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Design and Development of a Pneumatic Bread Board and ”Sandbox” for Students in Mechanical Engineering Capstone Design

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Introduction

Many students entering senior design have never taken a fluid power course or worked with pneumatic circuits in any way. Most have only taken an introductory Fluid Dynamics course, and even those who have taken a fluid power course may not have any hands-on experience designing, testing, or controlling pneumatic circuits. However, there is a wealth of interesting and challenging design projects involving pneumatic circuits that can lead to rewarding careers in automation and controls. If left unfilled, this gap between student skill sets and project requirements will significantly limit what students can achieve on a design project and may prevent students from working on these types of projects altogether. This paper describes the development of a pneumatic breadboard and associated "sandbox" for students in a mechanical engineering capstone design course. The pneumatic breadboard, similar to an electronic breadboard, offers students the opportunity to build pneumatic circuits while the "sandbox" contains all of the common materials needed for these circuits. The breadboard and "sandbox" allow students to build common circuits to develop core knowledge, as well as custom circuits specific to their capstone design project. When building common pneumatic circuits, students are guided by instructor-developed tutorials with minimal, on-demand help from trained teaching assistants. These common circuits help students to develop lower levels of learning as described on Bloom's taxonomy, namely knowledge, comprehension, and application. While building these common circuits and developing their basic knowledge, students are also encouraged to explore and develop solutions to the open-ended problems they are encountering in their capstone design projects. By providing the opportunity and encouraging this side-by-side development, students can reach the higher levels on Bloom's taxonomy, those of analysis, synthesis, and evaluation. The bread board and "sandbox" design presented here was developed under faculty guidance as a senior design project, but ultimately, both will be continually used by future capstone design students who can provide feedback for continuous improvement and, if successful, provide a foundation for future hands-on pedagogical prototyping aids.

Course background and the challenge

The mechanical engineering senior design course at the University of Wisconsin – Madison is a two-semester sequence in which teams of four student engineers are tasked with designing a solution to a client's problem. In recent years, this course has grown to nearly 280 students, starts both in the fall and the spring, and supports a variety of projects, including industry collaborations, design competitions, research, and community service. The course is managed by a coordinator and supported by several teaching assistants (TAs) along with a host of faculty who consult with teams weekly, advising them on technical issues and basic project management.

As part of the course, we ask students to iteratively prototype, and to prototype often, as it is one of the best ways to evaluate a design [1], [2] and develop a more satisfying solution for a client. Prototyping is also highly engaging, especially for mechanical engineers, which is why we place a great deal of emphasis on it. Supporting students as they build, however, is particularly challenging in this course given the number and variety of the projects as well as the number and variety of instructors. In addition, senior design project time is limited and helping students maximize this time is critical to increase the number and quality of prototypes a student team can build. I propose there are two main actions we as instructors can take to help students build more prototypes with higher quality, and in turn help our students develop better solutions. The first is to provide students with educational equipment and instruction necessary to catalyze student effort. This is a time-consuming process that if left to students can significantly impeded prototype development. The second is to help students connect their prototyping effort to their domain knowledge, helping them to appreciate the interplay between the analytical and physical domains and how one can feed off and inform the other. By appreciating this, the hope is that students will better evaluate where and how to invest their time.

Identifying the need

To take the two actions described above, it's first necessary to identify common prototyping experiences students encounter while working on senior design projects. When identified, instructors can then develop appropriate equipment and instructional material to help catalyze student effort and connect prototyping effort back to domain knowledge. To help us identify common prototyping experiences, we challenged a senior design team, Bucky's Busy Builders, to engage with past and present design students. Through this work, they identified two main areas where student design teams were commonly asked to prototype and where student teams felt they could be better supported in their effort: 1) motors (and motor controllers) and 2) pneumatic circuits. The team decided that supporting the development of pneumatic circuits was the best path forward, not only because these typically involve several mechanical engineering disciplines (i.e., controls, machine design, etc.) but also because they felt the unknowns surrounding this equipment were a significant hurdle for a majority mechanical engineer students and that helping students overcome these barriers could lead to a wide variety of interesting projects for future students.

