Multi-Institutional Electromechanical Pinball Component Design

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ABSTRACT

An international, project-based collaboration between a German and U.S. university focuses on the end-to-end design and fabrication of a fully functional pinball machine. The project adopts a top-down systems-engineering approach in which changes to the playfield architecture propagate directly to mounted hardware, wiring, control logic, and game progression, reinforcing systems thinking across both student cohorts. The German mechanical engineering (ME) students design and additively manufacture key playfield components—flippers, bumpers, drop targets, slingshots, and a servo-driven goalie—while the U.S. electrical and computer engineering technology (ECET) students develop the sensing and control architecture using Programmable Logic Controllers (PLCs) and embedded systems. All playfield components are designed for Fused Deposition Modelling (FDM) with Polylactic Acid (PLA) to meet cost and reproducibility constraints. This paper reports the mechanical design methods, the design constraints, and the structure of the international collaboration. Evaluation encompasses technical testing and a critical review of the cross-cultural, cross-disciplinary teamwork experienced by both student groups.

1. INTRODUCTION

Interdisciplinary and intercultural design projects provide effective preparation for engineering students entering industry. Such projects require participants to consider the impact of their decisions on components and systems outside their own domain of expertise, while simultaneously navigating differences in communication styles [1], time zones, semester schedules, and access to shared hardware and software tools.

Project- and problem-based learning (PBL) is well established as a vehicle for developing these competencies [2]. At the Westphalian University of Applied Sciences, prior courses have applied PBL to the design of mechatronic systems, with real-world engineering challenges, integrated failure scenarios, and game-based assessments used to build student endurance [3] and collaborative competence [4]. In capstone design projects in particular, student teams address real engineering problems by applying knowledge accumulated across prior technical courses. Intercultural capstone projects extend this framework further by adding the demands of cross-national coordination. Representative examples include collaborative projects between Purdue University and institutions in Germany and Poland [5], an exchange program between the United States and Brazil [6], and international humanitarian capstone projects involving students travelling to the Dominican Republic [7]. Despite their documented benefit, such projects remain uncommon due to the practical difficulty of identifying a compatible international partner, securing funding for travel and shared resources, and designing a task that requires genuine interdependence between the two student groups—so that success is only achievable when both teams are fully engaged and communicating.

When intercultural projects are also interdisciplinary, the coordination challenge for faculty increases significantly. Each institution must align its curriculum, its assessment calendar, and its available laboratory infrastructure to a shared project goal, while ensuring that neither student group can complete the work in isolation. A pinball machine satisfies this requirement naturally: the mechanical subsystem is inoperable without the electrical control architecture, and the control system is meaningless without functioning physical actuators and sensors. The machine therefore creates a hard dependency between the two cohorts, ensuring that collaboration is not merely encouraged but structurally required.

A pinball machine also offers further pedagogical advantages. Its size conveys that the outcome is more than a proof-of-concept; industry-relevant tools such as CAD, PLCs, and embedded systems are directly applicable; and the playability of the finished product provides an immediate, intuitive quality measure that motivates students to design and build well.

2. INTERNATIONAL COLLABORATION OBJECTIVE

A central objective of this project was to establish a sustainable international collaboration between the Westphalian University of Applied Sciences (Germany) and Purdue University (USA), using the pinball machine as a concrete, motivating engineering vehicle. On the German side, three undergraduate students from the mechanical engineering department contributed to the project: two students as part of supervised senior design projects and one student as part of a bachelor thesis. Their combined work covered the complete mechanical design of the machine, from the frame and playfield geometry to all individual playfield components. On the U.S. side, five undergraduate students from the electrical and computer engineering technology (ECET) department participated as part of a capstone design project. Their responsibilities encompassed Programmable Logic Control (PLC) and embedded system programming, wiring, sensing, and the physical construction of the pinball machine. The German team thus provided the design to ensure the playfield and frame could be manufactured, while the U.S. team integrated those components into a functional system. This division of responsibility ensured genuine interdependence between the two groups: neither could complete their work without clear communication and well-defined interface specifications from the other.

