# Green Fund Project
# Final Report

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Identify if the person completing report is a student, faculty, and/or staff: Faculty
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Faculty Advisor (if applicable): Arash Komaee
Project Title: Development of Sustainable Laboratory Setups for SIU's Robotics and Control Laboratory
Project ID #: **24SP105**
Award Date: April 18, 2024
Completion Date: March 15, 2025
Total Funds Used: $17,400

1. Provide a summary of your project/project experience.

The project was aimed to design a collection of laboratory setups with minimal usage of non-eco-friendly material, and to manufacture them by biodegradable 3D-printing material for research and instructional purposes in SIU's Robotics and Control Laboratory. Simultaneously, it was planned to serve as a vehicle for training students on the concept of environment-friendly engineering design and its related research topics. To that end, a team consisting of 1 PhD, 1 MS, and 2 undergraduate students was considered to collaboratively implement the project under the PI's supervision. The PhD student was in charge of leading the team, while the MS and undergraduate students were each assigned to one of the setups planned to develop.

Considering the minimal usage of non-eco-friendly materials as a design constraint, the project was planned to develop three laboratory setups: an inverted pendulum, a magnetic levitation system, and a magnetic manipulator for stabilization of a magnetic object in a planar workspace. All three systems are dynamically unstable in essence and require feedback control for stabilization; hence, they are frequently used world-wide for hands-on training of control systems, and as benchmarks for evaluation of novel control algorithms.

The PI has a track record of developing laboratory setups for research on control and surgical robotic systems. These setups are usually manufactured by 3D-printing of their parts with excessive consumption (about 1-2.5 kilograms for each setup) of printing material, which are often harmful to the environment. The project was originally motivated by the observation that a smarter design of the 3D-printed parts, for instance using light structures such as truss or honeycomb, could substantially reduce the use of non-eco-friendly materials. Such smart design would certainly require more time and engineering efforts for strength of materials analysis; however, its environmental impact could be significant when the reduction of non-eco-friendly material in each unit is multiplied by the large number of units built over a long period of time. The project was a step toward achieving such a positive impact on the environment.

2. Provide a summary of your results (environmental, social, and/or economic) including quantifiable data as appropriate (ex. # of individuals reached, lbs. diverted from landfill, energy saved, etc.).

In this project, 3 laboratory setups were designed, prototyped, tested, and calibrated, as explained later in this report. The project was performed by 1 PhD, 1 MS, and 2 undergraduate students as a collaborative team within the School of Electrical, Computer, and Biomedical Engineering. Throughout the project, they learned about environment-friendly engineering design within the framework of feedback control systems, in particular those used in medical robotics. The design emphasis was on minimal usage of non-eco-friendly material, through which, the participants received extensive training and gained substantial experience on environmental-friendly design of engineering structures.

In addition to research purposes, the laboratory setups developed in this project will be used for instruction of undergraduate and graduate courses within the School of Electrical, Computer, and Biomedical Engineering. The price for commercial versions of these setups (particularly, inverted pendulum) is around $15,000-$20,000 per unit, which for 3 setups, would cost about $45,000-$60,000 for SIU. In case more setups are needed in the future, each unit can be replicated using parts not costing more than $500.

This project positively impacted the environment in three different ways:

1) By extensive training of 4 new engineers and partial training of many new engineers (those who will take courses benefiting the developed setups) on environment-friendly design of engineering structures. It is expected that their experience on such design procedures will result in significant reduction on consumption of non-eco-friendly material over long period of their engineering career (35 years+).

2) By reduction of non-eco-friendly material in the developed setups. The PI is working to make the design of these setups available to the public, so it will be replicated, supposedly, at large numbers all over the globe. Hence, significant reduction in the consumption of non-eco-friendly material for each unit will be multiplied by a large number for a long period of time.

3) The techniques developed in this project for minimal usage of material in engineering structures can be applied to a wide range of other applications. In particular, the availability of 3D-printing technology together with the low price of the printing material have led to excessive consumption of these materials, which are often harmful to the environment. The PI hopes that the optimized 3D-printing techniques resulted from this project will help to meaningfully reduce the consumption of such non-eco-friendly material in other engineering designs.

The setups developed in this project are briefly discussed below.

