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Constraint-Driven Pinball: Fostering Creativity in Embedded Systems Education

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Abstract

This paper presents an approach to embedded systems education through a constraint-driven pinball course project. We introduce a method that leverages physical constraints to foster creativity and problem-solving skills in undergraduate engineering students. The project centers around building an embedded automatic pinball machine with a Pinbox 3000, a cardboard pinball kit, presenting unique challenges that diverge significantly from typical embedded system projects based on previous ideas that others have explored.

Our approach addresses one concern in embedded systems education: the ubiquity of off-the-shelf solutions and well-documented projects on the web, which can limit students' opportunities for original problem-solving and system design. By imposing the constraint of working with a small-scale cardboard pinball machine, we force students to design unique solutions rather than relying on existing designs or off-the-shelf components. This paper details the implementation of this project in a 2024 embedded systems course at Miami University. We discuss how students tackle key challenges, particularly in developing launchers and flippers within the cardboard structure's physical constraints. The project is divided into four main subsystems: launcher mechanism, flipper system, playfield elements, and overarching control system, each presenting its own set of design challenges.

We argue that such constraint-based projects offer a compelling alternative to traditional embedded systems projects. This approach promotes student engagement and practical skill development and better prepares students for real-world engineering challenges where constraints are often immovable. The paper concludes by suggesting future directions for constraint-driven embedded systems projects, emphasizing the potential of this method to continually create novel, challenging learning experiences in the face of rapidly evolving technology.

1 Introduction

Embedded systems education often struggles to balance theoretical knowledge with practical, engaging projects. While microcontroller-based projects are common, they frequently lack the scale and complexity that mirror real-world engineering challenges. Additionally, with the success of Maker Spaces and the popularity of many of these projects, finding interesting projects that have not already been covered deeply on the web is difficult. This paper proposes an approach: utilizing simple constraints to an existing embedded system design that changes the domain and makes the project challenging for undergraduates. For this work, our sample project is pinball machine development, and the constraint that changes the space from off-the-shelf solutions to much more interesting ones is changing the physical scale of the machine.

Building upon our previous work that pushed Embedded System design educators to embrace Arduino-based projects [1] [2], we introduce a project design approach centered around building an embedded automatic pinball machine with a Pinbox 3000 (`https://pinbox3000.com/`). These kits are cardboard pinball kits designed to allow individuals to create their own pinball games - though the focus is on mechanical solutions using cardboard, plastic, and rubber bands. For embedded system design, our challenge to the learners was to create an electronic pinball game using the kit. This presents unique challenges due to the physical scale and material constraints that diverge from typical industrial pinball machines - embedded electromechanical systems. The small scale of these pinball machine kits forces students to grapple with issues of control, mechanical design, and system integration in ways that a typical pinball machine has documented approaches and off-the-shelf solutions for many of the problems.

This paper presents how the addition of these simple constraints makes the design problem a challenge for students. However, there is still a body of knowledge that provides system design solutions for a similar problem—in this case, the physical dimensions and materials of a cardboard pinball machine—we can create problems. This constraint-driven approach encourages creative problem-solving and helps engineers build systems similar to what they will be required to perform in industry, where design constraints are often immovable and must be worked around rather than changed. Our approach in this work is to describe our experience with this approach and recommend it as a way to create future embedded system projects.

The remainder of this paper is as follows: Section 2 provides context and related work in embedded systems education, pinball's use in this space, and constraint-based design. Section 3 details our methodology and implementation of the pinball project in our 2024 embedded systems course at Miami University. Section 4 presents the outcomes of the student projects, highlighting innovative solutions, common challenges they experienced, and novel solutions they created. Finally, Section 5 concludes the paper and suggests future directions for constraint-driven embedded systems projects.

2 Background

For this work, our project of choice is broadly related to the pinball space as related to embedded system design. Fuchs *et. al.* [3] described a pinball-based embedded system course. Fuchs has published two other Pinball-focused research papers focused on automated control [4] and [5]. Also, within higher education, a course at Rochester Institute of Technology (RIT) focused on pinball game design [6]. Finally, some works have been related to pinball game design, and we highlight the work by Wong *et. al.* [7]. Besides our work, there is not a broad array of research into Pinball in the academe that we are aware of.

