The UNM Mechanical Engineering
Lego Robot Competition

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Abstract

Modern mechanical systems are increasingly being controlled by digital electronics, yet many mechanical engineering programs have not incorporated this topic into the curriculum. Also, ABET has recently emphasized the importance of design in engineering education. The LEGO Robot Competition is a course offered by the Mechanical Engineering Department which addresses the integration of digital electronics and mechanical design, along with the areas of software development, real-time control, testing and evaluation, and working as part of a team. Teams of students are required to design and construct a fully autonomous computer-controlled mobile robot using LEGO pieces, and compete against other robots at the end of the semester.

I. Introduction

Modern mechanical systems are increasingly being controlled by microprocessors and digital electronics. Common digital control applications include electronic engine management (fuel and electrical systems) in automotive engines, antilock braking systems, numerically-controlled automation, and even digital appliances. This proliferation of digital controllers in traditional mechanical domains requires educating mechanical engineers about the integration of microprocessors and mechanical devices. This combination of electronics, sensors, and mechanisms has been termed “mechatronics[1].”

Background

To integrate microprocessors, software, sensors, and actuators in mechanisms I developed a senior-graduate level course offering in 1980. This course, entitled “Microprocessors in Mechanical Systems.” The catalog description is

**ME 470. Microprocessors in Mechanical Systems.** Introduction to microprocessor organization, interfacing, machine and assembler-language programming. Several projects involving the use of a microcontroller in various mechanical systems. Prerequisite: senior standing or permission of instructor.

The objective of this course, which is open to all engineering students, was to familiarize students with microprocessors and their use in mechanical systems. The Motorola 68HC11 EVBU microcontroller evaluation board was used, with all programming in assembler language. Since computer education without hands-on experience is ineffective, ME 470 relies heavily on laboratory projects, with all apparatus pre-configured. It is not feasible to allow the students to construct the apparatus themselves, since other students must use the same setup. While students understand this, they would prefer it to be otherwise. This, and other comments may be seen from a sampling of student evaluations...
...would be nice to set up and wire the apparatuses (sic), but this would be hard to implement...more emphasis on interfacing...more memory, more hardware...add more memory!...the projects were great but if we had to setup some of the hardware would have been great too...it would be nice to redo the assembler programs in C language."

Another course was needed, one that still contained the essence of mechatronics, but allowed the students more room for creativity. Thus was born the LEGO Robot Competition.

The UNM Mechanical Engineering LEGO Robot Competition

The LEGO Robot Competition is a course offered by the Mechanical Engineering Department at UNM and is open to all engineering students. The course was first taught in 1996, and yearly thereafter. The students work in teams of three or four. Each team is given the same kit containing various sensors, electronic components, batteries, motors, and LEGO parts, plus a small budget for discretionary items. Their challenge: design and build an autonomous mobile robot that will compete with other robots on the last day of class. Instruction during the latter part of the course is largely defined by student input...let them work until they have a question!

The following components of the course will be described:

- The Challenge—what kind of competition?
- LEGOos—I thought they were for kids!
- The Handyboard—a surprisingly capable single-board computer
- Actuators & Sensors—what is needed and how to use them
- The Day of the Competition—getting a product out the door!

The Challenge

In 1996 and 1997, the essence of the competition was to navigate a maze which was constructed from plain black electrical tape on a “whiteboard” background. Running a maze requires sensors to detect the maze, and software for navigation. The difficulty of the maze can be easily varied.

At the end of the maze, the robots of the 1996 competition were simply required to sense a barrier and stop. The 1997 competition required the robots to drop a ping-pong ball into a box, which defined completion. Two identical mazes were placed beside each other, so two robots could compete head-to-head, thus enhancing the drama for the spectators.

Figure 1 shows the maze used in 1996, with two robots competing, and boxes at the end of the maze. Some spectators may be seen lining the course.