1) **Inverted Pendulum:** This setup incorporates a set of components such as electric motors and sensors in order to stabilize a pendulum upward along a vertical direction by means of a computer-controlled feedback loop. The prototyped setup shown in Figure 1 was designed modularly using SolidWorks and each module was separately fabricated by 3D-printing using biodegradable material. A major design constraint was the minimal consumption of material by exploiting light structures such as truss or honeycomb, as shown in Figure 2. The steps taken toward the development of the setup are shown in Figure 3.

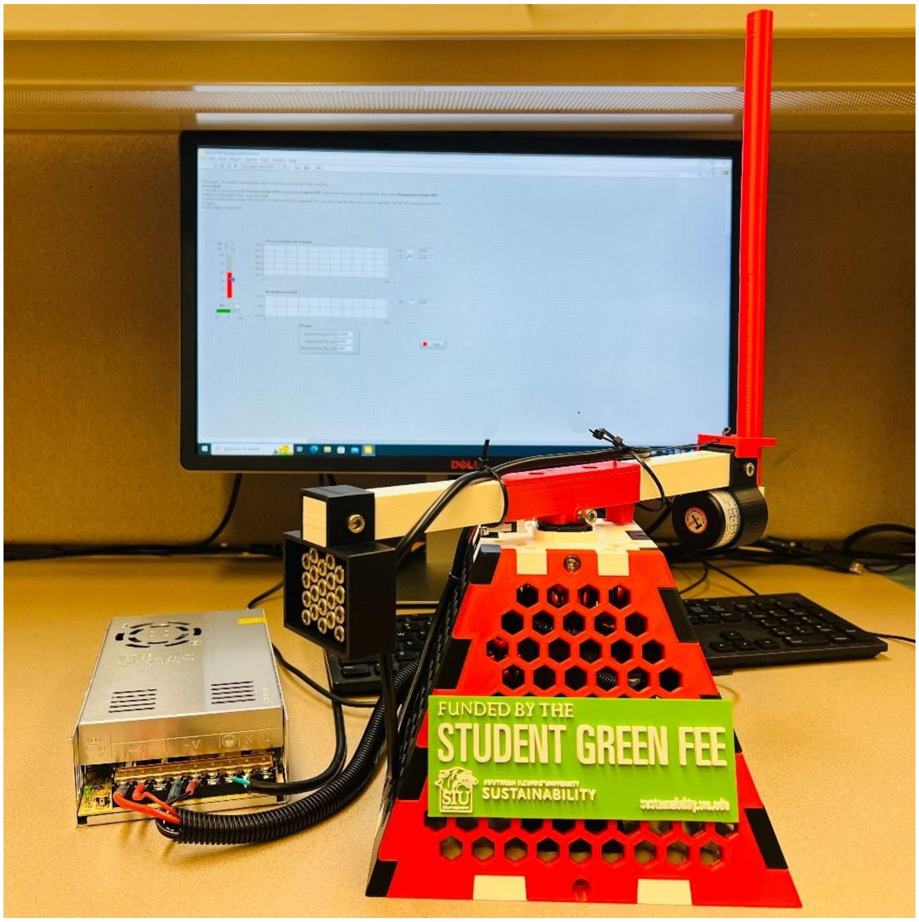



Figure 1: Inverted pendulum, designed, prototyped, tested, and calibrated in this project. The Green Fund Marker has been 3D-printed on the fixture of the setup.

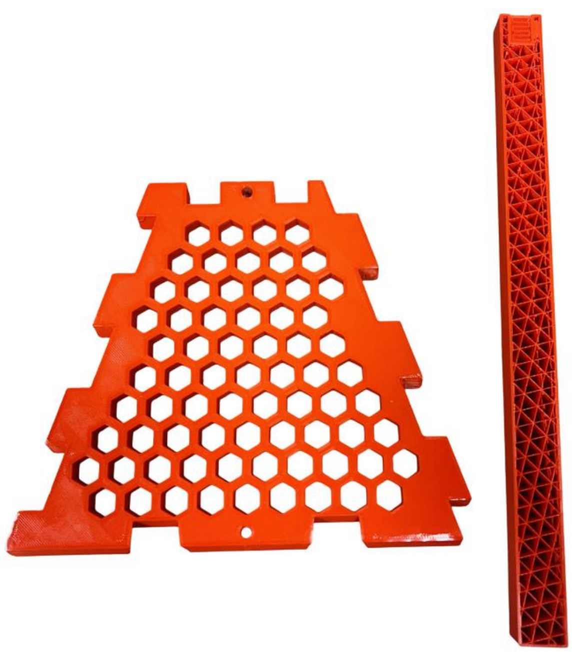


Figure 2: Individual modules designed based on light structures such as truss or honeycomb, aimed to minimize the consumption of the 3D-printing material often harmful to the environment.

