough time to start from the most basic ideas, such as motor dynamics, and work incrementally up to the Grand Challenge. As such, good design and pacing of the labs is key to the success of the class.

2.2 Labs

All of the coursework for RSS is presented in the form of labs. Design of the labs for RSS involves constructing a good set of problems that can be worked independently, but also walked through by the professor to elicit key concepts.

The class builds a body of knowledge from the ground up, so the very first lab covers low-level ideas such as familiarization with a PCB. Students are given a partially populated ORCBoard. They are then instructed to discover the components that are missing, and solder them onto the board by hand.

In the next series of labs, students are slowly familiarized with all of the hardware that is available to them. First the students play with the assembled ORCBoard alone. Motors and a few simple sensors are introduced in the second lab. The chassis is built in the third lab, and students get to move their robots around "blind" (i.e. without any sensing of the environment). The fourth lab introduces the light sensors, and students get to construct Braitenburg vehicles by connecting the light sensors directly to the motors.

At this point, the course becomes much more software oriented. The fifth lab introduces Carmen, a complex mobile robot control package, as well as an on-board computer for the robots. Students also got a camera in this lab, and began to deal with computer vision. The sixth lab covers local navigation, and the seventh lab covers high level navigation. The eighth lab introduces the 3-DOF robotic arm, and deals with grasping and object transportation.

Beyond this, the final effort is the course challenge. For this term, the course challenge involves high-level navigation and localization, as well as object manipulation. Various blocks are strewn around the challenge course, and robots have to pick up 'good' blocks (differentiated by color) and transport them to a goal location. A sketch of the final challenge course can be seen in the next section.

3 Discussion

This section details my contribution to the RSS project. I joined this project at the beginning of the fall 2004 term. It sounded like an incredible and interesting challenge to try to help design a class on the exact topic that captures my own interest — in short, to help design a class that I would die to take. My work for the class falls into three categories: inventory, design, and fabrication.

During the fall term, I essentially worked as an assistant for James McClurkin, doing anything that he asked of me. This mainly involved researching and ordering parts that we would need for the class. The bulk of my work for the class didn't start until IAP, for two reasons: I could work full time, and the deadline was fast approaching.

3.1 Design

My first major design responsibility was a prototype of the exemplar robot for the class. I designed, modeled, and built it, and that robot evolved into the exemplar robot that we are now using. The chassis is built using 80/20, a commercially available extruded aluminum building material. 80/20 was chosen because of its ease of use; see the materials section for details. The bed of the robot is pegboard, also chosen because of its ease of construction. The two plates on the side of the prototype represent the motor mounts. The prototype robot chassis can be seen in figures 1 and 2.

I transformed the original prototype robot into the current exemplar robot for the class, modifying it to use the lab rig (described below) as its platform. I dealt with mounting the motors, wheels, and casters, and I kept the whole design as open as possible. Very little on the robot must be disassembled to work on any specific part, making modification easy and fast.

In addition to that, I designed the lab rig. This rig is used as a tabletop apparatus for the first two labs, and it can be mounted directly onto the chassis and transform into a robot

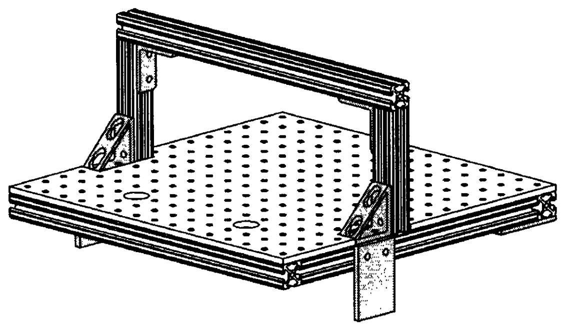

Figure 1: Rendering of robot chassis. The ‘roll bar’ can be moved back or forth as desired, and can be used as a mount for various sensors. In the base design, the roll bar is used as a mount for light sensors, and later on, a camera and the 3-DOF arm. Students are encouraged to alter this design later on in the term.

