Combatting Ad Hoc Fabrication in a Senior Level Mechatronics Course

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Mechatronics is a popular elective offered to mechanical, electrical and computer engineering students at Roger Williams University. The course format, in use since 2006, challenges students to build a robot 'from scratch' to accomplish an autonomous mission on a tabletop playfield. In the instructor's experience, students without restriction will employ ad hoc fabrication, i.e. free-form construction of robots without advance design or planning, using trial and error experimentation as the primary guidance for design decisions. After presenting an overview of the course structure, this paper will discuss the instructor's multi-year attempts to combat ad hoc fabrication. In the first instantiation of the course, students were permitted to use any materials or techniques, so long as the robots accomplished the mission autonomously. Although this approach generated a delightful variety of clever and fanciful robots, little of their activity could truly be called "design'. Terms more cogently describing the activity might be "tinkering" or "cobbling together". The instructor has repeatedly attempted to modify course structure and requirements to encourage the employment of careful pre-planning and computer aided design. Many of these attempts failed, produced mixed results or were entirely counterproductive. This paper will describe these attempts and the results each produced, then describe the instructor's current thinking and course structure. The current structure is an improvement; but is not completely successful in combatting ad hoc fabrication.

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Introduction

Roger Williams University offers a Bachelor's of Engineering degree with specializations in computer, electrical and mechanical engineering, plus a computer science degree, all within the School of Engineering, Computing and Construction Management. A heterogeneous population of students in these majors take Mechatronics [1] as a senior level elective. The objectives of the course are similar to many similarly named courses: [2-6] electromechanical sensors and actuators, supporting control and power circuitry and software for embedded microcontrollers.

Prior to 2006, the course was titled Robotics and covered robot kinematics, dynamics and programming typical of similarly named courses. In that year, the fixed base serial link manipulator was abandoned in favor of smaller, autonomously navigating vehicles with on-board sensors and embedded microcontrollers. Although the microcontroller has evolved from the PIC, to the iSTAMP to the Arduino, the functionality and role of the microcontroller has changed little since 2006. Likewise locomotion by small DC gear motors with H-bridge control circuitry and manipulation by Hobby Servo motors has changed little. The use of phototransistors, potentiometers and contact switches as sensors has also varied little. What has dramatically changed over the history of the course are the mechanical fabrication techniques employed to physically construct the robot.

This paper will therefore primarily discuss the evolution of the mechanical design process employed in the course. The following details are presented to allow the reader to understand the context and administrative structure of the course.

- The course is a 3-credit elective meeting twice weekly for eighty minutes.
- The population is strictly limited to fifteen students each semester working in six teams of two and one team of three students.
- The course meets in the electronics laboratory and utilizes laboratory equipment such as

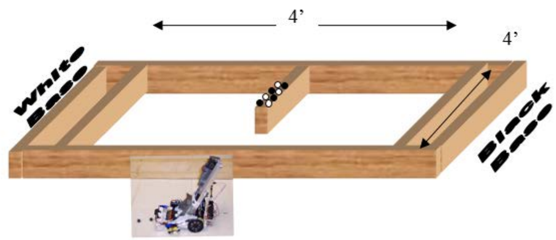

Figure 1 Image from the design project assignment document, fall 2015.

multi-meters, oscilloscopes and bench power supplies during most meetings.

- The instructor lectures on the underlying electronic theory for part of each lesson and then guides the students through a series of hands-on laboratory experiments.
- The primary graded activity is a full-semester design project in which students must use the introduced technology to construct an autonomous robot to perform a given task.

Design Project

Early in the semester, students are presented with the requirements of the design project. The scale and context of the design project can be gathered from Figure 1, the fall 2015 design project. Students must develop a small autonomous vehicle to navigate the desktop playfield shown and accomplish some task. Task specifics vary each semester, but always involve sorting white and black objects and moving each to their respective base. Objects have been marbles, ping-pong or wood balls, located on the rails, in some container or distributed on the field, sometimes with additional obstacles on the playfield. The vehicle must always perform the task autonomously with no assistance from the students. Student modification of the playfield is limited to placing black or white electrical tape anywhere for detection by light sensors.

