



Programming Printers Printed by 3D Printers

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Gavin Garner holds a bachelor's degree in Physics from Colby College and Master's and Ph.D. degrees in Mechanical and Aerospace Engineering from the University of Virginia. His primary area of expertise lies in the burgeoning field of mechatronics (aka robotics). Over the past decade, he has built UVA's mechatronics program from scratch, developing over 50 hours of unique laboratory experiments as well as dozens of open-ended design projects. Through this experience, he has gained valuable insight into how to engage engineering students and teach them difficult, interdisciplinary material both efficiently and effectively. He was named a "Graduate Teaching Fellow" by the American Society of Mechanical Engineers from 2007-2009. Since then, he has won numerous other teaching awards for his creativity and dedication to student learning. He is especially interested in updating traditional mechanical engineering courses to better integrate the modern tools and techniques used to solve today's design problems in industry.

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Abstract

Mechatronics is a burgeoning new field that involves the synergistic integration of mechanical, electrical, and software engineering in the design and manufacture of industrial products and processes. It represents the modern evolution of traditional mechanism design techniques. Mechatronics proves to be a difficult subject to teach because it inevitably requires mechanical engineering undergraduate students to delve into realms and concepts with which they are inherently less comfortable. A primary pedagogical challenge associated with the teaching of mechatronics relates to devising new teaching styles and methods that seamlessly stitch together these traditionally separate engineering disciplines within the coherent context of modern mechanism design.

Presenting students with hands-on laboratory experiments and open-ended design projects has proven to be an effective way to encourage them to synthesize the concepts that are covered within the traditional lecture environment. It is important to give students as much creative license as possible throughout this learning process. The more pride and agency that students can instill into their own unique solutions, the more invested and dedicated they become to working on the project.

This paper specifically examines the development and successful implementation of a novel, final design project within a survey Mechatronics course that is taught each year to around a hundred 3rd-year Mechanical Engineering majors at the University of Virginia. A fleet of 2D ball-point-pen plotters, called “HooPrints,” were designed and constructed out of plastic parts formed using state-of-the-art 3D printers. Students were then given blank 3 x 5 index cards and two design objectives: 1) Develop a manual, fly-by-wire “etch-a-sketch” mode through which each member of their team must write out his or her initials as quickly and neatly as possible and 2) Program their HooPrint to automatically/autonomously draw something interesting (and sophisticated in terms of programming technique) in under two minutes.

Background

According to the American Society of Mechanical Engineers (ASME) and IEEE, Mechatronics is defined as “the synergistic integration of Mechanical Engineering with electronics and intelligent computer control in the design and manufacture of industrial products and processes.”^[1] In some ways, the word “mechatronics” has evolved to become technical jargon that embodies a new philosophy in engineering technology rather than simply a new technology in and of itself.^[2] It is clear that Mechatronics is not so much a new branch of engineering, but rather a new concept that addresses the integration and interaction between different branches of engineering.^[3] In many ways, mechatronics is simply the natural evolution of modern mechanism design. The burgeoning field of Mechatronics also includes the much more familiar field of robotics. A quintessential mechatronic system is one that includes a sensor sending information to a controller (typically an inexpensive microcontroller chip), which then, via software, decides how to move some form of mechanical actuator (typically an electric motor of some sort).

The recent and dramatic drop in the cost of microcontroller chips and the availability of “smart” actuators such as servo and stepper motors have revolutionized the way that engineers can now tackle mechanism design problems. Precision sensors and actuators have substantially increased the performance of machines well beyond anything that was possible in the past.^[4] No longer does one always have to devise brilliant kinematic linkage mechanisms to translate continuous rotation motions (from say a water wheel or induction motor) into precisely controlled intermittent motions. Instead, one simply has to program a computer to tell a smart motor when to move, in which direction to move, and exactly how far to move. While this simplifies design challenges in many ways (and also allows engineers to tackle much more difficult problems that would be virtually impossible using traditional techniques), it also complicates the design process by taking what was a problem that fell squarely into the traditional boundaries of Mechanical Engineering and cross-pollinating it with Electrical Engineering, and Computer Science. Thus, Mechatronics proves to be a challenging subject to teach since it inevitably requires undergraduate students to delve into realms and concepts with which they are less comfortable. In the Mechatronics course that the author has developed and taught at the University of Virginia (U.Va.) over the past five years, the primary challenge has been to teach 3rd-year Mechanical Engineering majors the basics of electronics and computer programming within the context of modern mechanism design.