The work presented here focuses on the international collaboration and the mechanical design from the German students. Discussion of the electrical and software design will be addressed as future work.

3. DESIGN CONSTRAINTS AND REQUIREMENTS

The design was governed by a defined set of customer and engineering requirements. The customer requirements focus on operational quality and user experience, while the engineering requirements impose quantitative bounds on system performance and safety.

3.1 Customer Requirements

- Reliable operation of at least 30 continuous minutes without failure.
- Clear scoring display, game lighting, and point feedback to the player.
- Mobile and serviceable machine design (locking castors, accessible wiring space).
- The finished machine must be engaging and fun to play.

3.2 Engineering Requirements

- Sensor response time ≤ 0.5 s from ball contact to PLC acknowledgement.
- Power supply compatible with both 120 V/60 Hz (U.S.) and 230 V/50 Hz (Germany).
- All circuits above 30 V must be fully enclosed.
- Wiring must comply with the National Electrical Code (NEC).
- Standard steel pinball diameter of 27 mm; all ball guides and return channels dimensioned accordingly.
- Playfield incline of 6–7° to ensure consistent ball return under gravity without excessive speed.
- Maximum machine weight of approximately 100 kg to allow transport and repositioning by two persons without mechanical lifting aids.

3.3 Cost Constraints

The project budget was structured across three principal cost categories. The system design and mechanical components (frame materials, fasteners, bearings, and miscellaneous hardware) were limited to $750. The PLC and electrical hardware, including all associated I/O modules, communication interfaces, and solenoids, was capped at $1500. Embedded system components, including interfaces with the PLC and audio system, were allocated a budget of $750. This results in a total project budget of $3,000. The students benefitted from having access to 3D printing systems on campus, as well as a CompactLogix PLC, to help allay the overall cost. However, machining of the playfield had to be accomplished off campus for an additional cost. The cost constraint directly informed the initial choice of Fused Deposition Modelling (FDM) 3D printing with Polylactic Acid (PLA) as the manufacturing method for all playfield components, as this approach eliminates tooling costs and enables rapid iteration without external procurement lead times. Concerns about the robustness of the PLA when being hit by the pinball led to some components (e.g., the drop targets) being reprinted using Acrylonitrile Butadiene Styrene (ABS).

3.4 Manufacturing Constraints

All playfield components are designed for FDM using PLA as the build material. PLA was selected for its low cost, wide availability, ease of post-processing, and compatibility with standard desktop FDM printers accessible in both institutions' laboratories. The requirement for FDM compatibility directly influenced component geometry: all parts are designed to avoid overhanging features that would require support structures, and bearing housings are designed as split two-part assemblies to allow installation of ball bearings after printing. This manufacturing constraint also means that post-print dimensional verification is a mandatory step in the assembly process, as FDM tolerances for holes and slots regularly deviate from nominal values by 0.2–0.4 mm.

3.5 Overall Machine Dimensions

The machine frame was designed to match the dimensions of a standard commercial pinball machine. The cabinet width is 559 mm, the cabinet depth is 1,270 mm, and the total height including the headboard is approximately 1,830 mm. The playfield plate measures 520 mm × 1,067 mm. These dimensions ensure that standard pinball hardware—legs, side rails, and lockdown bars—can be sourced commercially where required, and that the finished machine is recognizable and proportionate to players familiar with commercial machines.

3.6 Component-Level Functional Requirements

In addition to the system-level constraints above, detailed functional requirements were established for each individual playfield component as part of the bachelor thesis [6]. These requirements were developed collaboratively during weekly project meetings and deliberately kept concise to avoid over-constraining the design space at an early stage. They are summarised by component below:

- **Drop Targets:** targets must be clearly identifiable by the player and reachable directly from the flippers; a struck target must drop below the playfield surface (flush with the field plate) and remain inactive until reset; hit detection must trigger a PLC event; and all targets must reset simultaneously on command.
- **Drop Hole (behind Drop Targets):** the hole must capture and hold the ball (interrupting play), detect the ball via sensor, subsequently release and accelerate it in a defined direction (towards the goal), and be accessible exclusively once all drop targets have been triggered.
- **Goalie:** the goalkeeper figure must move laterally in front of the goal opening, be capable of deflecting the ball, detect a scored goal via sensor, capture and hold the ball on a successful goal (interrupting play for effects), and release it back into play thereafter.
- **Slingshots:** each slingshot must redirect the ball towards the playfield centre using a single solenoid actuator, detect ball contact via sensor, and form the boundary of a defined runoff channel alongside the flippers.