In the instructor's experience, a single high-stakes competition at the end of the semester is not effective pedagogy. This approach often leads to procrastination followed by eleventh hour crash sessions in which student groups redesign their robot perhaps three times in a seventy-two hour period. In addition, the most conscientious and well-prepared groups can do everything right and simply have an electrical or mechanical breakdown that day. Objective grading is a nearly impossible under these circumstances.

To address these issues the course has employed objective milestones since 2010. These milestones are hard deadlines by which the robot must demonstrate necessary, but not sufficient, capabilities for completing the design task. For example, by the fourth week of the semester the robot must be capable of navigating the playfield as demonstrated by touching the left and right base rails and returning to base. By the eighth week the robot must be able to distinguish a black object from a white object, although it need not do anything else with the object. Although the final competition is important, the student's grade in the course depends more on the completed milestones than the final competition. By the use of milestones, students are compelled to follow a natural path of gradually increasing robot capability.

Robot Fabrication

In the first offering of the course in 2006 the naïve instructor placed no restrictions whatsoever on the fabrication of the robot. Students were issued a working base robot from an off-the-shelf kit (visible in the lower part of Figure 2) and permitted to modify and/or supplement the kit with any materials they provided. The instructor had

Figure 2 Fully Ad Hoc Fabrication in 2006.

imagined the students would supplement the base frame with perhaps small hobby servo actuators and maybe one additional wheel. To the instructor's surprise, students completely disassembled the base robot (sometimes just scavenging parts), and constructed fanciful concoctions of wood, sheet metal and hot glue (see Figure 3). These robots were incredibly time consuming to develop and often entertaining to watch, but few of the many hours the students spent could honestly called design. Students were happily slapping together contraptions through trial and error, a task that certainly involved creativity; but hardly any skills learned in four years of engineering coursework.

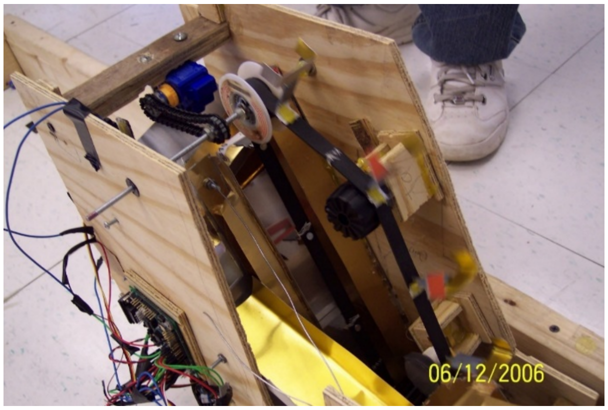

Figure 3 Wood, metal and hot glue construction.

Faculty colleagues offered a valid criticism of the course. Students were enthusiastically spending all of their time constructing these robots, conservatively six to seven credit hours of work for a three credit course. This naturally diminished student performance in competing courses and drew the ire of faculty colleagues returning from lectures delivered to sleeping students. Some faculty colleagues even banned the word ‘mechatronics’ from being mentioned in their classes. Although it is tempting to suggest that students working hard is always a good thing, it is the responsibility of the faculty teaching in a carefully constructed engineering program to ensure that three-credit courses require about three credit hours of effort. It is simply poor course design when students devote more than twice that effort, even if the students themselves are happy to do so.