Once decided, the students embarked on the design process. They researched previous solutions, defined specifications, generated and evaluated concepts, and iteratively prototyped solutions. The remainder of this paper describes the requirements for the design and the final physical prototype.

Previous solutions and defining client requirements

Several commercial solutions for learning about pneumatic and hydraulic circuits exist on the market [3], [4], [5], [6]. They have different features and different support, but all attempt to help learners develop foundational knowledge. All are also prohibitively expensive and provided limited or no ability to prototype custom solutions. There are also several non-commercial trainers available [7], [8], [9]. All appear to be modeled on the commercial trainers and like, those, focus on the development of fundamental knowledge of pneumatic circuits. Like their commercial counterparts, these aren't designed to help learners develop custom circuits. Both commercial and non-commercial solutions help students develop lower levels of learning as described on Bloom's taxonomy, namely knowledge, comprehension, and application [10]. Developing these will undoubtedly help students accelerate prototype development, so they remain a requirement of our design, but there is more we can do. Specifically, we want to give students the opportunity to develop custom circuits as they are developing basic knowledge about the equipment. By doing so, students can begin to reach the higher levels on Bloom's taxonomy, those of analysis, synthesis, and evaluation. In addition, we want the equipment to help foster a sense of play [11] or at least playfulness, to spark student imagination and creativity.

Due to the varied nature of the projects in the course and the high degree of TA involvement, the general requirements just described must not mandate constant attention from instructional staff. That is, the solution must be primarily self-guided with targeted intervention by instructional staff as needed. In addition, we don't need an entire course in pneumatics, but something a student can engage with and get up to speed with in a relatively short amount of time, typically less than 6 hours, which is the weekly amount of work outside of lecture for a student in the course.

The pneumatics cart

The solution designed and built by Bucky's Busy Builders, shown in Figure 1, is a customized Milwaukee Tool 40" Steel Work Cart [12] that was donated to the senior design program by Milwaukee Tool. The customization consists of three main components: the breadboard, the control panel, and the sandbox. The bread board is the primary space for building pneumatic circuits. The control panel provides a mounting surface for air prep and electrical components. The sandbox, consisting of a drawer and storage space, is where all of the associate components and parts are stored for rapid prototype development. More detail on the design and construction of each component is provided below.

Figure 1: Bucky's Busy Builders pneumatic cart. The main components of the cart are the breadboard, the control panel, and the sandbox.

A top view of the bread board is shown in Figure 2. The main components are the 10 series 80/20 t-slotted aluminum extrusion, the DIN rail, and the manifold. The array of 80/20 is secured to a ¼ inch piece of high-density fiberboard (HDF) and provides a secure and adaptable mounting surface for pneumatic components and associated hardware. The arrangement of 80/20 shown in Figure 2 was chosen to provide the most mounting surface area and sturdiest base, but the layout and the HDF are both customizable. At the top of the breadboard is a DIN rail for mounting a variety of data acquisition and control hardware, including power distribution for solenoids and Arduino microcontrollers, instrumentation, custom circuits, PLC components, etc. The manifold is a custom 3D-printed structure that supports a variety of off-the-shelf components from Automation Direct [13]. It supplies up to 5 separate pneumatic circuits, each of which can be shut off and vented with a low-profile, manual 3-way control valve.