- **Standing Targets:** targets must be clearly visible to the player, detect a hit via sensor, and return immediately to their upright position after a strike (making the hit repeatable); they are deployed in single, double, and triple configurations across the playfield.
- **Ramp:** provides a one-way connection from the lower to the upper playfield area (ball cannot roll back down); must minimize obstruction of the player's line of sight to other elements; must not impede ongoing play; ball passage must be detectable via sensor; the ramp is a passive element with no actuator.
- **Angled Wall:** passive deflector (no actuator) positioned in the upper right corner of the playfield; must reliably redirect the ball towards the playfield center after arrival from the ramp exit.

4. MECHANICAL DESIGN

The mechanical design was completed by the German student team over the course of one semester (October–January). The work was distributed across two senior design projects and one bachelor thesis. The principal subsystems are described below.

4.1 Frame

The frame was designed to match the dimensions of a standard commercial pinball machine (see Figure 1). The playing field incorporates a 6° incline to ensure consistent ball return towards the flippers. Locking castor wheels are integrated for portability. The vertical headboard provides mounting space for a video display. The frame structure is fabricated from wood, with the playing field plate manufactured from 5/8″ Baltic birch plywood. A cavity beneath the playing field plate accommodates all wiring and the undersides of playfield components.

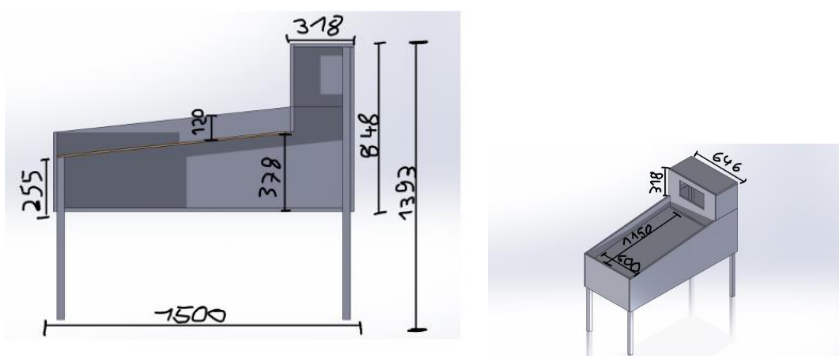

Figure 1. Pinball Machine Frame Dimensions (dimensions in mm)

4.2 Playfield

The playfield layout is shown in Figure 2. The design specifies the location of all cutouts for component insertion and is themed as a soccer game. A servo-driven goalie in the upper left corner moves laterally via a timing belt; a pinball passing the goalie constitutes a scored goal and the ball returns along a dedicated ramp. A kickback solenoid in the lower left corner redirects balls back towards the centre of the playing field.

4.3 Bumpers

Three pop bumpers are distributed across the playfield (Figure 3) to add speed, unpredictability, and excitement. When the ball contacts the bumper skirt, the skirt tilts and actuates a spring-loaded pin that triggers a microswitch, energizing the solenoid beneath the playfield. The solenoid plunger pulls down a pop ring via adjustable threaded rods; the ring strikes the ball and ejects it outward.