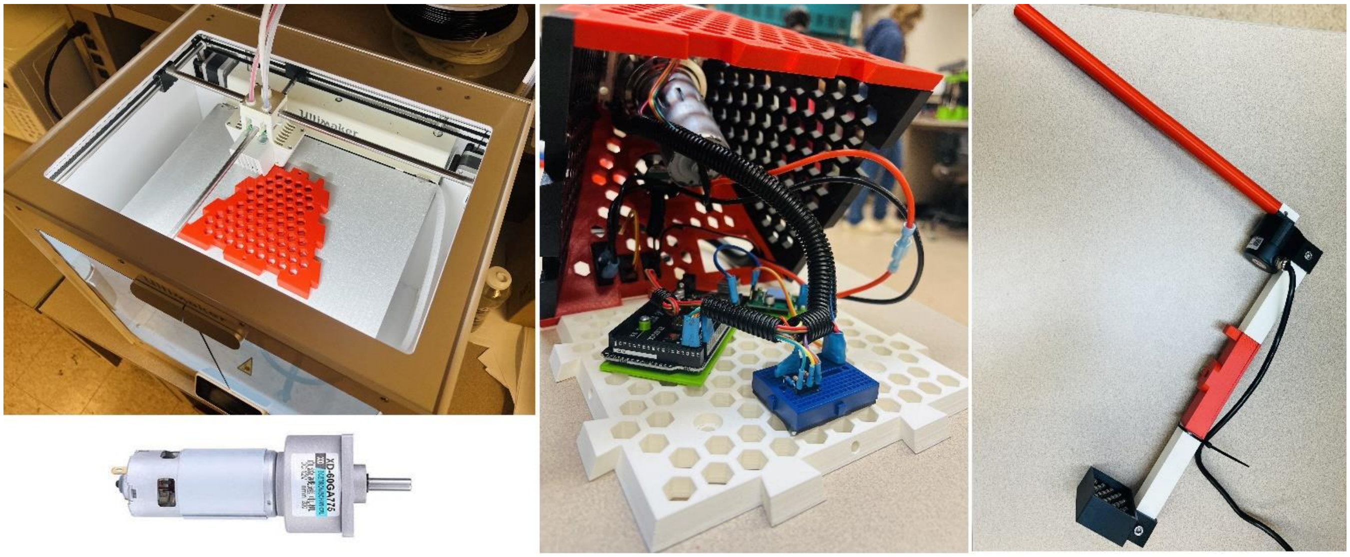


Figure 3: Steps taken for prototyping the designed inverted pendulum.

2) **Magnetic Levitation System:** Magnetic levitation systems employ magnets facing toward the ground in order to attract magnetic objects against gravity and levitate them at a distance from the face of magnets. Since these systems are dynamically unstable in essence, they must be stabilized by means of computer-based feedback control, which adjusts the magnetic force applied to the levitating objects as a function of their measured positions. The magnetic levitation system developed in this project is shown in Figure 4. The successful operation of this system within a computer-controlled feedback loop is illustrated in Figure 5. The development and successful operation of this system was reported in a paper (see Figure 6) published in the proceedings of the 2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2024), and also was orally presented in the conference meeting held in July 2024, Boston, MA.