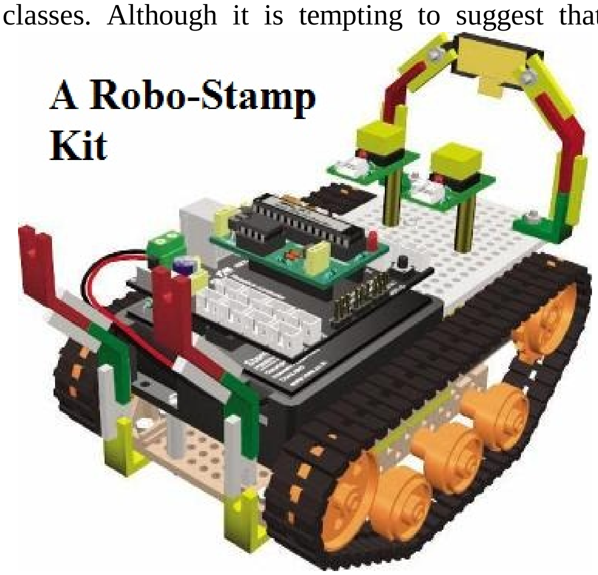

Figure 4 Starting kit used in 2008 and 2010.

For the next offering of the course in 2008, the instructor attempted to limit the variations in the design by introducing some restrictions on the robot. Again, students were provided an off-the-shelf base robot kit, shown in Figure 4, but this kit had more potential for building onto the structure with the material provided in the kit. The instructor introduced a restriction that the robot use a maximum of 12 AA batteries as its only power supply. Wood was disallowed and the robot was limited to fitting in a sixteen-inch cube. These restrictions produced the observable result of reducing the total time spent in fabrication, as students were no longer running out to purchase materials and were not attempting far-fetched designs such as helicopters, hovercraft and vacuum cleaners. Nonetheless, they continued to find the base robot kit inadequate for completing the mission and discarded the structural materials, salvaging the motors, wheels, sensors and CPU. The resulting robots (see Figure 5) resembled each other to a greater degree than the prior offering, but were no less the result of ad hoc fabrication. Figure 5 shows hot glue construction of bent metal, hair

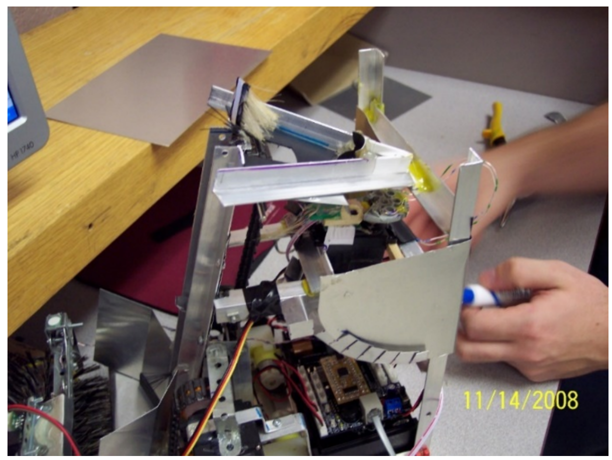

Figure 5 2008 Robot with some restrictions on materials.

brushes, Lego pieces and the original treads of the robot kit used as a conveyor belt.

In the following offering, fall 2010, the instructor attempted to improve design practices by introducing relevant course content. The instructor delivered lectures on the topic of mechanical design and presented tutorial videos as shown in Figure 6,

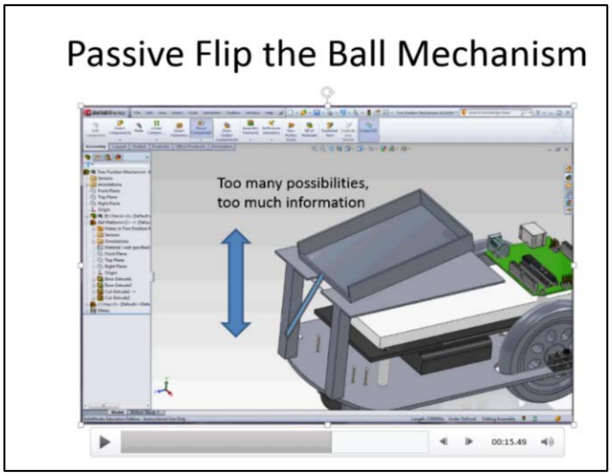

Figure 6 Tutorials and case studies in design.

with case studies and design primers such as shown in Figure 7. However, although the students attentively listened to the lectures, the instructor noticed few instances where the students actually