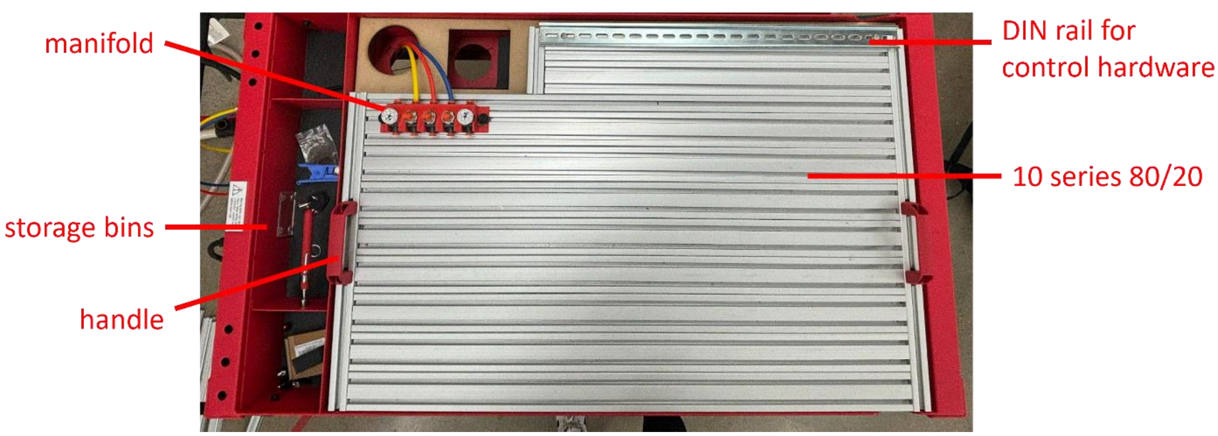


Figure 2: Top view of the breadboard. The main components are the 10 series 80/20 t-slotted aluminum extrusion, the DIN rail, and the manifold.

The breadboard is not mounted to the cart but is free standing. It is placed on two ridges that are built into the cart. The ridges create a 1.5” gap between the bottom of the breadboard and the top surface of the cart, allowing a convenient space for tubing and wiring to be routed. To facilitate the use of this space, the HDF supporting the 80/20 and the 80/20 itself are customizable. That is, both can be relatively easily changed to allow tubing and wiring to emerge from below the breadboard surface at virtually any desired location. A top view of the current HDF is shown in Figure 3 and consists of two penetrations, one circular and one square, as well as a 1” x 1” grid. The circular penetration was chosen to match the hole built into the cart and the square one was chosen to fit an optional bin should the penetration not be used. The HDF was cut with a laser cutter at the university’s makerspace. Handles are mounted to the sides of the breadboard to allow easy access to the space beneath the breadboard and the storage bins on the left-hand side provide a convenient space to store hardware and tools, including hexagonal wrenches and a commonly used tubing cutter.

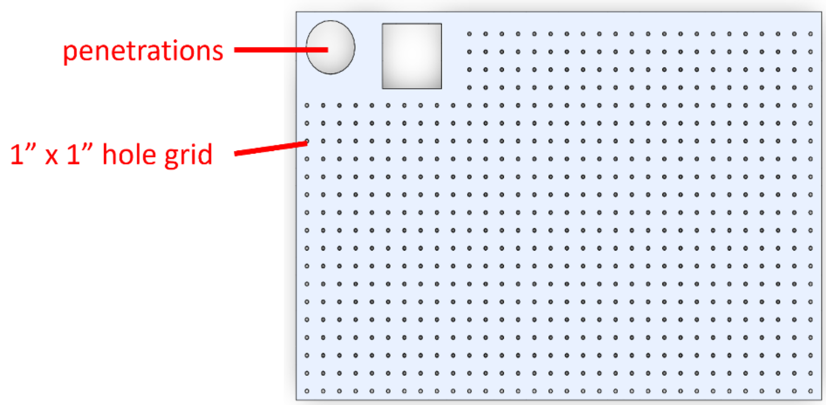
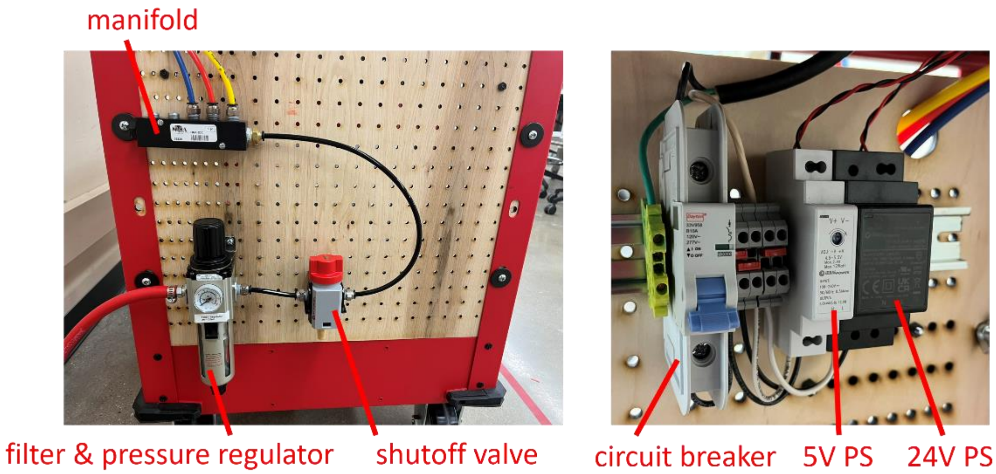


Figure 3: Top view of the HDF pegboard that supports the 80/20 rails.