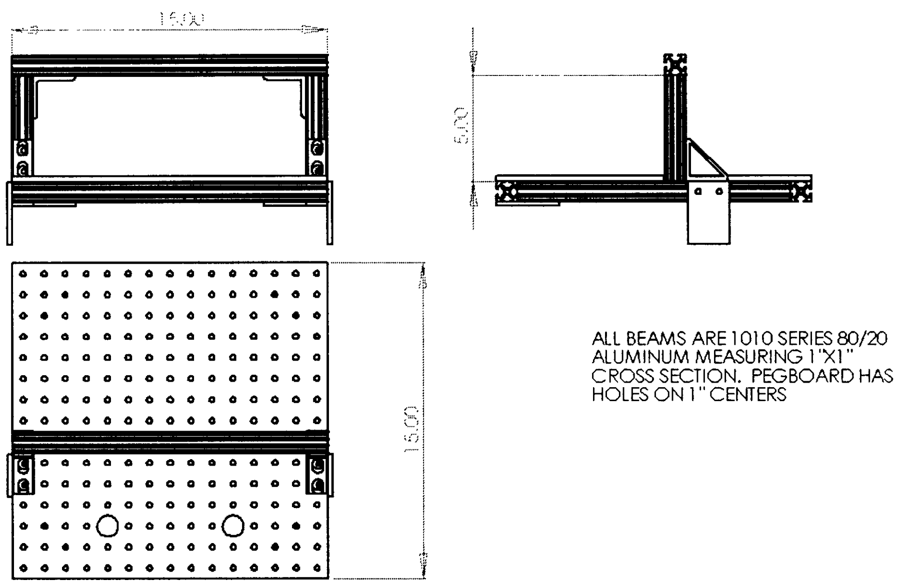

Figure 2: Drawing of robot chassis

for the third lab. This rig holds two motors, an ORCBoard, a Single Board Computer, and a battery. I chose and modified the enclosure for the ORCBoard to allow for easy modification by the students; they can move or remove the ORCBoard from the rig without having to separate it from the enclosure at all. Consequently, the ORCBoard is protected from abuse. I built all custom cabling for the rig, including the optical encoder cables and a ribbon serial cable for the SBC.

For the first group of labs, the students are instructed to closely follow the hardware configuration laid out by the staff. These labs focus on introducing new hardware, so it is instructive to dictate the robot architecture until students familiarize themselves with all the tools at their disposal.

In later labs, after all the various hardware components have been introduced, the students will be allowed (in fact, expected) to modify the layout of their robot in order to optimize it for certain behaviors. For this reason, the staff architecture is intentionally sub-optimal: it is much larger than necessary, for example.

Another design responsibility of mine was a bump sensor. James wanted a bump sensor with a number of properties: It had to be sensitive in a range of directions, it had to trip immediately but have a decent amount of throw (for shock absorption purposes), and the actual button had to be completely out of the force path. I did design and model an effective solution, though it seems we're going to opt for store-bought sensors in the end. A picture of the modeled bump sensor can be seen in figure 3.

I also worked on many of the other sensors for the class. For example, I designed a simple photo-sensor as a voltage divider between a photo-resistor and a resistor. Other sensors, such as the sonar range finder, were off-the-shelf items.

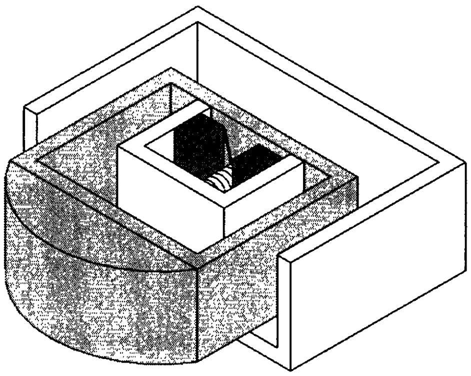

Figure 3: Rendering of bump sensor. Notice that for any perturbation of the front bumper, one or both of the switches must be tripped due to geometrical constraints. Also, notice that this design creates an 'active low' bump sensor: both switches are high in the rest state.