We have been teaching embedded systems design for years, noting a quote from Jay Carlson (`https://jaycarlson.net/`, accessed September 2024):

> Embedded Systems isn't well-grounded in fundamental concepts; rather, it often serves as the application of all the above concepts into real-world systems. And it's not because embedded systems are the end-all/be-all of electrical engineering — rather, because embedded systems are the simplest real-world examples of these fundamental principles of EE.

From a research standpoint, we were some of the early adopters of Arduino and RaspberryPi prototyping boards into this education space [1] [2]. The relatively cheap existence of these microcontrollers and boards allowed, and the support of the respective communities allowed students to create very sophisticated systems. One challenge, however, was at what level the microcontroller should be explored, going at the top from high-level design to the low-level coding of the system. Over our time teaching the course, we have tried many approaches. The thesis of this work, which is that enforced constraints on the design problem and space make the embedded system projects much more interesting, was conceived based on many projects delivered in our course drifting from good projects to copies of others' work.

Design under constraints is a fundamental concept in engineering education. Dym *et. al.* [8] argue that constraint-based design is an important part of the development of engineers. In embedded systems, constraints can take many forms - from limited computational resources to physical scale limitations. From an education of learning design perspective, constraints are a direct focus of art-based design by Laamanen and Seitamaa-Hakkarainen [9]. In engineering education, there is no specific exploration of constraints to enforce new projects, but Kojamne *et. al.* [10] and Andrea *et. al.* [11] add to the constraint discussion as it relates to design in similar vanes to Dym *et. al.*.

3 Constraint-based Pinball Project

In our 2024 embedded systems course at Miami University, we implemented a constraint-based pinball project centered around the Pinbox 3000 cardboard kit. The Electrical and Computer Engineering department provided funding to support the purchase of 1 kit per 4 students (approximately 50 USD per kit). This kit provides a cardboard pinball machine that can be built with no tools and is shown in Figure 1. This kit is significantly smaller in size than an industrial pinball machine, is entirely mechanically controlled for the flippers and launchers via cardboard, plastic and rubber bands, and includes no electronics. The base premise of the kit is that designers can theme the game and add playfield features for grades K to 6 as a creative STEM-based project. In our project, the challenge was to electrify the kit, working within the constraints of its physical structure and materials. This provides the benefit of having an easily manipulated and fabricated system (which electrical engineers are not experienced in) while being constrained at a size that is not typical of actual industrial pinball machines and their off-the-shelf components.

The project was divided into four main subsystems:

1. Launcher mechanism
2. Flipper system
3. Playfield elements (targets, bumpers, etc.)
4. Overarching control system

(a) Top-view of a built Pinbox 3000 with two blue marbles

(b) Side-view of a built Pinbox 3000 with two blue marbles

Figure 1: View of the Pinbox 3000 after assembly.

Students are organized into teams of four, with each student responsible for one of the above subsystems. These systems need to be integrated to complete the project.

The launcher and flipper systems are the most challenging design components of the project. The cardboard construction of the Pinbox 3000 meant that traditional, powerful solenoids used in commercial pinball machines were not feasible to add to the system. Therefore, designers needed to prototype their components and experiment with their designs to determine if their solution was adequate. Students had to devise creative solutions using smaller, less powerful actuators while still achieving the necessary ball speed and control. Also, the design constraints did not directly state that the system should be similar to modern-day pinball machines. Therefore, the solutions were open to non-traditional systems that might not include the launcher and flipper.

For the playfield elements, students were tasked with designing and implementing various targets, bumpers, and scoring mechanisms. This requires careful consideration of sensor placement and experimenting with the sensitivity of the detection mechanisms. The marbles are not made of metal and are lighter than traditional metal pinballs, of which those two properties are used in industrial games.

Finally, the overarching control system must integrate inputs from all playfield elements, manage game logic, and potentially control the launcher and flippers. This presents challenges regarding real-time processing, pin limitations, and power management, as the entire system needs to run on portable power sources.