The second major component of the pneumatic cart is the control panel, shown in Figure 4. The control panel provides two mounting surfaces, a front and a back. The front is used for mounting air prep components, including a combination filter and regulator, a shutoff valve, and a manifold, while the back is used for mounting power supplies for control and data acquisition. The control panel is currently sparsely utilized, allowing for future expansion and customization.



(a) (b)

Figure 4: Control panel (a) front and (b) back. Air prep and manifolding are mounted to the front of the control panel for easy access while 5V and 24V power supplies are mounted to the back. The remaining pegboard provides additional mounting space for future builds.

The final component of the pneumatic cart is the sandbox. The sandbox consists of a drawer and storage space beneath the deck of the cart (see Figure 1). The sandbox houses a number of common directional control valves, air cylinders, fittings, a variety of colored hoses, mufflers, control valves, standard hardware, and much more. This gives students easy access to commonly used components and standard parts so they can play [11] and build custom circuits for their design projects. The sandbox minimizes the need for ordering parts and reduces development time by providing students with examples they can quickly mimic to customize the cart to suit their needs.

To facilitate this play and development, the student team designed a simple, cost-effective, and adaptable solution for mounting control valves and cylinders to the cart. An example of one of these baseplates for a 3/2 directional control valve (DCV) is shown in Figure 5. The baseplate is a laser cut piece of acrylic that is bent into shape using a hot strip bender and a 90-degree rafter square to help maintain the part shape as it cools. The DCV is then bolted to the baseplate using the manufacturer's mounting holes. Note that the bend in the baseplate lifts the DCV from the 80/20 surface to accommodate the mounting bolt nuts (not shown). Through holes at the left and right of the baseplate provide a means to mount the DCV to the 80/20 using thumbscrews and drop-in t-nuts. The thumb screws and t-nuts allow components to be adjusted or replace quickly and without the need for any tools or access to the end of the 80/20. The acrylic sheet is relatively inexpensive and the laser cutting and bending can be done at the university's makerspace, thus allowing students to quickly and easily make changes if needed. A similar baseplate for a single-acting cylinder is shown in Figure 6. Note that the cylinder uses the manufacturer supplied mounting brackets to connect to the baseplate.