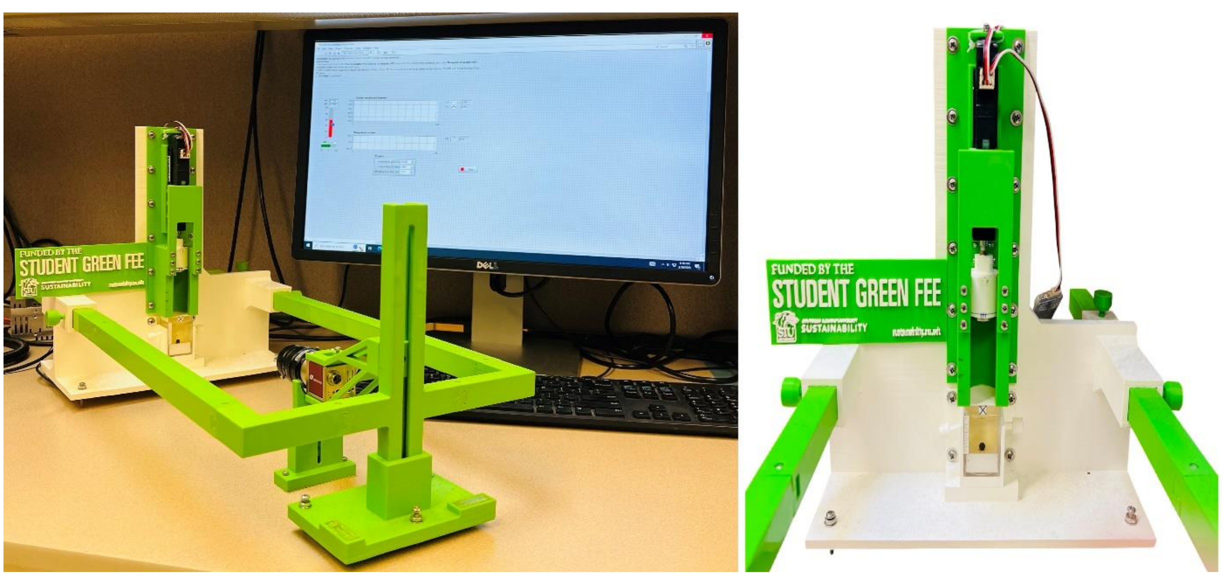



Figure 4: Magnetic levitation system developed in this project. The Green Fund Marker has been 3D-printed on the fixture of the setup.