The design time for the project was approximately two months, and the students had two cycles of proposals, during which they described what they wanted to build, how they were going to build it, and detailed their plan. These proposals have been part of the course where instructor experience is used to provide feedback on how challenging their proposed work is. In many cases, students tend to be overambitious, and we use the proposal to describe a spiral-like design approach where the over-ambitious ideas can be promised as additional features instead of promised deliverables.

4 Results and Discussion of the Activity

The constraint-based pinball project yielded an array of designs from our student teams. Figure 2 showcases 10 of the 13 completed projects (where 3 of them were not properly documented by the author), where each design demonstrates different approaches to the challenges posed by the cardboard pinball framework. Also, the quality of the final products differs greatly depending on both the time students spend and access to 3D printing tools and related experience. Miami University does have a student Maker Space that all students have access to, which includes materials. Still, students made choices on whether they wanted to take advantage of these resources.

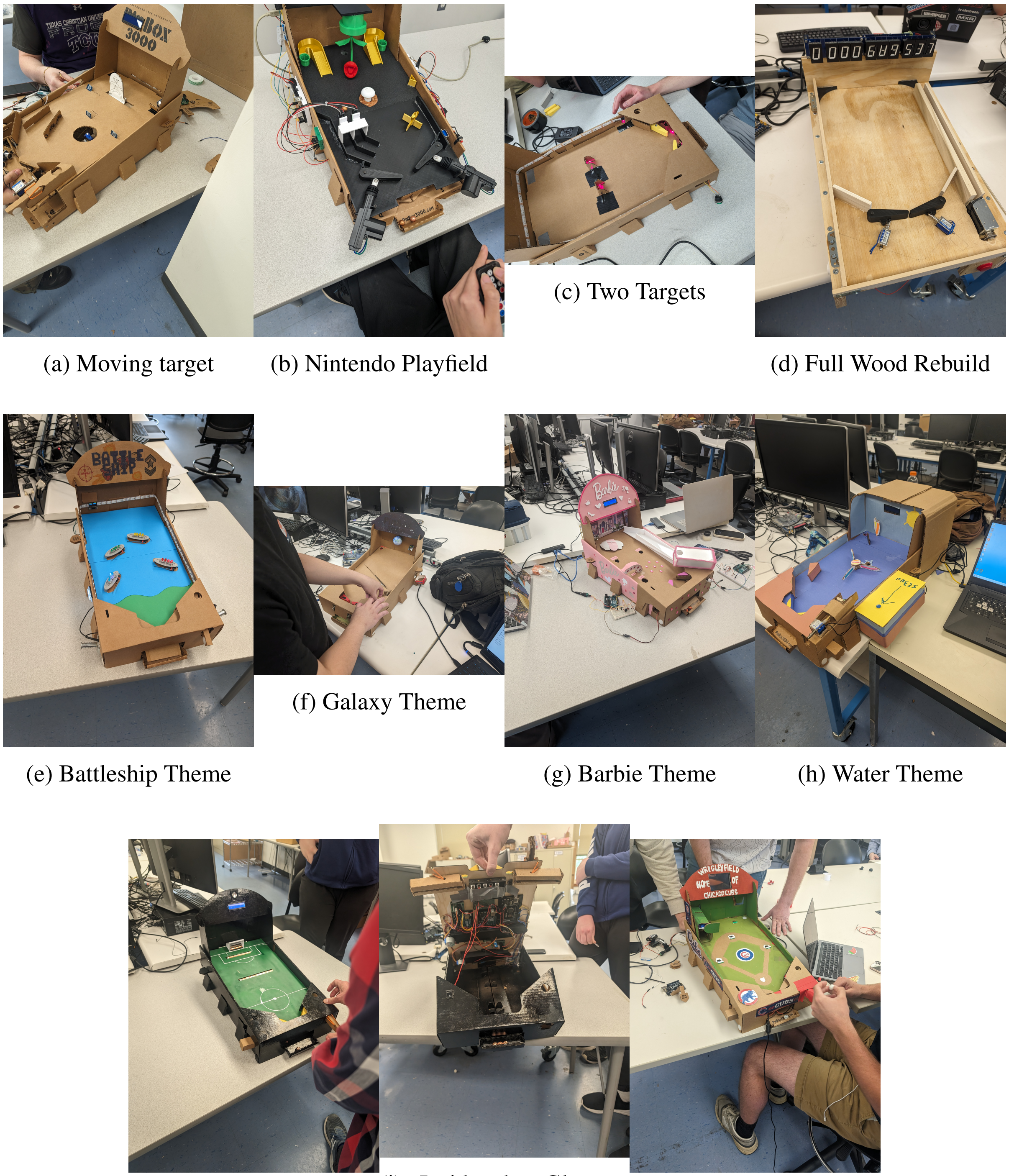
One of the most significant challenges faced by students was developing effective launcher and flipper mechanisms within the constraints of the cardboard structure. Several teams experimented with servo motors and linkage systems to create flippers that could provide adequate force without compromising the machine's structural integrity. For launchers, some groups experimented with spring-loaded mechanisms actuated by smaller solenoids, demonstrating an innovative blend of mechanical and electrical engineering. Ultimately, most groups implemented their flipper and launching systems using solenoid-based circuits. However, a small subset of groups used car door lock actuators (pre-fabricated solenoid structures) for their flipper designs (see Figure 2 (b)).