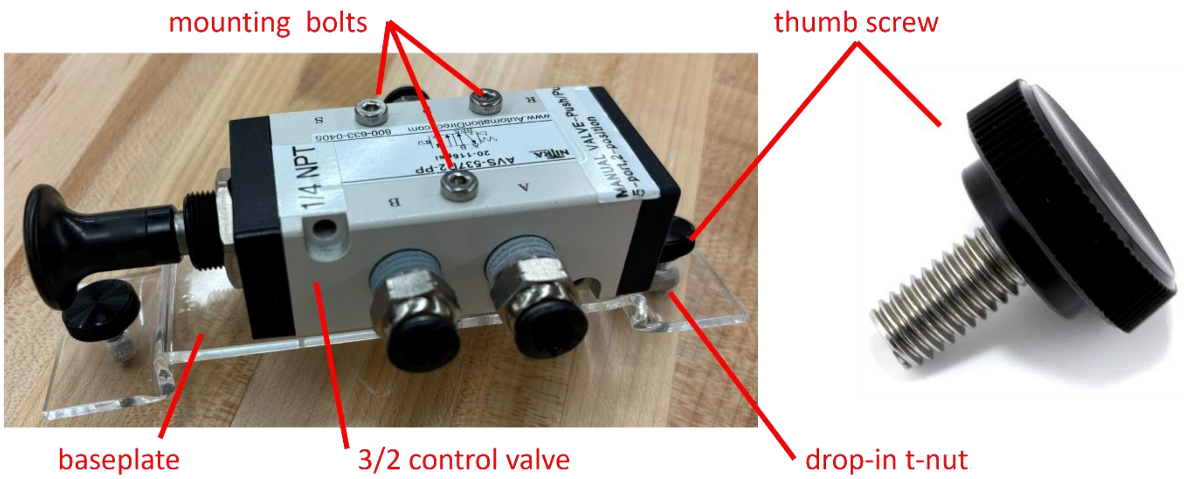


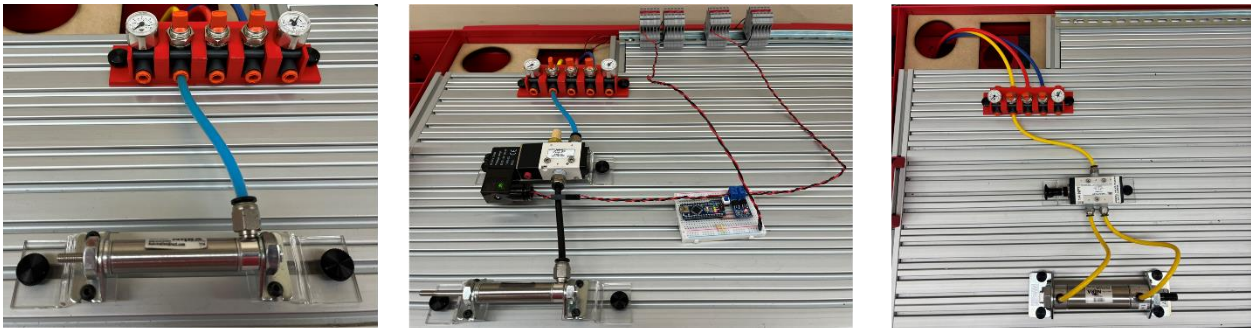
Figure 5: Directional control valve mounted to an acrylic baseplate with mounting bolts. Thumbscrews, and drop-in t-nuts are used to secure the baseplate to the 80/20 rail (not shown).

Figure 6: Cylinder mounted to an acrylic baseplate with mount, thumbscrews, and drop-in t-nuts.

Website

As noted earlier, the pneumatics cart needs to be design so students can use it self-guided with minimal instructor intervention. In addition, any solution should provide relevant background and theory to help students connect what they are building to their undergraduate domain knowledge. To facilitate this, a Google website was created as a repository for tutorials, a resource for applicable theory, and a guide to help students customize the cart to support their specific design project. The website can be found here: https://sites.google.com/wisc.edu/senior-design-pneumatics/start-here.

Once they have been given a short introduction to the cart with an instructor, including basic safety, students are allowed to begin tutorials. At the same time, they're encouraged to design and test their own circuits. Circuits for three of the basic tutorials are shown in Figure 7. The website also contains basic theory on pressure regulators, solenoid valves, cylinders, the dangers of compressed air storage, and a schematic tool to help students layout potential circuits and communicate their design to TAs, faculty, and clients. An example schematic is shown in Figure 8. Finally, the website contains information on purchasing new equipment, creating custom baseplates, as well as examples of design projects built by previous student teams. Figure 9 shows two such examples built by the design team to test out their cart. The long term hope is to continue to add to these examples as the cart gets used by future design teams.



(a) (b) (c)

Figure 7: Basic circuits built in tutorials: (a) single-acting cylinder with manual control, (b) single-acting cylinder with solenoid control, and (c) double-acting cylinder with manual control.