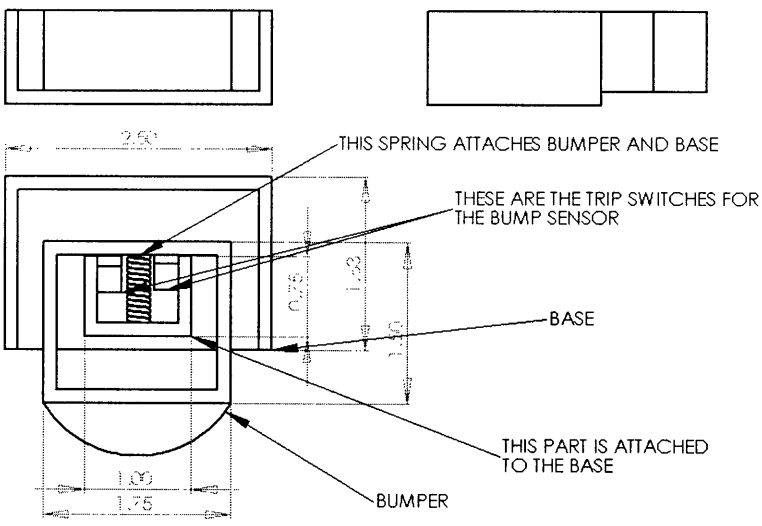

Figure 4: Drawing of bump sensor

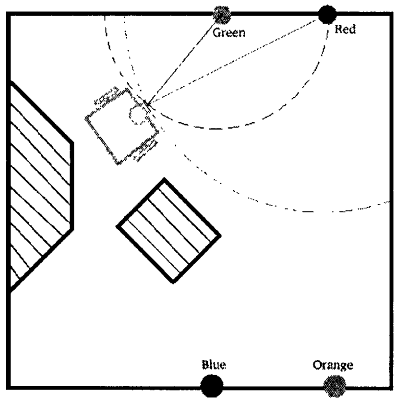

Figure 5: Design of first maze. The robot is given a priori knowledge of the maze and the location, color, and size of all fiducials. With this information, if it sees two fiducials, it has enough information to determine its own position uniquely. The robot can calculate its distance from the fiducial by comparing the visual size of the fiducial with its known size.

My most recent design responsibility dealt with the course layout for the grand challenge. I designed the layout of the first maze used in the class, as well as the placement of the fiducials for all iterations of the maze. Initially, the fiducials were laid out such that a robot would be able to see two of them in one frame from any location on the map. This led to a simple 'couplet' design: two fiducials were placed a couple of feet apart. The intended utility of this design was that students would be able to use the color and perceived size of the fiducials to figure out their location on the map. In a sense, it's like reverse–triangulation. See Figure 5 for a graphical explanation of the idea.

When the class moved into a different space for the grand challenge, the purpose of the fiducials changed as well. The new course was divided into three rooms, and one fiducial was placed at the center of every wall. The colors of the fiducials were constrained as follows: no ordered pairing of adjacent colors could be repeated. (Also, a particular color could not be repeated in a single room.)

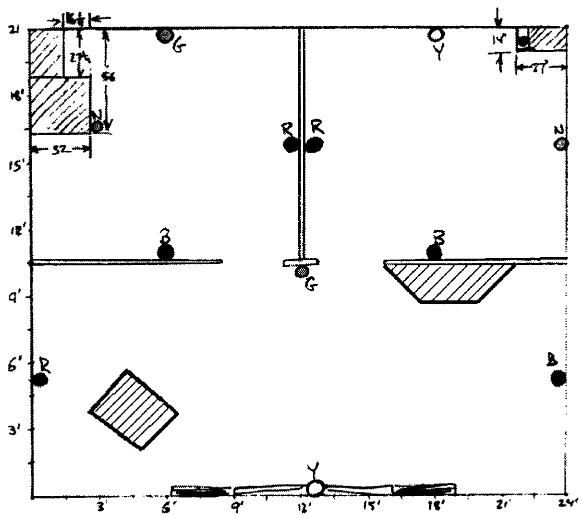

Figure 6: Design of challenge course. Again, the robot is given a priori knowledge of the maze and the location, color, and size of all fiducials. In this case, the colors of the balls are chosen through a simple constraint–maximization problem such that no adjacent ordered pairing is repeated. As a result, if a robot spies a fiducial and turns to one side until it spies another fiducial, it has enough information to determine which room it is in, where it is in that room, and which direction it's facing.