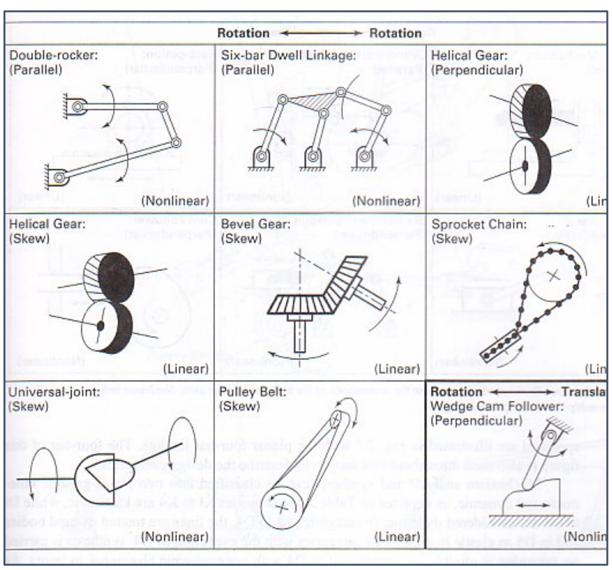

Figure 7 Representative design primer content.

put the information into practice. On questioning, students would confess that a more solid design was “a good idea, but right now they don’t have time”.

As in the prior offerings, students who arrived with prior fabrication and tinkering experience predictably outperformed students with none. As can be seen in Figure 8, the robots were still fanciful contraptions of wires, metal and plastic concocted out of the materials at hand. Concluding that the mechanical design lectures had no effect on the outcomes, the instructor discontinued these and began to consider employing non-voluntary measures to improve student design practices.

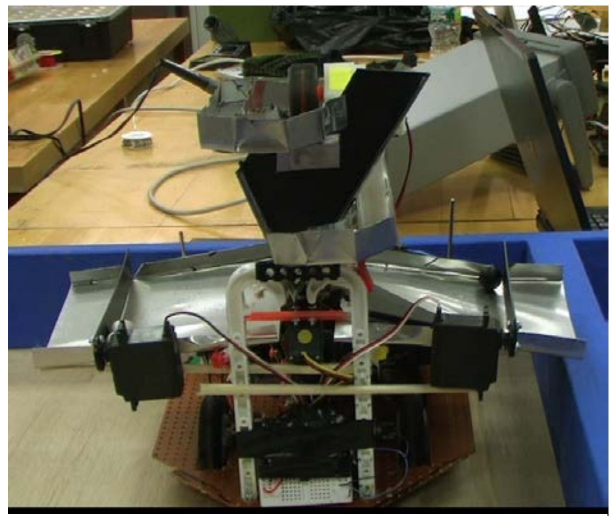

Figure 8 Winning robot in 2010 showing no reduction in ad hoc fabrication.

The instructor introduced an entirely new fabrication scheme in the subsequent, 2011 offering. Rather than supplying students a robot from an off-the-shelf kit, students would fabricate the starter robot (similar to Figure 9) from raw materials. A one-credit laboratory was added to the class, and in this laboratory students would learn three-dimensional fabrication using MasterCAM and a numerically controlled mill.

The robot base plate and breadboard support plate were cut of 1/8” thick PVC sheets on the numerically controlled mill using a 2D tool path, a mill bit and a drill bit. Bearing blocks were fabricated in 3D using nylon stock and a steel shaft coupler was fabricated in 3D from steel stock. Students were provided the G-code for these parts and were therefore required only to physically perform the fabrication. This was itself a valuable educational experience for the engineering students, although a very time-consuming process.

The naïve instructor expected that once students experienced firsthand the power of CNC fabrication they would naturally adopt it. Students started the process in good faith, adding features to the base robot first in SolidWorks and then using MasterCAM to produce parts on the milling machine. Some of the challenges of this fabrication scheme were:

- MasterCAM is a complex program requiring a great deal of training even to make the simplest part.
- There is considerable time spent physically setting up the CNC mills and executing the program.
- RWU machines have limited travel (5 ¾") in one direction. Groups desiring larger parts needed to fabricate in two passes, carefully remounting the piece in between passes.
- 3D fabrication was 'beyond the pale' for the students who limited themselves to fabricating 2D parts.