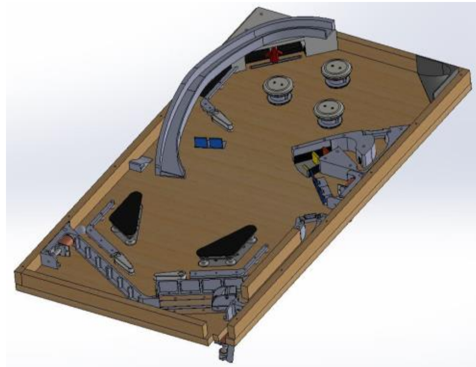

Figure 2. Preliminary Pinball Machine Playfield Layout

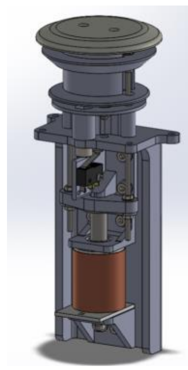

Figure 3. Bumper Design

4.4 Flippers

Three flippers are included, two at the bottom of the playing field and a third near the goalie (Figure 4). The flipper is mounted on an M8 screw acting as a rotational axle; the hex head of the screw is form-fitted into the flipper arm to prevent slipping and ensure direct torque transfer. Plain bearing bushings support the shaft. A dual-coil system drives the flipper: a power coil (solenoid) delivers the initial kick and a low-current hold coil maintains the fully rotated position. A lever beneath the playfield connects the shaft to the solenoid plunger via a clamping hub, allowing precise angular alignment.

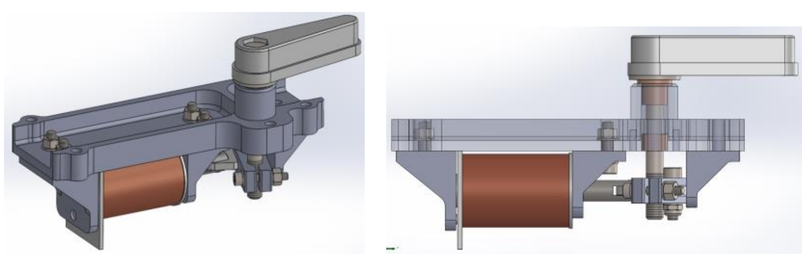

Figure 4. Flipper Design

4.5 Slingshots

The slingshot assembly (Figure 5) uses a rubber band to detect ball contact. Two microswitches behind the rubber band energize a solenoid on contact; the solenoid drives a shaft through a linkage that deflects the ball. The microswitches simultaneously signal the PLC to update the score.

4.6 Standing Targets

The standing target (Figure 6) triggers a microswitch when the ball strikes and deflects the target rearward. The microswitch signal is transmitted to the PLC to register a scoring event.

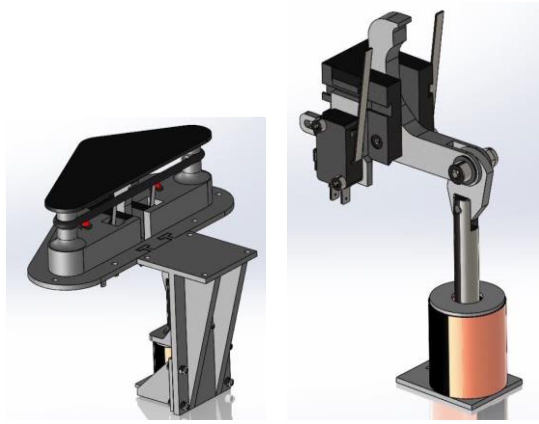

Figure 5. Slingshot Design

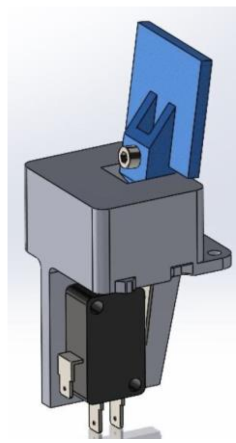

Figure 6. Standing Target Design

4.7 Drop Target System

The drop target assembly (Figure 7) is the most mechanically complex subsystem. The ball must successively strike each target; once struck, each target remains in the lowered position until all targets have fallen and a reset signal drives a solenoid that engages a cam mechanism to return all targets to their raised position.