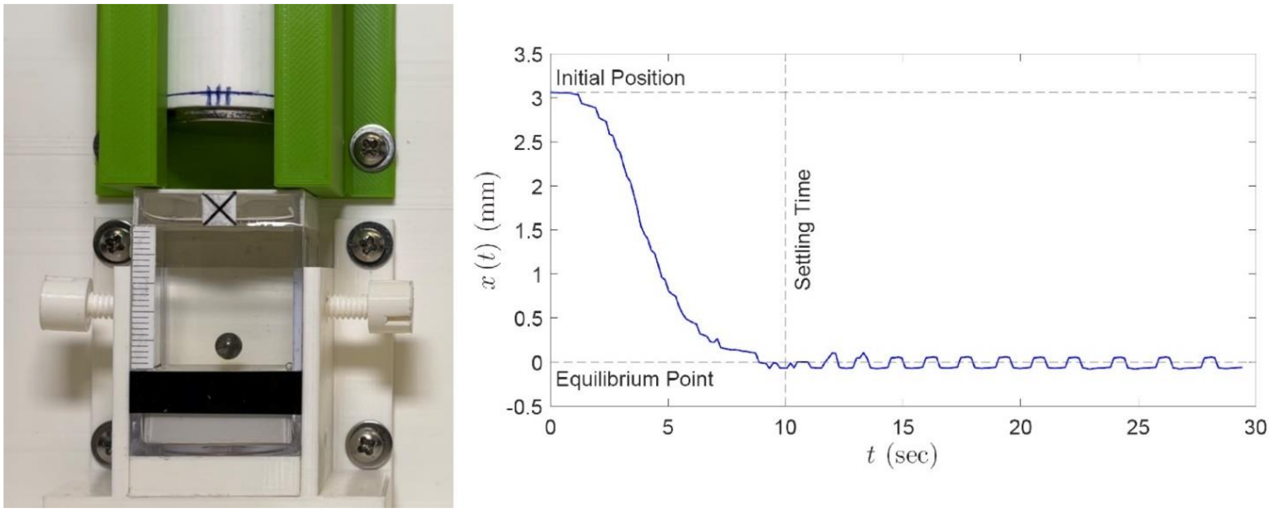
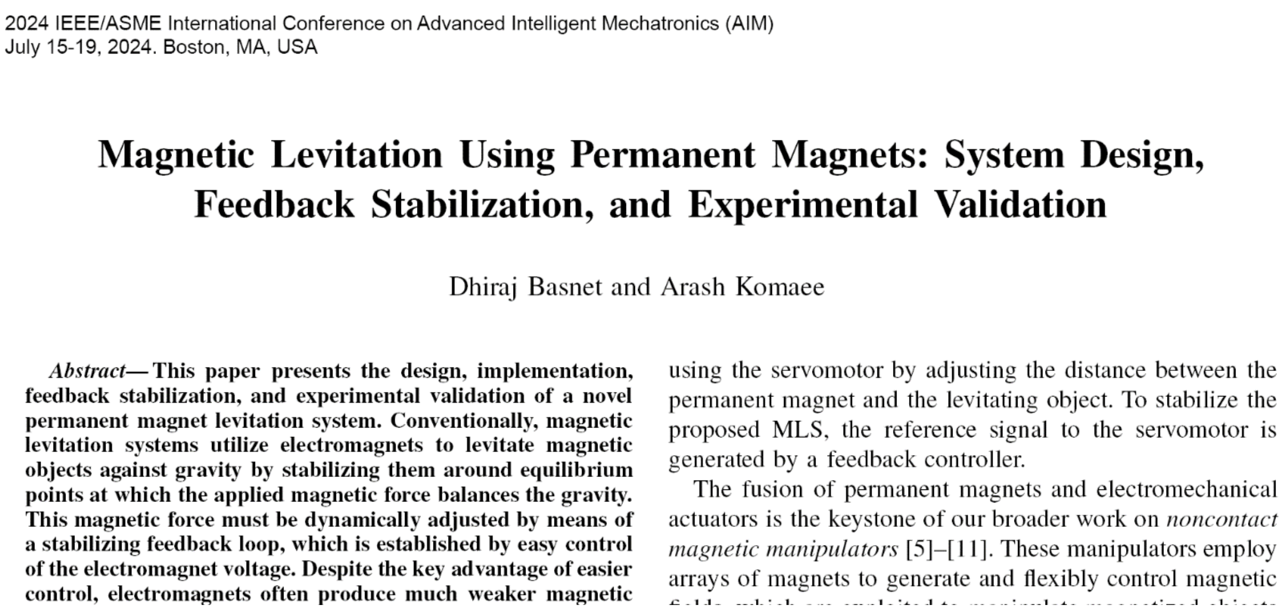



Figure 5: Successful levitation of a small magnetic bead by the setup developed in this project. The graph on the right-hand side illustrates the position x (t) of the magnetic bead versus time during the levitation process, starting at t = 0. As shown in this graph, the magnetic bead is initially at x (0) ≃ 3 mm (i.e., 3 mm below its equilibrium point), and within about 10 seconds, it reaches the steady state with an error of ±0.08 mm from the equilibrium.



2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
July 15-19, 2024. Boston, MA, USA

# Magnetic Levitation Using Permanent Magnets: System Design, Feedback Stabilization, and Experimental Validation

Dhiraj Basnet and Arash Komaee

***Abstract*— This paper presents the design, implementation, feedback stabilization, and experimental validation of a novel permanent magnet levitation system. Conventionally, magnetic levitation systems utilize electromagnets to levitate magnetic objects against gravity by stabilizing them around equilibrium points at which the applied magnetic force balances the gravity. This magnetic force must be dynamically adjusted by means of a stabilizing feedback loop, which is established by easy control of the electromagnet voltage. Despite the key advantage of easier control, electromagnets often produce much weaker magnetic**

using the servomotor by adjusting the distance between the permanent magnet and the levitating object. To stabilize the proposed MLS, the reference signal to the servomotor is generated by a feedback controller.

The fusion of permanent magnets and electromechanical actuators is the keystone of our broader work on *noncontact magnetic manipulators* [5]–[11]. These manipulators employ arrays of magnets to generate and flexibly control magnetic

Figure 6: Design, development, and successful operation of the magnetic levitation system was disseminated to the relevant research community via a conference paper and its oral presentation.