Once pressed for time and no longer explicitly required to fabricate parts on the milling machine, students gradually switched to ad-hoc fabrication. In some cases, students verified a design concept with an ad hoc robot and then used SolidWorks & MasterCAM to cleanly produce a final design. As seen in Figure 10, the winning robot was fabricated from gray PVC, clear acrylic and aluminum flashing based on a SolidWorks model (shown in the inset). This was regretfully the exception, the majority of students used the ad hoc test robot as their final demonstration robot. Mechanical failure set the students back hours and sometimes days, and in some cases caused the complete failure of the robot to move. Although there was a valuable lesson to be learned that slipshod fabrication produced unreliable parts, the price for this lesson was too dear in the context of this course.

The subsequent offering the instructor attempted to correct some of these issues by simplifying the robot, particularly in the drive train. For the first time, Lego® components were incorporated, (see the drive train in Figure 9), greatly reducing the fabrication time and also improving reliability. The starter robot only required NC fabrication of the base plate and the breadboard support. This fabrication was accomplished within three weeks of the semester so that by the fourth week all groups had a working base platform capable of navigating the playfield. These modifications showed some results in improving student design practices. Some student groups retained the base platform and only added components on top. These components were often the products of ad hoc fabrication. A larger number of student groups designed a completely custom robots with no option but to use SolidWorks as the only means to generate the tool paths necessary for CNC fabrication of the components. The resulting robots, (winning robot shown in Figure 11) could more readily be described as hybrid fabrication, with some complex components fabricated by CNC augmented with ad hoc components. Students were still hand-fabricating components from aluminum flashing and hot glue.

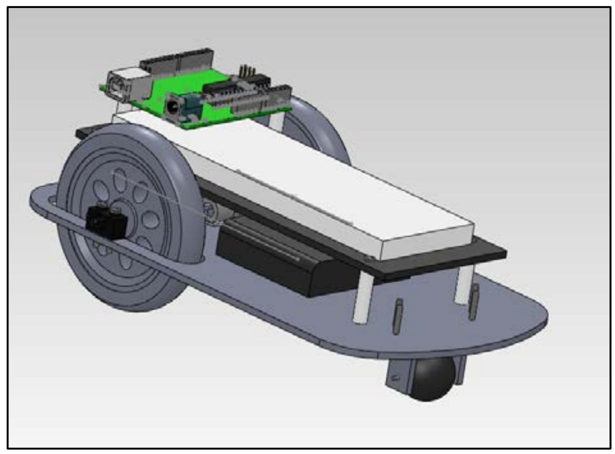

Figure 9 SolidWorks model of base robot beginning in 2011. Figure shows the 2012 version incorporating Lego® parts.

In this offering students were first required to submit SolidWorks models of their completed robot. The naïve instructor hoped that students would decide they "might as well use SolidWorks" since they had to submit the model anyway. However, few if any students were so inclined. Rather, students would continue ad hoc fabrication and then after-the-fact constructed the SolidWorks model to match their hand fabrication. They naturally considered this after-the-fact modeling busy work, as it was indeed labor expended for no discernable benefit.