A unique aspect of mechatronic systems that sets them apart from traditional engineering systems is their dependence on sophisticated real-time computation. This is what defines the nature of the engineering systems in which the computation is embedded. An organized approach to the design of the software for these computations is essential for a mechatronic system design to be successful.^[5] It is widely accepted that the most important aspect of mechatronics education is to provide haptic (hands-on) experience that allows students to gain an understanding of high level theoretical concepts as well as an in-depth appreciation of integration issues.^[4, 6, 7] Virtually all of the available literature agrees that the best approach to teaching mechatronics to today’s Mechanical Engineering students is within a laboratory environment in which students actually see mechatronic systems in action and experiment with them directly.



Figure 1: Dimension uPrint FDM 3D printers in the University of Virginia’s new Advanced Manufacturing Lab (all of the HooPrint’s custom parts were fabricated using these machines)

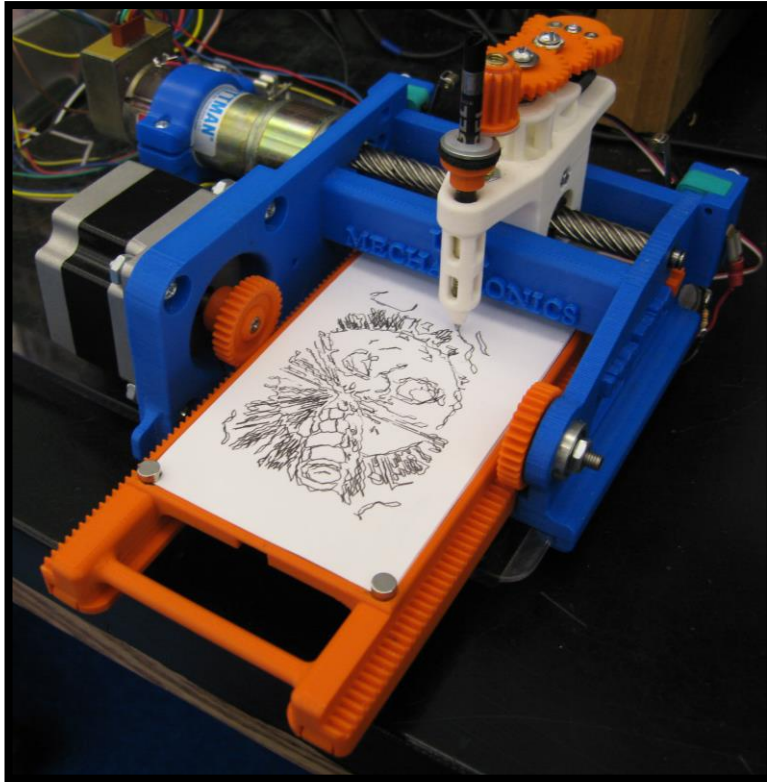


Figure 2: A picture of a HooPrint executing software code that a student wrote that prints out the “Trip to the Moon” image that was featured in the recent movie *Hugo*.