Construction with LEGO pieces

LEGO Technics are fun to play with and allow rapid prototyping and iteration, but they are not always easy to use. In fact, it is often quite challenging to build a LEGO device that does not fall apart at the slightest provocation. A well-designed LEGO device should be reliable, compact, and sturdy. Our robots typically make extensive use of gears, and those geartrains must be able to
rotate cleanly and easily. Some LEGO design principles have been developed by Martin and Sargent at MIT[2].

LEGO Bricks and Beams

The cross-section of a Unit LEGO brick is 9.6mm × 8.0mm. Interestingly, this is the ratio of 6 to 5. This ratio, coupled with the existence of one-third height flat pieces, allows the creation of vertical spacings that perfectly match unit ones. By using these perfect LEGO spacings, vertical stacks of bricks can be reinforced with cross-beams, creating sturdy structures that will not fall apart.

A little mathematics helps compute all feasible standard combinations. Suppose \( a \) represents the number of full-height vertical units and \( b \) the number of one-third height vertical units. Then the height of a LEGO assembly (in mm) would be

\[
9.6(a + \frac{1}{3}b)
\]

since a full vertical unit is 9.6 mm high.
If $c$ represents the number of horizontal units, then $8c$ is the length of a LEGO beam in mm. We then need to find integral solutions that make these two quantities equal:

$$9.6(a + \frac{1}{3}b) = 8c$$

which reduces to

$$2(3a + b) = 5c$$

Solutions to this integer equation yield perfect vertical spacings. Bracing LEGO structures using these spacings is a key method of creating a structurally sturdy machine.

LEGO Gearing

Making a good LEGO geartrain is indeed a fine art. However, this art can be learned, and having some simple information can make a big difference. One of the first things to notice about LEGO gears is their diameter, which indicates at what spacings they can be meshed together.

One of the first things to notice about LEGO gears is their diameter, which indicates at what spacings they can be meshed together. The natural units for the sizes of LEGO gears is the horizontal LEGO spacing unit. The following table shows the radii of the various LEGO gears:

<table>
<thead>
<tr>
<th>Gear Teeth (number)</th>
<th>Gear Radius (horizontal units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Notice that three of the gears (8-tooth, 24-tooth, and 40-tooth) have radii that, when used together in pairs, an integral spacing is formed. So, for example, the 8-tooth gear may be used with the 24-tooth or the 40-tooth, but not the 16-tooth.

High performance geartrains are necessary to drive a mobile robot. We suggest the teams adhere to some geartrain design principles, most of which are just good mechanical design practice.

Computer Hardware and Software

The on-board computer used on the LEGO robots is based on the Motorola 68HC11 microcontroller, and is sold in kit form as the Handy Board. The software is Interactive C, which includes a compiler and a run-time machine language module.

The Handy Board

The Handy Board[3] is a small battery-powered microcontroller board which has been designed for personal and educational robotics projects. Based on the Motorola 68HC11 microcontroller, the Handy Board includes:

- 52-pin Motorola 6811 microprocessor with system clock at 2 MHz.
- 32K of battery-backed CMOS static RAM.
- Two dual H-bridge L293D chips capable of driving four motors.
- 16 × 2 LCD screen.
- Two user-programmable buttons, one knob, and piezo beeper.
- Powered header inputs for 7 analog and 9 digital sensors.
- 8-pin powered connector to 6811 SPI circuit (1 Mbaud synchronous serial interface)
- Board size of 4.25 × 3.15 inches.

A photograph of the Handy Board is shown in Figure 2. We obtain Handy Boards in kit form, and require each team to construct their own board. This encourages the development of good electronic fabrication techniques which will pay dividends in their sensor and actuator wiring.

Interactive C

Interactive C (IC for short) is a C language consisting of a compiler (with interactive command-line compilation and debugging) and a run-time machine language module. IC implements a subset of C including control structures (for, while, if, else, local and global variables, arrays, pointers, 16- and 32-bit integers, and 32-bit floating point numbers).