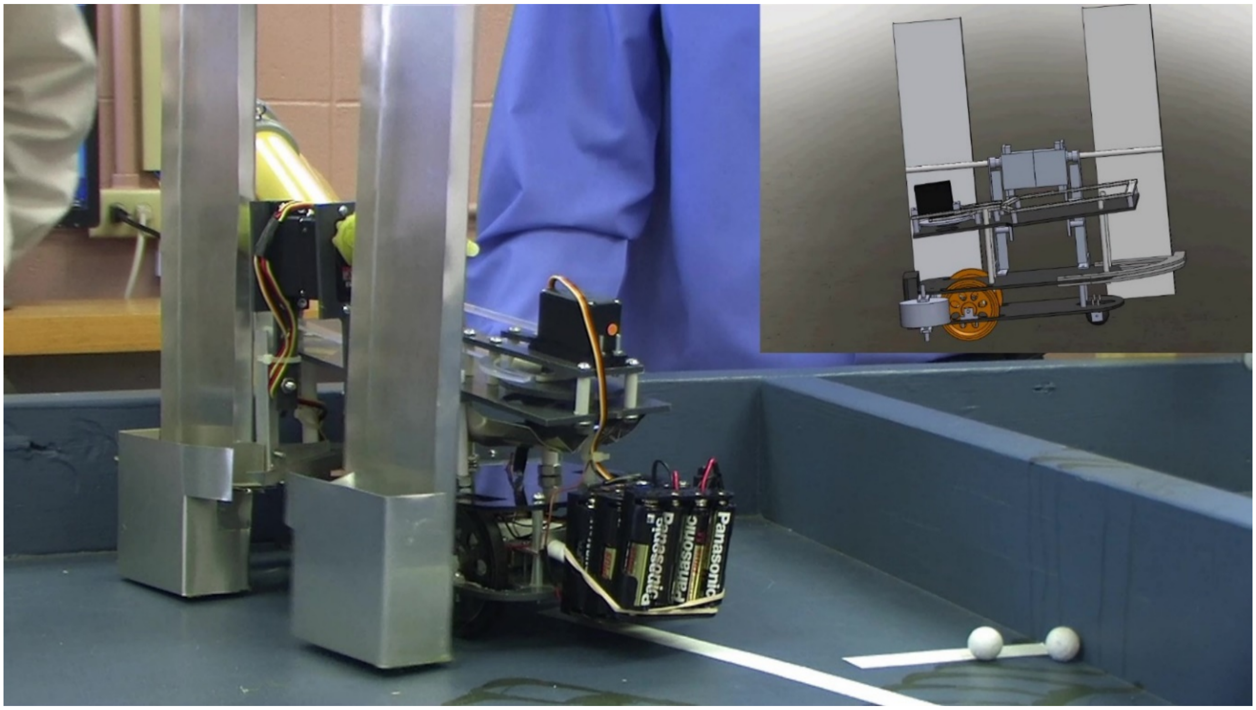

Figure 12 Fabrication in 2011 using SolidWorks and MasterCAM.

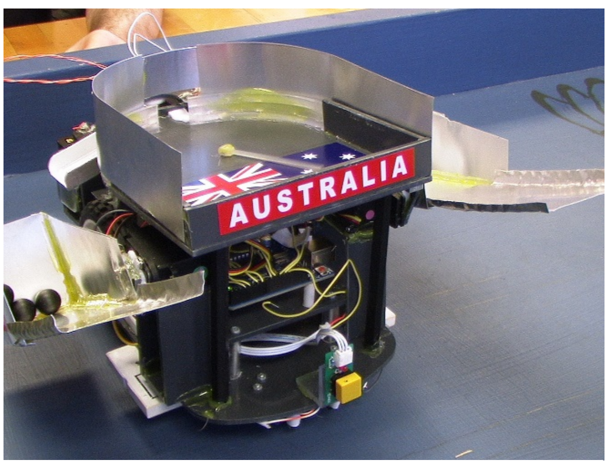

Figure 10 Robot in 2012 starting from simplified base platform.

Sensing some progress, the next offering the instructor introduced stricter requirements that the constructed robot must match the SolidWorks model. Students were required to present a matching SolidWorks model before demonstrating their robot at each milestone demonstration and before the final presentation. These restrictions were worse than ineffective. Not only did most modeling still happen after the robot was constructed, the administrative restrictions just