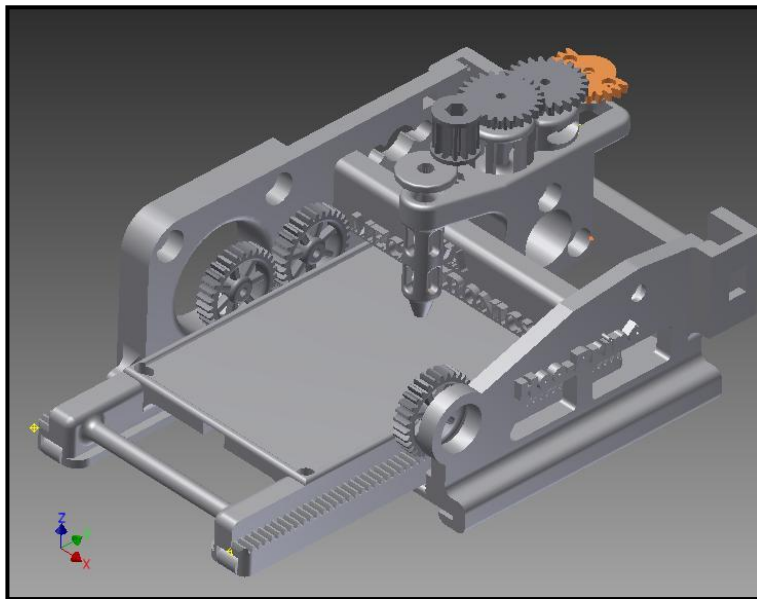


Figure 3: CAD model assembly of the custom 3D-printed HooPrint parts

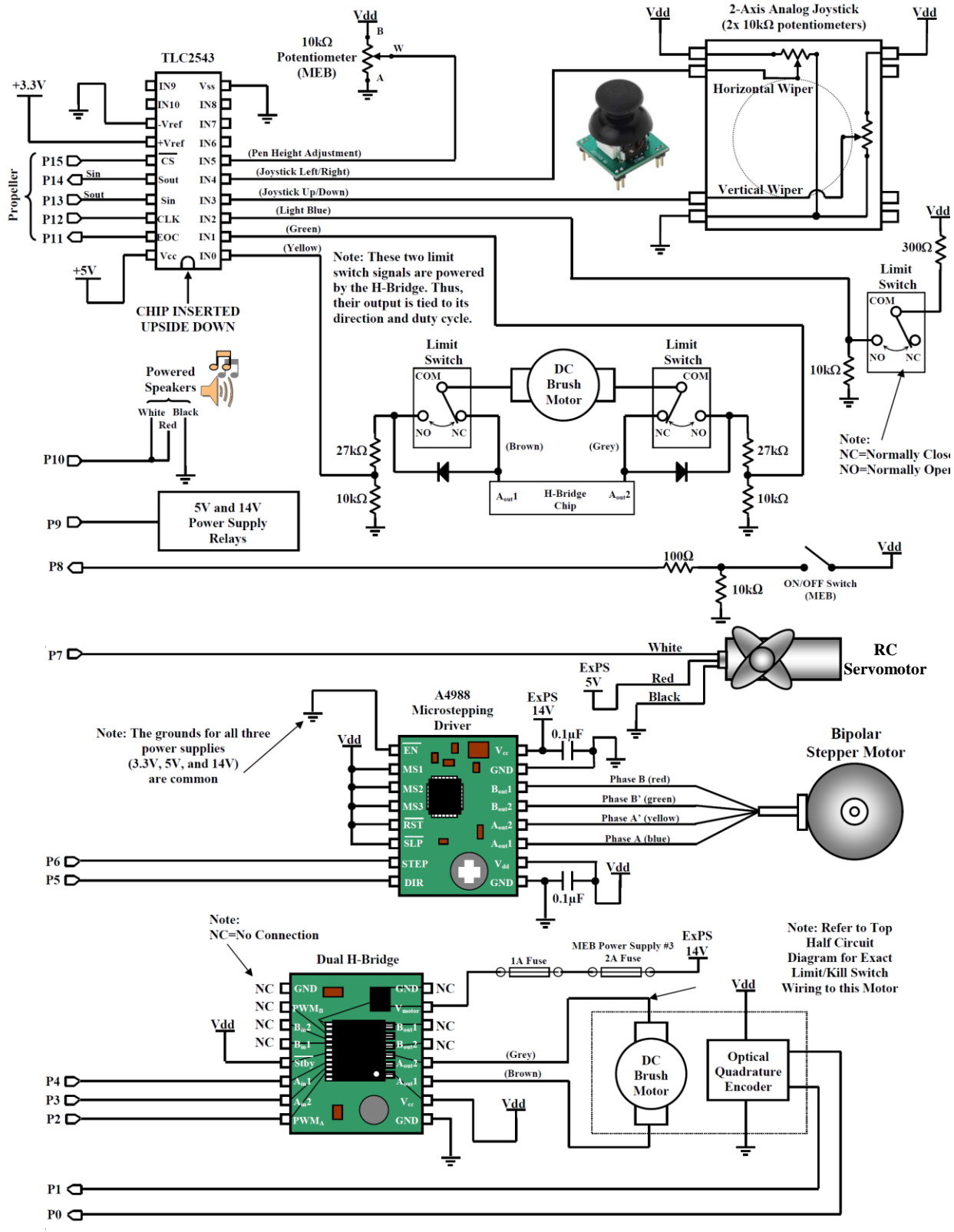


Figure 4: Circuit diagram of a HooPrint's control electronics and hardware peripherals



Figure 5: Some examples of actual (scanned) results of student project solutions

Another major technological advancement that is changing the way that mechanisms are designed is the recent availability of easy-to-use, three-dimensional rapid prototyping machines. This breakthrough technology is being hailed by some as the first stirring of an American industrial revival.^[8] Rapid prototyping machines are starting to appear in high schools and universities around the world. The author has recently convinced his university to invest in a fleet of fused deposition modeling (FDM) 3D plastic printers to be housed within the new U.Va. Advanced Manufacturing Lab. See Figure 1. This facility is unique in that it is dedicated primarily to undergraduate engineering education and has enough machines to accommodate the throughput required by large survey and design classes. Using these new machines and rapid prototyping techniques, the author was able to prototype a working HooPrint from scratch and print and assemble an initial fleet of seven HooPrints all in less than a week's time. Using traditional manufacturing techniques to design and produce custom learning tools such as a HooPrint would have taken months and cost tens of thousands of dollars. Furthermore, whenever a part broke during this project, all that the instructor needed to do was simply hit "print" again to fabricate a replacement part.