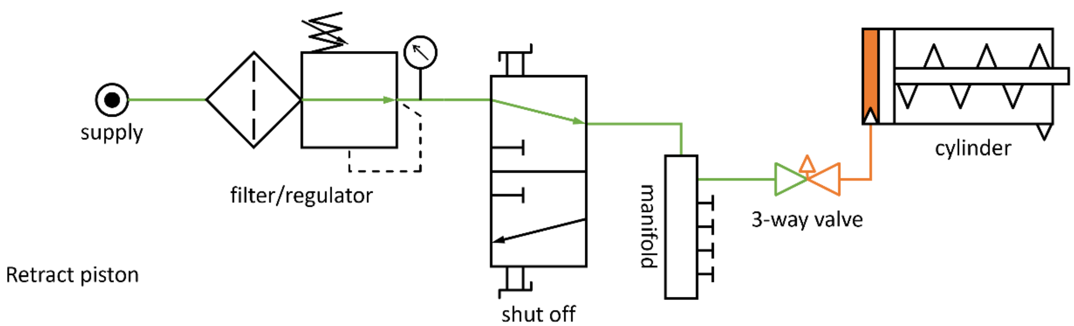
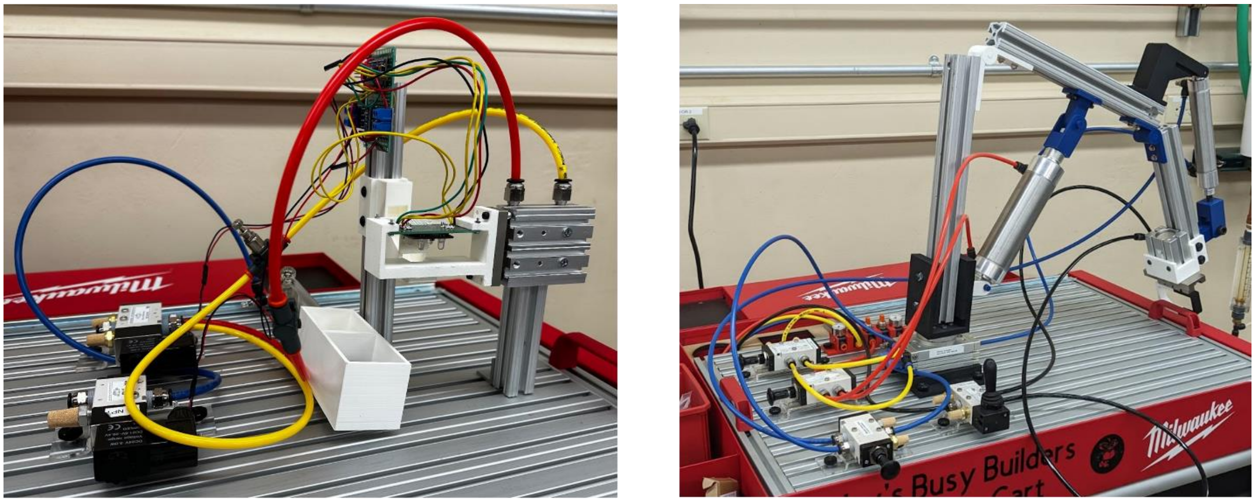


Figure 8: Schematic example of a single acting cylinder in the retracted position.



(a) (b)

Figure 9: Two student builds: (a) a marble sorter and (b) a pneumatic arm.

Plans for data collection

Fundamentally, this project proposes that well-designed equipment can catalyze student effort, leading to more prototype iterations and ultimately better designs. In addition, if we design our instruction to help students connect their prototyping effort to their domain knowledge, we can help students appreciate the interplay between the analytical and physical domains thereby helping student design better prototypes.

To determine if we achieve this with the pneumatics cart, we will be collecting data on the following two metrics: 1) has the pneumatics cart increased the number of pneumatics-related projects and 2) are students, instructors, and clients confident that the cart has lead to more prototype iterations, and ultimately a more satisfying solution than without the cart.

The first question will be answered over the next several years as we use the cart to recruit more pneumatics projects for the course and informally gauge student engagement with the cart. The second question will be answered with surveys to students, clients, and advising faculty. An draft outline of pre and post survey questions for students are detailed below.

Student survey questions before the project:

1) What was your background with building/prototyping?
2) Do you have any background with pneumatics?
3) How confident are you in developing controls for mechanical systems?
4) How confident are you in your understanding of basic fluids concepts including pressure, force, and compressibility?

Student survey questions after the project:

1) Did the cart help you develop a better prototype?

2) Did the cart help you prototype more quickly?
3) Did the cart help you develop more prototypes?
4) Did your final design benefit from using the cart?
5) Did the cart motivate you to engage with your project?
6) How confident are you in developing controls for mechanical systems?
7) How confident are you in your understanding of basic fluids concepts including pressure, force, and compressibility?

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