The playfield designs showed considerable creativity, with teams incorporating various sensors and actuators to create interactive elements. For instance, the "Nintendo Playfield" (Figure 2 (b) integrated themed targets and scoring zones and allowed a second player to control aspects of the field via remote control. The "Battleship Theme" (Figure 2 (e)) incorporated ship-based targets that needed to be hit repeatedly before the "ship" was sunk.

Integration of the subsystems proved to be a significant challenge. Most teams approached the integration to a scoring mechanism using multiple Android UNOs communicating via Serial Peripheral Interface (SPI). As illustrated in Figure 2 (f), the complexity of wiring even a simple playfield is complex.

The diversity in themes and gameplay mechanics across the projects (as seen in Figures 2 (e) through (k)) shows how the constraints of the project actually fostered creativity rather than limiting it. Students must think and design beyond conventional pinball systems, resulting in unique gameplay experiences.

From an assessment standpoint, we evaluated the project with less conventional methods, as both the instructor and learners were placed in a space where failure was an option. Normally, for the



(a) Moving target (b) Nintendo Playfield (c) Two Targets (d) Full Wood Rebuild

(e) Battleship Theme (f) Galaxy Theme (g) Barbie Theme (h) Water Theme

(i) Glasgow Celtic Theme (j) Inside the Glasgow Celtic (k) Cubs Theme

Figure 2: Pictures of pinball machines with themes created for 2024 course project.

course, the two deliverables for the group project are a demonstrated working system and a report on the artifact. Both assessments are accompanied by a rubric that is provided to the students before the project so that they are aware of what standards need to be met. For this project, however, the detailed rubric for the working system was removed, and we shifted to a broad assessment classification.

- Exceeded design expectation
- Met expectation of a working system
- Failed to meet expectation

All groups designed projects that "Met Expectations" or higher, which corresponds to course points in the "A" range. The design report was assessed in the same way as previous years of the course and included a detailed rubric. The performance here was in line with previous years, where students faced the challenge of reporting their system as opposed to narrating the challenges of building the system.

5 Conclusion

This work showed how changing the constraint on an embedded system design project allows for challenging projects to be designed and made by students. In this case, using a pre-designed pinball kit, smaller than industrial pinball machines, was a sufficient constraint to add to the project that resulted in difficult-to-build designs but still allowed for creative solutions and embedded system design experiences. Overall, the students enjoyed the process, and the experience was interesting for educators and learners. In general, we believe that creating design projects with new constraints can significantly change the result of the designs. The constraint-based pinball project described in this paper demonstrates the potential for creating challenging embedded system projects that offer several ideas on how similar designs were approached.

We are considering exploring other constraint-based themes for future iterations of these course projects. Some potential constraining ideas include:

- Design a fully functional embedded system with a size constraint.
- Create embedded systems that operate on a power budget (potentially scavenged environmental energy).
- Limit the market that the system targets - for example, the exercise embedded market.

These ideas continue the theme of using constraints to drive interesting new projects.

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