Design & Motivation

There are three primary types of "smart" direct current motors that are commonly applied to the design of most mechatronic systems: stepper motors, servomotors (brush or brushless motors with external encoders attached), and RC servomotors (common hobby motors wherein a motor, encoder, and controller come pre-packaged as a single system). Each type of DC smart motor is controlled in a very different manner and each one brings its own unique advantages and disadvantages to a mechatronic system design. The HooPrint uses a standard ball point pen whose X, Y, and Z-direction motion is controlled by the aforementioned three common types of smart motors to draw things on a standard 3 x 5 index card. See Figure 4. Thus, this HooPrint project allows students to juxtapose the nuances of each of these three types of smart motors and forces them – in a fun way – to master how to control all three.

The author has spent the better part of the last decade helping to develop a unique Mechatronics program at U.Va. from scratch. For the past five years, he has personally taught a survey course in Mechatronics that all 3rd-year Mechanical Engineering majors are required to take. The HooPrint platform was originally developed in the spring of 2011 as a final project for this survey Mechatronics course. It was then redesigned and improved to use again as a final project in this course during Spring 2012 semester. Each time, there were about a hundred students enrolled in the course. They were split into teams of two or three students and these teams shared the seven workstations in the U.Va. Mechatronics Lab. The author constructed and maintained a HooPrint at every workstation throughout the two-week duration of this final project so that, at any given time, there were at least seven active units that the hundred students could share.

Project Objectives & Teaching Philosophy

For this project, the students are given a blank 3 x 5 index card and two design objectives: 1) Develop a manual, fly-by-wire, "etch-a-sketch" mode through which each member

of their team can write out his or her initials as quickly and neatly as possible and 2) Program their HooPrint to automatically/autonomously draw something interesting and sophisticated in terms of programming technique in under two minutes.

The author has found that it is important to give students as much creative license as possible while challenging them with design projects. The more pride that students can take in their own unique solutions, the more invested and dedicated they tend to become to completing the project. The motivation that most students find in trying to show off in front of their peers far exceeds the motivation derived from simply threatening to give them a poor grade on the assignment if they do not work hard on it. Unfortunately, the more open-ended a student design project is left, the more resources are usually required to complete it effectively. Resources not only include the cost of expensive, expendable materials but also the time that the instructor and teaching assistants must dedicate to helping and coaching students through difficulties. The HooPrint project was developed to be an efficient compromise through which students learn the primary pedagogical objectives yet still maintain a sense of agency and comfort in the fact that their solution is unique and undeniably their own creation. Figure 5 depicts some examples of the solutions that students have printed on HooPrints as their final project submissions. Every student team's submission is undeniably unique and creative.

Project Assessment & Conclusions

Each year, at the end of this final project, the author has personally interviewed every student individually for 10-15 minutes each to quiz them on the details of their project solutions including their understanding of the unique software code that their team has developed, the function of *all* of the hardware and circuitry they have implemented, and the general mechatronic concepts that were covered in the course that related to this project. Students were therefore tasked with the challenge of reverse-engineering all of the circuits (Figure 4) and mechanisms at work in their HooPrint.

The author has performed individual interviews of all of his students at the end of other open-ended final projects in previous iterations of this course. There has been an obvious improvement in the students' general understanding of course concepts and their level of involvement in this new final project. Since the final projects have always held about the same amount of weight in terms of grading, it is assumed that the increase in student participation is a result of this project being carefully crafted to be fun and open-ended – encouraging creativity and innovation. The fact that students seem to learn much more through completing this project than their predecessors have with other similar final projects suggests that this HooPrint platform is a more efficient teaching tool.

The student feedback for this final project and the course in general has, on the whole, been excellent. Inevitably some students have complained that this final project takes too much of their time (especially during the final two weeks of the semester), but it is important to note that since this project is open-ended, students decide what constitutes an acceptable solution for themselves. They usually end up competing with each other and continue working until they are stratified with their results. Some students have even continued working on this project long after

their course grades have been finalized – just because they enjoy this fun and engaging challenge.

The author is currently developing a new iteration of this HooPrint project and will test it out as the final project for his Mechatronics course in the spring of 2013. The design is being simplified so that it is easier to print and assemble. Once all of the parts are perfected and optimized for manufacturability, all of the CAD files will be made freely available online (most likely through the popular website thingiverse.com). Once posted, anyone with an FDM 3D printer will be able to download and print their own HooPrints to use as a learning tool in their own Mechatronics courses. Thus this project may help to show the way toward a new era of teaching collaboration whereby educators around the world can easily share their custom-designed, 3D-printable teaching tools.

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