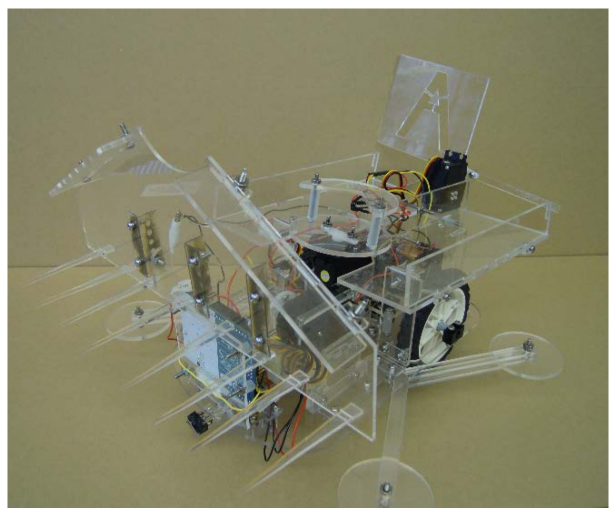

Figure 11 Robots fabricated from laser-cut acrylic.

encouraged the students to spend their time concealing this fact. The time required for NC fabrication was still a prohibitive factor preventing its wide employment. The resulting robots were not significantly different than the prior year, so no representative image is included.

Witnessing that administrative restrictions were ineffective, the instructor concluded that only direct

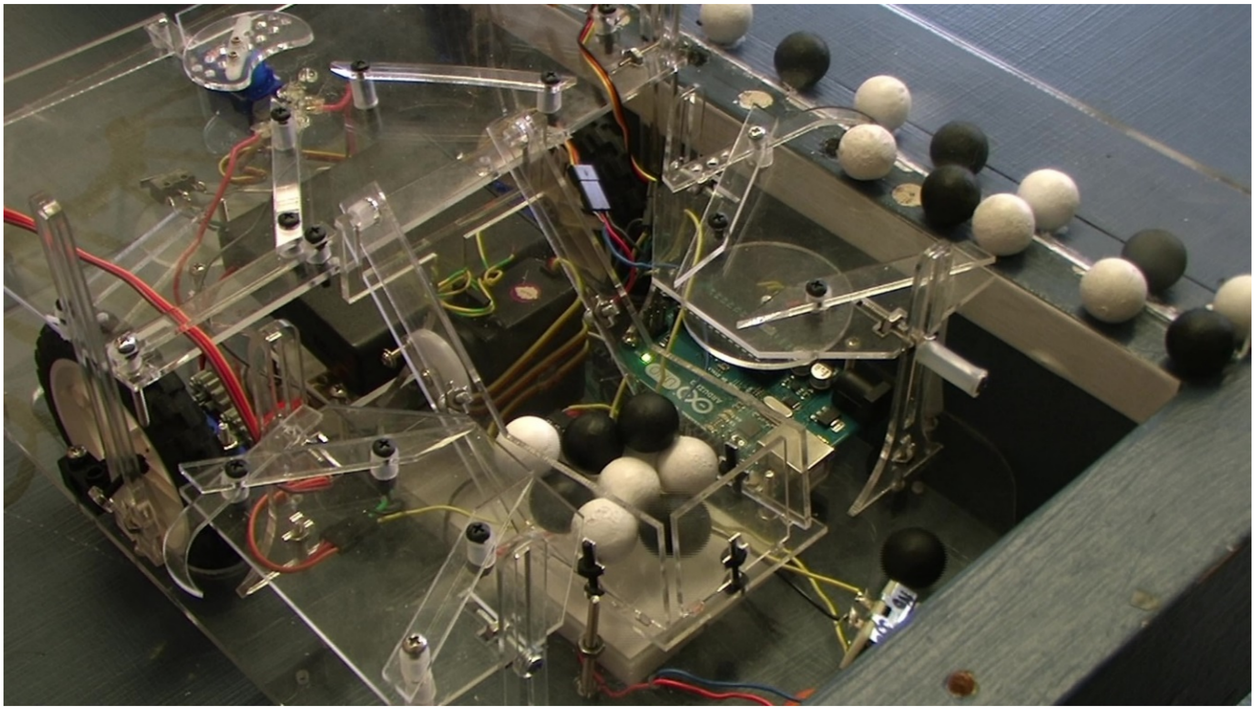

Figure 13 Most recent robot fabricated fall 2015.

self-interest could motivate the students. In the 2014 offering the instructor revised the course yet again. This time, student were provided a complete but disassembled starter robot at the beginning of the semester. CNC machining of PVC was replaced with laser cutting of cast clear acrylic. Laser cutting is orders of magnitude faster than NC machining. All of the pieces of a complete robot may be fabricated in about 30 minutes. This acrylic also has the desirable property that it is virtually impossible to shape manually. It is readily drillable by small drill bits, but will shatter on any bending, cutting or sharp working. It is therefore very challenging to make usable parts by any means other than laser cutting.