IC works by compiling into pseudo-code for a custom stack machine, rather than compiling directly into native code for a particular processor. This pseudo-code (or p-code) is then interpreted by the run-time machine language program. This approach to compiler design allows IC to offer the following design tradeoffs:
- *Interpreted execution* that allows run-time error checking and prevents crashing. For example, IC does array bounds checking at run-time to protect against programming errors.

- *Small object code*. Stack machine code tends to be smaller than a native code representation.

- *Multi-tasking*. Because the pseudo-code is fully stack-based, a process’s state is defined solely by its stack and its program counter. It is thus easy to task-switch simply by loading a new stack pointer and program counter.

IC includes a full library of math functions, servo and DC motor control, analog and digital sensors, and is supported on PC, Macintosh, and Unix workstations.

Actuators and Sensors

The actuators used in our LEGO robots are an radio-control (RC)-style servomotor (often used for steering), and small DC motors for drive. Infrared reflectance sensors are used for detecting the black tape during maze-following.

Servo Motors

Servo motors incorporate several components:

- A small DC motor
- Gear reduction for torque multiplication
- Electronic shaft position sensing and control

A servo motor has three wires, power, ground, and control. Most servo motors operate from six to nine volts.

The control signal consists of a series of pulses that indicate the desired position of the shaft. Each pulse represents one position command. The length of a pulse in time corresponds to the angular position. IC allows direct specification of position in degrees or radians using the `servo_deg(float angle)` and `servo_rad(float angle)` functions.

DC Motors

Small DC motors are usually used for driving the robots. In selecting a motor, students must confront the issues of speed vs torque, operating current (L293s can deliver 1A), and voltage. RC car motors and the like work well. Small 3.5V “toy” motors are extremely noisy and should not be used.

IC and the Handy Board have provision for pulse-width-modulation (PWM) operation of DC motors, with seven levels of duty cycle. Matching the motor to the gear train is one of the most important engineering design issues of the robot, and it is obvious during robot testing if this is done poorly.
Sensors

Infrared reflectance sensors consist of two discrete devices, an infrared LED emitter and an infrared phototransistor receiver. The receiver and emitter are matched in wavelength, and are in a single package.

The emitter is powered by the Handy Board’s 5V supply, and the receiver collector voltage is read by the Handy Board analog inputs. Experimental determination of a threshold value is required for detecting the black tape on a white background.

The Day of the Competition

The LEGO robot competition is held on the last day of class, in the Mechanical Engineering building atrium. Local print and TV media are invited. Robots compete “head-to-head” until batteries are exhausted. The large crowd, enthusiastic competitors, and media presence make this an enjoyable spectacle.

Although there is a winner of the competition, the students are judged more on the quality of their engineering design and documentation than on the performance of their robot. However, there is usually a correlation.

![Figure 3: A LEGO robot using a conveyor ball delivery system.](image)

There are a variety of robot designs. Figure 3 shows a robot using a conveyor belt to deliver the ping-pong ball in the box. While this design was ingenious, the conveyor approach was unnecessarily complex, and was not reliable. Alternative mechanical delivery systems performed better, and this lesson was not lost on the students.

A robot using a differential drive system is shown in Figure 4. This robot used two front drive wheels, but the team recognized the need for differential speeds during cornering. A differential can be built using LEGO parts, and this is shown in the figure. A small spring (not easily seen)
made this a “limited-slip” differential and improved traction. The rectangular infrared sensors can be seen above the differential in Figure 4.

Figure 4: A differential drive system.

Summary

The LEGO robot course in the Department of Mechanical Engineering at UNM serves as an excellent example of mechatronic design, where digital electronics, computer control, and mechanical design are brought together in a single project. The experience of bringing a design from concept to working prototype is one all too few students experience, and is valuable preparation for subsequent education or employment.

3. Handy Board WWW site:
   http://1cs.www.media.mit.edu/groups/el/projects/handy-board/

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