3) **Magnetic Manipulator:** Magnetic fields present a unique capacity to manipulate magnetized tools without any direct contact. Magnetic manipulators have been widely designed using arrays of electromagnets in order to exploit this potential for a range of medical, micro-robotics, and microfluidics applications. By feedback control of these manipulators, magnetized tools can be effectively driven in the directions required by an application of interest. As illustrated in Figure 7, a benchtop magnetic manipulator has been developed in this project for the purpose of both research and instruction. In Figure 8, the magnetic manipulator is operated within a computer-based feedback loop, and its successful operation is illustrated in Figure 9.


Figure 7: Magnetic manipulator, designed, prototyped, tested, and calibrated in this project. The Green Fund Marker has been 3D-printed on the fixture of the setup.

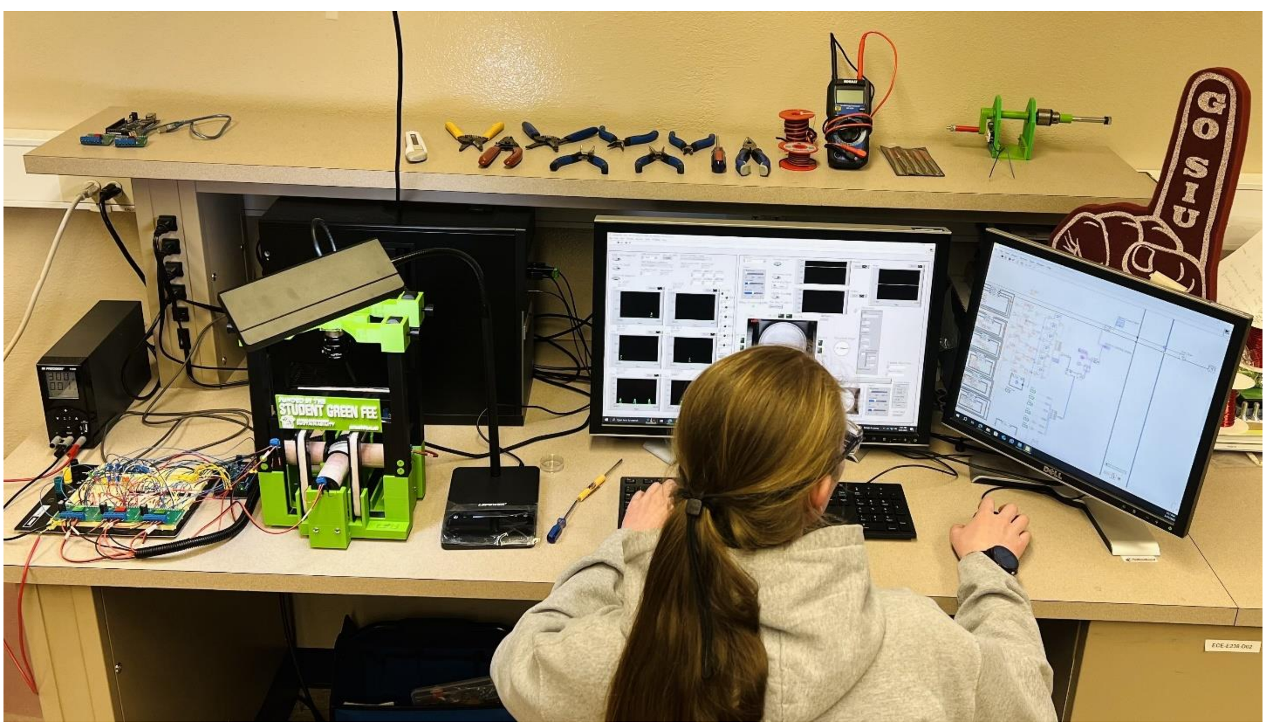



Figure 8: Undergraduate student operating the magnetic manipulator within a computer-based feedback loop.