By the 2013 offering, robots were made predominantly of acrylic produced from SolidWorks models. As can been seen from Figure 12, robots are the result of cleaner fabrication and more advance design. This innovation dramatically advanced efforts to discourage ad hoc fabrication, but some challenges remained. Students were only provided rather weighty 1/8” thick stock, so some groups employed the practice of drilling numerous holes in the completed pieces to reduce weight,. This problem was remedied in the subsequent offering by providing the students both 3/32” and 1/8” thick stock, incidentally creating an interesting design parameter for students to consider.

A problem remained that students had the opportunity to use SolidWorks as just a faster form of ad hoc fabrication. When pressed for time, students can sketch quick 2D contours and readily fabricate these shapes using the laser cutter, skipping the step of fitting the part into the 3D model.

One telltale sign indicating the course had not quite eliminated ad hoc fabrication is the prevalence of hot glue. Students are doing more advance design in SolidWorks than in the past, but still stop once they have the overall shape defined and leave the details for on-the-spot adjustment. As a positive development, students discovered the benefit of prototyping designs using discarded chipboard from the architecture school. Most robots are now rapid prototyped in chipboard before final fabrication in the relatively expensive acrylic. As a natural result, designs are close to final before fabrication in acrylic and the robots show few visible signs of ad hoc modification.

Starting in fall 2015 the instructor began limiting the use of glue to fasten members. Glue was at first limited to small dabs to secure wires and electronics to acrylic, but this just caused students to work energetically to stretch and circumvent this restriction. The result was predictably farcical; with the instructor acting as the "glue police" inspecting structures for any unauthorized application of glue. Unsatisfied with this process, the spring 2016 offering, at the time of this writing, bans altogether the use of glue. This is a far from perfect solution, as there are instances such as securing a small transistor to acrylic, where glue might be the best choice. Figure 13 shows the most recent robot from the fall 2015 semester. This robot was primarily designed in SolidWorks prior to fabrication. Note the inset fasteners securing the sheets of acrylic, slots for adjustable positioning and the use of two thicknesses of acrylic. Also note the robot shows few visible signs of ad hoc tinkering.

Conclusions

Mechatronics is a mature course at Roger Williams University that will likely be offered to an eager population each semester for the foreseeable future. The core content of the class has changed little in a decade of offerings: students dissect motors, wire up electronics, write real-time software and build a mechanism bringing all of these together.

This paper relates the history of mechanical fabrication in the context of this course. Although not intended as a mechanical design course, the instructor has attempted to limit the employment of ad hoc fabrication techniques for the mechanical components. To this end, the instructor has employed a variety of strategies, most of these unsuccessful. The instructor found that encouragement, instruction and moral authority had little effect on student behavior. Likewise, most forms of administrative restriction proved counterproductive. It seems that only when students perceive that it is to their direct and tangible benefit to employ advance design will they begin to do so. Even in these cases, the shortcuts available via ad hoc fabrication are a continuous temptation.

The greatest progress the instructor can report came through the somewhat accidental employment of material that is impossible to work by hand. This combined with the rapidity of laser fabrication produces the environment where SolidWorks is the fastest means of fabrication at the student's disposal. The temptation still remains to use SolidWorks as a quick way to stamp out parts to be used in ad hoc fabrication. The instructor is currently struggling with this issue. The most recent iteration of the course bans the use of all glue, and this semester will help determine if this is yet another restriction to be circumvented or a motivation to employ good design practices. The instructor hopes to report the results in future meetings.

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