The reasoning behind this constraint is that it allows students' robots to easily determine which room they are in. Once a robot sees a fiducial, all it has to do is turn 90 degrees in a particular direction, and note the color of the next fiducial. Since no ordered pairing of adjacent colors is repeated, the robot can now uniquely determine which room it is in, and which direction it is facing. See Figure 6 for details.

3.2 Inventory

During the fall term, I worked with James to order all the parts we thought we'd need for the class. I did lots of Digikey orders, as well as random parts (e.g. the 80/20 materials we needed, possible enclosures for the ORCBoard, and options for sensors that we might use in the class). I worked out various calculations for desired parts as well. For example, I calculated the torque output we would need from our motors to get the kind of speed and performance we were looking for.

At the beginning of IAP, I took on the responsibility for all ordering. I became the 'Parts-Czar:' any new orders went through me. In this position, I implemented and managed a simple shopping list and inventory system, allowing the group to keep track of items that were ordered but hadn't yet arrived. This prevented redundant ordering of the same item. I also implemented a purchase order system. I continued in this capacity through the beginning of the spring term.

3.3 Fabrication

Many, many parts had to be designed, fabricated, and assembled for this class. The strain of completing all of this is lessened somewhat by having students do most of the assembly for their own team. For most of the parts that the staff provides, a single exemplar robot is assembled by the staff. Each team then copies the exemplar architecture on their own robot.

Still, the staff had to fabricate nearly every part that the students used. A large part of this fabrication fell to me. Some examples of hardware that I fabricated for the class include: 80/20 for the robot chassis, pegboard for the lab-rig/robot-bed, motor mounts, ORCBoard enclosures, bump sensor mounts, sonar mounts, 3-DOF robotic arms, many of the sensor cables, and testing stands for the robots.

3.4 Miscellaneous

Aside from the duties described above, I took care of various minutiae for the class. I helped deal with the Sun computers, both hardware and software (I have decent Linux expertise). I dealt with the cooling issues on the SBC's, putting in a chip fan and a case fan in order to keep them from overheating. I gave a few micro-lectures to students explaining the finer details of assembling the robot.

4 Materials

The main building material for RSS is called 80/20. This is a set of materials that include special extruded aluminum stock and all types of fasteners. It is designed to be extremely fast to assemble and disassemble, and has earned its nickname as the 'industrial erector set.' Also, because it is extruded aluminum, it can be easily machined if students want to work out custom designs for their robot. Considering the breadth and depth of RSS, this kind of versatility is a requirement.

For the bed of the robot, we chose pegboard, a kind of particle board that has holes in it at 1" centers. This made it very easy to attach the components to the bed — as long as all mounting holes were put on one inch centers, they would fit anywhere on the pegboard. Similarly, the pegboard can be screwed right into the robot chassis.

The students use various other hardware not detailed in this thesis, such as an on-board computer and camera, that were purchased through normal commercial channels and used as off-the-shelf parts.

5 Conclusion

The process of putting together a class is an intensive one. The entire curriculum must be laid out beforehand to ensure that the class covers all of the desired topics, with enough time to concentrate on each. If this class is project based, the challenge becomes even greater; in addition to a curriculum, a lab must be constructed for nearly every week of the term. Each lab needs an overarching goal, but it must also have a specific set of tasks that are laid out in order and explained in detail. The work detailed in this thesis represents the contribution of one person towards this incredible effort; consequently, the amount of work described herein is just a fraction of the total work required for putting together a class such as RSS.

In helping to put together and run RSS over the past year, I have developed an appreciation for the difficulty of this project. I handled many minor issues and a few major ones, but my primary function was simply to help make the class happen. Judging by the reaction from the students, it seems that RSS has been a successful teaching and learning experience.