Only the inlay is fastened directly to the playing field plate; all other components are pre-assembled as a unit, with alignment defined by the inlay itself. Funnel-shaped walls within the inlay guide the ball into the drop zone. The base element houses target guides, microswitch brackets, tension spring hooks, and split pillow blocks for the reset shaft. Target guides are dimensioned so that the upper surface of a triggered target is flush with the inlay and playing field surfaces. Microswitches with roller levers are mounted laterally and can be adjusted via slotted holes; lateral positioning ensures that only horizontal force acts on a triggered target, preventing unintended tilting. A split two-part bearing housing for the reset shaft allows assembly with pre-installed ball bearings. The shaft cross-section is rectangular to facilitate FDM production and enable form-fitting torque transmission to the reset fingers (Figure 8).

4.8 Ball Feed

The ball feed (Figure 9) holds up to four pinballs in a sloped channel and feeds each ball to the launch area via a solenoid-actuated mechanical pusher. The slope ensures consistent ball positioning prior to each launch.

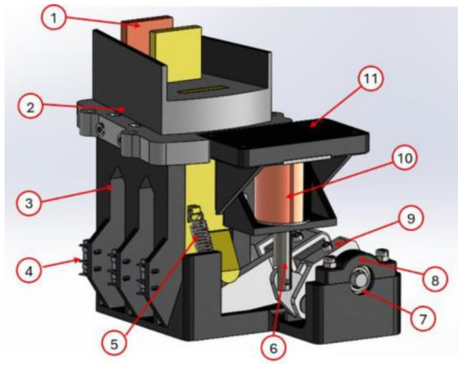

Figure 7. Drop Target System Design Assembly (1=Targets, 2=Inlay, 3=Base element, 4=Microswitch, 5=Tension spring, 6=Plunger, 7=Ball bearing, 8=Housing, 9=Shaft with fingers, 10=Solenoid, 11=Solenoid bracket)

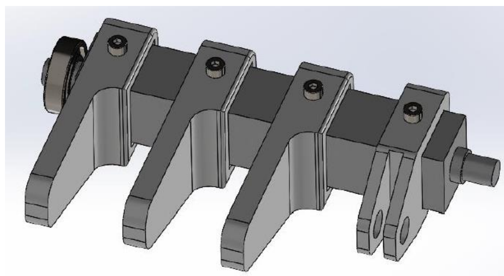

Figure 8. Reset shaft with three fingers and solenoid attachment

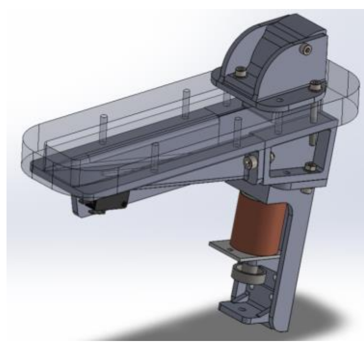

Figure 9. Ball Feed Design

4.9 Goalie

The goalie is a unique feature of the presented playfield (Figures 10–11). A stepper motor mounted beneath the playing field drives a GT2 timing belt (1.38 mm thick, 6 mm wide, 400 mm long) to produce lateral linear motion of the goalkeeper figure. GT2-5-16 timing belt pulleys with integrated flanged discs are used to prevent lateral belt displacement. A trapezoidal guide geometry (45° leg angle) was adopted specifically to allow FDM printing without support structures. Belt tension is adjusted via a screw accessible from the exterior of the base element. Two microswitches detect end positions via the lower guide block, preventing the clamping block from reaching the timing belt pulleys. IR sensors positioned behind the goalkeeper detect ball passage without false triggering. All edges of the goalkeeper that may contact the ball are rounded to prevent trapping.