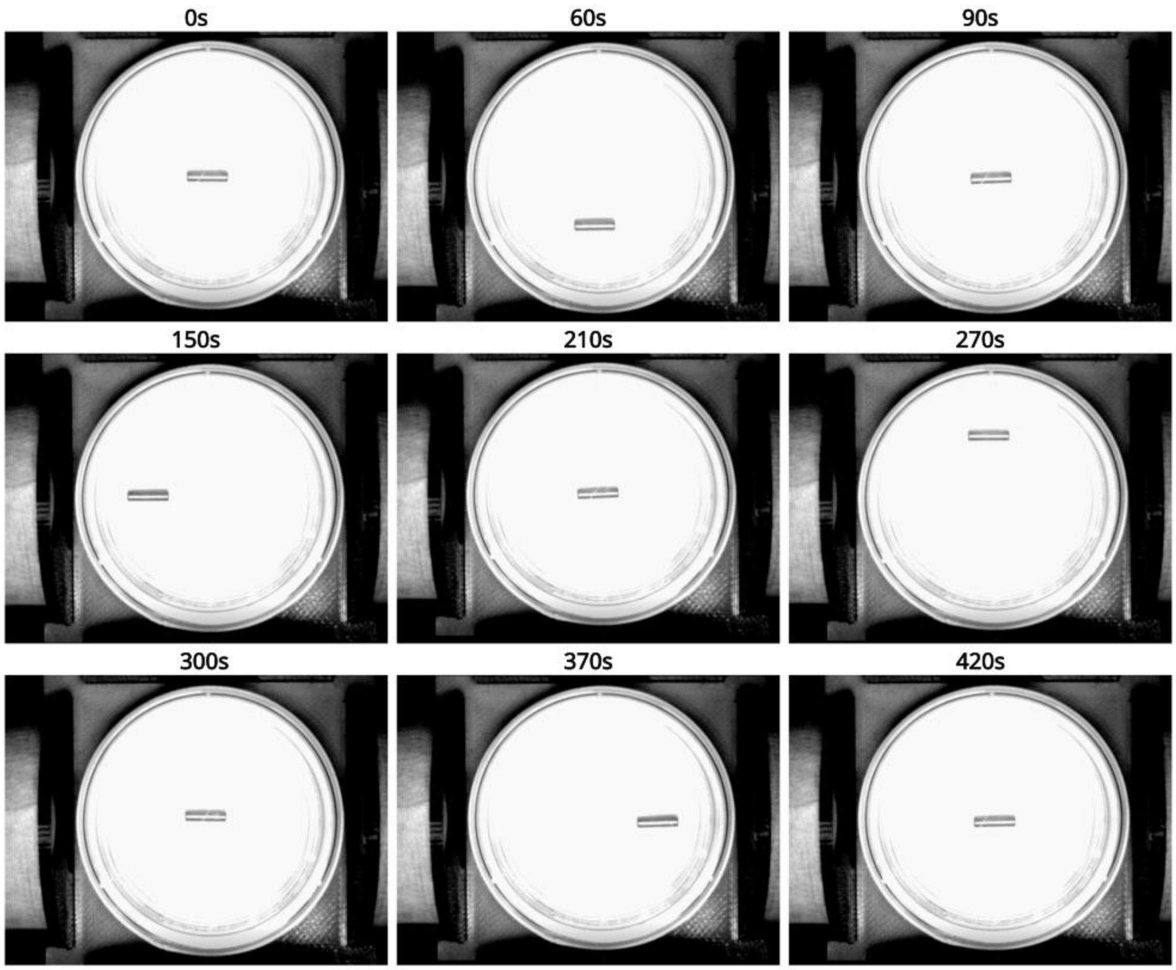



Figure 9: Successful operation of the magnetic manipulator: a small magnetic rod is moved arbitrarily around the center of a circular workspace while maintaining its heading unchanged.

3. Summarize how your project promoted the Green Fee/Sustainability on campus including, but not limited to, flyers created, screenshots of website, signage, etc. Please include website links, if applicable. (Reminder: you are required to promote your project using at least 2 items from the awardee website promotion list.)

The project promoted (or will promote) the Green Fee/Sustainability in the following ways:

1) **Instructional Activities:** The PI will leverage the laboratory setups developed in this project to improve the instruction of the undergraduate courses ECE356/ECE356L (Linear Control Systems) and BME356/BME356L (Physiological Modeling and Control), as well as the undergraduate/graduate course ECE456/561. These setups present a great potential to introduce new topics to these courses, particularly extending their experimental component. As part of each experiment/lecture that will be based on these setups, a brief introduction on their environment-friendly design will be provided, which will offer a first-hand experience of such designs to all ECBE graduates taking these courses.