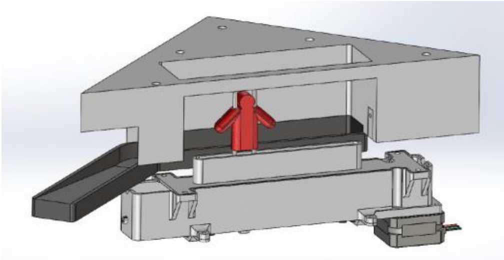

Figure 10. Goalie Assembly

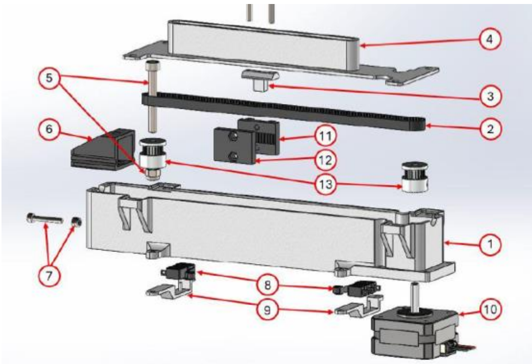

Figure 11. Exploded View of Goalie Lower Assembly (1=Base element, 2=Timing belt, 3=Lower guide block, 4=Inlay, 5=Fastening screw and nut, 6=Slide, 7=Tension screw and nut, 8=Microswitch, 9=Bracket, 10=Stepper motor, 11=Inner terminal block, 12=Outer terminal block, 13=Timing belt pulley)

5. DISCUSSION AND LESSONS LEARNED

With the mechanical design complete, fabrication started using FDM with PLA at both institutions' laboratories. Empirical observations during the prototyping phase confirm that post-print dimensional verification is critical: deviations between the digital model and the printed part emerged consistently at critical fit locations, particularly for microswitch housings and solenoid mounting points. This underscores the importance of the mandatory print-and-measure step stipulated in the manufacturing constraints (Section 3.4). The assembled pinball machine is provided in Figure 12 with some modifications still underway. Results from functional testing of the assembled system will be presented in a follow-up paper.

Figure 12. Assembled Pinball Machine

Collaboration between the two student groups has proceeded positively. Weekly virtual meetings of up to one hour have provided a regular synchronization point and have maintained momentum across both teams. A student field trip to Germany for the U.S. ECET students is scheduled and adds an in-person cultural dimension to the collaboration. Faculty are actively pursuing partial funding to support student participation. The structured feedback collected from the German ME students (Table 1) confirms that working in English, operating within an international team, and engaging with a technically substantive project were all perceived positively. The principal negative element cited by the students was schedule pressure arising from the small team size and the tight semester timeline.

A systematic reflection on the project to date yields seven lessons learned that are relevant for faculty and students planning comparable international, interdisciplinary engineering collaborations (Table 2). These lessons are derived from the project experience described above and from the student feedback collected at the end of the design phase.

Table 1. German Student Project Feedback

Student	Pros	Cons
1	• Working in English throughout the project was a valuable first step toward future international collaborations in an industrial environment. • The clear division of technical topics helped structure the work, while each meeting remained constructive and contributed to improvements for both teams. • Discussions were open, solution-oriented, and focused on improving technical concepts rather than defending fixed ideas. • The project had a playful and engaging character, making the technical work enjoyable and motivating.	• Mechanical components had to be defined early to enable parallel development, even when electrical details were still evolving. • The overall schedule was relatively tight given the small team size of only two members.
2	• A highly valuable opportunity to work with an international team. • Positive and appreciative atmosphere within the team. • As the project progressed, the mechanical effort required became more apparent; support was provided wherever possible. • Meetings were well organised.	• The schedule was quite tight for the volume of work involved; initial uncertainties about the project approach and task distribution required early resolution. • The time difference did not always allow for quick communication.

Table 2. Lessons Learned from the International Pinball Machine Project

#	Lesson	Description
1	**Define the mechanical interface early**	Electrical and mechanical sub-teams must agree on connector positions, mounting holes, and solenoid specifications before either team begins detailed design. Late changes to shared interfaces propagate across both domains and generate rework on both sides of the collaboration.
2	**Verify printed tolerances before assembly**	FDM-printed parts (e.g., PLA) often deviate from nominal dimensions, particularly for holes and slots that accept microswitches or solenoid bodies. A dedicated print-and-measure cycle for each critical feature should precede integration to avoid fit failures during final assembly.
3	**Establish a shared CAD repository from the outset**	Without a common version-controlled repository, parallel design branches diverge and integration becomes uncertain. A single shared platform with agreed naming conventions prevents this and reduces meeting time spent reconciling conflicting file states.
4	**Structure weekly meetings around decisions, not updates**	Weekly virtual meetings of up to one hour work well when each agenda item concludes with a defined decision or action item. Informational updates are better handled asynchronously, freeing synchronous time for cross-team problem solving.
5	**Communicate time-zone constraints explicitly**	A six-hour time difference between Germany and the U.S. East Coast limits the window for same-day responses. Both teams benefit from agreeing on a maximum expected response time and flagging time-critical items in advance rather than at the moment they arise.
6	**Align grading structures across institutions from the start**	The German participants completed the work as senior project and bachelor thesis credits, while the U.S. participants treated it as a capstone project. Mismatched deadlines and grading milestones created schedule pressure that could be mitigated by mapping each institution's assessment calendar at the project kick-off.
7	**Use a tangible, motivating product as the integration target**	A pinball machine proved to be an effective project vehicle precisely because the end product is visible, interactive, and immediately assessable by anyone. Students invested discretionary effort because the outcome was intrinsically rewarding, supporting the Constructive Alignment principle that assessment and activity should reinforce the same learning goals [8].

6. CONCLUSION

This paper presents the mechanical design of a pinball machine developed as part of an international, interdisciplinary collaboration between German ME students and U.S. ECET students. The project was deliberately structured to establish a sustainable collaboration between both institutions, with genuine technical interdependence between the two student cohorts. The German team, comprising three undergraduate students working across two senior design projects and one bachelor thesis, completed the full mechanical design of the machine: frame, playfield layout, and nine distinct playfield subsystems. All components are designed for FDM production with PLA within a total project budget of $3,000.

The design constraints – cost, dimensions, manufacturing method, and operational requirements—were satisfied by the presented design. The collaborative structure, with weekly virtual meetings and a clear division of technical responsibility, proved workable, though schedule pressure and interface uncertainty in early phases were identified as areas for improvement. Seven lessons learned are distilled from the project experience to inform future iterations of this collaboration and to support other faculty planning comparable projects.

Future work will focus on completing the physical build at the U.S. institution, conducting full functional testing against the stated requirements, and presenting both quantitative performance results and the electrical/embedded system design in a follow-up publication.

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REFERENCES

[1] Friesel, A. and Dubikovsky, S. (2019). Intercultural and interdisciplinary communication skills as a component of engineering education: International design projects. 2019 ASEE Annual Conference & Exposition.

[2] Kolmos, A., Holgaard, J. E., Routhe, H. W., Winther, M. and Bertel, L. (2024). Interdisciplinary project types in engineering education. European Journal of Engineering Education, 49(2), 257–282.

[3] Wendland, M. (2023). Failure as an Integral Part for Teaching the Design of Complex Mechatronic Systems. International Conference on Education and New Developments (END2023), Lisbon, Portugal.

[4] Wendland, M. (2024). An Approach to Game-Based Learning, Collaboration and Design Challenges for Teaching the Design of Mechatronic Systems. International Conference on Education and New Developments (END2024).

[5] Sanger, P. A., Ziyatdinova, J., Kropiwnicki, J. and Nguyen, P. V. (2015). Changing attitudes in cross-cultural diversity through international senior capstone projects. 2015 ASEE Annual Conference & Exposition.

[6] Ordonez, J. C., Vargas, J., Shih, C. and Costa, N. G. (2011). Integration of capstone design experience with the international exchange program. 2011 ASEE Annual Conference & Exposition.

[7] Layer, J. and Gwaltney, C. (2009). International capstone design projects: Evaluating student learning and motivation associated with international humanitarian projects. 2009 ASEE Annual Conference & Exposition.

[8] Wendland, M. (2024). Digital Assessment Methods in Mechanical Engineering: Case Study of a Computer-Aided Design Course within a Blended Learning Environment. ICERI2024 Proceedings, pp. 220–228.