2) **Conference Presentation:** The successful results of experiments with the magnetic levitation system developed as part of this project have been presented by the PI in the 2024 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2024). During the presentation, the magnetic

levitation system was introduced via Figure 4, and further, in a slide at the end of the presentation, Green Fee/Sustainability was acknowledged among the sponsors of the presentation. This procedure will be repeated for any future presentations originated from the setups developed in this project. In the future presentations, a sentence will be included to highlight the importance of environmental considerations in engineering design.

3) **Publication:** The PI and the PhD student led the project coauthored a paper for publication and presentation in 2025 IEEE 21st International Conference on Automation Science and Engineering to be held August 17 – 21, 2025, Los Angeles, CA. In the published version of this paper, the support from Green Fee/Sustainability will be explicitly acknowledged. Another paper is in preparation together with the MS student involved in the project, which will again acknowledge the sponsorship of Green Fee/Sustainability.

4. Provide evidence of how you used the Green Fund Marker in your project.

As clearly displayed in Figures 1, 4, and 7, the Green Fund Marker was 3D-printed on the fixtures of all 3 setups prototyped in this project.

5. Is there anything you would do differently if you were to do a similar project in the future? If so, please describe.

The PI believes the project was well planned, which in turn allowed for its smooth and successful implementation. Perhaps, the project scope could be broader to some extent by developing 4 or more setups rather than only 3. The PhD student who led the team demonstrated excellent leadership skills, and most likely, could successfully lead a larger team including at least 1 more student.

6. Provide as an attachment to the email (see email address below) a minimum of 5 digital images. A minimum of one of the five images should include a person. Images should be of high a quality as possible and be attached in jpg format, if available. Images will be used to promote interest in sustainability projects on campus and may be used on our website and in other promotional material. These can be photos of the progress of the project or the completed project. Provide captions for photos here.

1) Figure 1: Engineering design with minimal usage of non-eco-friendly material.
2) Figure 2: 3D-printing using biodegradable material.
3) Figure 3: Inverted pendulum optimally designed for minimal usage of material and prototyped eco-friendly using biodegradable 3D-printing material.
4) Figure 4: Magnetic levitation system optimally designed for minimal usage of material and prototyped eco-friendly using biodegradable 3D-printing material.
5) Figure 5: Student operating an eco-friendly laboratory setup, 3D-printed by biodegradable material.

7. In 2-5 sentences, describe what you learned from completing the Green Fund grant process. Include a detailed response (Do not simply respond “yes” or “no.”) to at least one of the following questions to help us understand how this project has impacted your overall university experience.
    - Do you have a different understanding of sustainability now than you did at the beginning of the process?
    - Did you apply knowledge or skills learned from courses at SIU?
    - Did the completion of the Green Fund grant process help to prepare you for your future career opportunities?

The PI would like to answer this question on behalf of the students involved in the project. The answer was prepared as a summary of an exit interview involving all the participants.

- This project has been a different experience for the participants, since for the first time in their training as engineers, it posed an environmental constraint on an engineering design process, namely, minimal usage of non-eco-friendly materials. Overall, they agree that the project has raised their environmental awareness.
- The participants extensively applied the engineering knowledge they learned from SIU courses, in particular ECE356 (Linear Control Systems), ECE456 (Mechatronics and Embedded Control), ECE566 (Linear Systems Theory), ECE564 (Optimal Control), and ECE565 (Nonlinear Systems).
- The participants believe that the experience they gained in this project will arm them with the environment-friendly engineering design techniques that essentially offer them many new career opportunities, specifically in a world that increasingly invests on sustainable technology.

8. List suggestions for the SIU Sustainability Council to improve the Green Fund Award Process here:

The process for Green Fund Award was well organized and easy to follow through its direct and accessible instructions. In particular, the simple, friendly templates for both proposal and final report were very helpful. On behalf of all team members, the PI would like to appreciate all your efforts in support of our Green Fund project, which can notably contribute to the goal of sustainability in SIU.