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Integrating Open-Source Artificial Intelligence Tools into Capstone Design and Undergraduate Research Projects

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Introduction

This paper presents the implementation of the learning-by-doing pedagogical method into the design and development of smart systems integrated with open-source artificial intelligence (AI) tools for their operations and automated controls. The goal is to provide students with opportunities to be creative in researching and developing open-ended solutions to practical problems, while satisfying the requirements and constraints. Assessment tools, success observed, challenges faced, lessons learned, and student learning outcomes (SLOs) aligned with the Accreditation Board for Engineering and Technology (ABET) criteria are discussed based on case studies of capstone design and undergraduate research projects. The following three case studies are discussed in this paper.

Case Study 1: Remotely Controlled Surveillance Vehicle – a completed capstone design project
A capstone design project completed by two undergraduate students majoring in Mechanical Engineering Technology (MET) and Electronics and Computer Engineering Technology (ECET). A remote-controlled vehicle equipped with a track drive system, a camera, and algorithms based on the open-source You Only Look Once (YOLO) AI tool and controlled by a Raspberry Pi (PI) single-board computer (SBC), was developed for surveillance and detection of targeted objects in unstructured terrain.

Case Study 2: Automated non-lethal Projectile Launcher – an in-progress capstone design project
Two teams, each consisting of three students majoring in Engineering Design Technology (EDT), MET, and ECET, are currently working on an industry-sponsored project to develop an automated non-lethal projectile launcher. The system automatically detects the presence and distance to the targeted objects, then adjusts the launcher in both horizontal and vertical directions before launching the projectile. Currently, the students are conducting literature reviews to detect the controller, actuator for adjustments, and image analysis tools for object detection. An initial system design has been completed at the end of the Fall 2025 semester, and the teams are focusing on building and testing prototypes in the Spring 2026 semester.

Case Study 3: Rapid Detection of Parasitic Nematodes – a completed funded research project
With the support of the US Department of Agriculture (USDA), 15 undergraduate students majoring in MET, EDT, ECET, and Computer Science (CS) worked on a project to develop a smart device that can be used for on-site tests to determine whether a plant is infected with parasitic nematodes, invasive plant pests, during the 2020~2024 academic years. TensorFlow and Open-Source Computer Vision (OpenCV) AI tools are deployed on a PI SBC, which controls a camera to capture images of plant root systems and then detect the presence and species of parasitic invasive pests using machine learning (ML) and object detection and identification algorithms based on image analysis. Similar approaches are being adopted in an ongoing research project to equip a robotic arm with computer vision for automated material handling. An autonomous mobile

vehicle is also being developed with environmental sensing capabilities, enabling a mounted collaborative robotic arm equipped with computer vision to perform various functions automatically and flexibly. The goal is to integrate these smart robots with other manufacturing equipment for a fully automated manufacturing system.

Case Study 4: Computer Vision for Robotic Arms – an ongoing unfunded research project
A volunteer undergraduate student majoring in ECET conducts this research focusing on integrating the vision kit for DexArm to equip the robotic arm with computer vision for more intelligent operation. The ultimate goal is to build an educational manufacturing cell that integrates robotics for fully automated operations.

Problem Definition and Objectives
With rapidly increasing capabilities, the availability of open-source tools, and the exponential growth of computational power in SBCs, the Industrial Internet of Things (IIoT), ML, and AI are being widely applied and adopted in the design and development of smart devices essential to Industry 4.0. Accordingly, there is a pressing need for qualified employees possessing fundamental knowledge and skills in these fields, with applications for solving real-world problems. It creates a new challenge for educational institutions to foster a learning environment that trains and equips engineering and technology students with the necessary knowledge and skills to be creative and thus enables them to lead and drive the further evolution of AI tools. Numerous studies and publications show that active learning, as defined by Bonwell, *is anything that involves students in doing things and thinking about the things they are doing*, is more effective, especially in the fields of engineering and technology education [1]. Capstone design courses and faculty-led research projects provide an ideal environment to incorporate learning-by-doing active learning pedagogy, engaging students by posing problems that require them to work in groups and be creative to develop open-ended solutions [2].

The ETEC4199 Senior Design I (one credit) and ETEC 4399 Senior Design II (three credits) at XXXX University are required major courses for Engineering Technology students with EDT, MET, and ECET majors, and they are offered in a Fall/Spring sequence. For research projects, both non-funded and funded either externally or internally, leading faculty always form a group of undergraduate students with diverse educational backgrounds and experience as research assistants, depending on the project's needs. The group will then work under the supervision of the faculty and meet weekly to discuss progress and plan for future work. The following are the overall objectives of the two courses and research projects, aligning with all SLOs specified in the criteria of the ABET Engineering Technology Accreditation Commission (ETAC).

1. understand the objectives of engineering design projects and processes for applying technical knowledge to solve practical engineering problems,
2. have hands-on experience in engineering design and analysis, prototype fabrication, experimental design, and testing to satisfy design requirements and prescribed constraints,
3. develop project management skills and experience in teamwork, planning, execution, and reporting, and

4. experience in technical communication in both written and poster presentation forms in an undergraduate research symposium, and oral presentation forms.

Case Study

In this section, case studies of completed and ongoing capstone design and research projects involving the use of various open-source AI tools are discussed. Brief background information about the projects, definition of the problems, system design and test, failed and successful implementation, further development plans, and project management are presented.

1. Remotely Controlled Surveillance Vehicle

In an age in which automated remote surveillance technologies are rapidly evolving, remotely controlled (RC) vehicles have emerged as valuable tools for both recreational and practical applications. This project focuses on the development of an RC all-terrain vehicle that integrates live video streaming, a wide-angle view via camera movement, and object detection. Designed with expandability in mind, the vehicle utilizes a PI 4B SBC as the central control hardware, making it a low-cost solution for real-time reconnaissance and remote monitoring.

The vehicle is equipped with a 64-megapixel autofocus camera, a 270-degree servo motor to rotate the camera, and a YOLO-based object detection model to identify and track objects in real time. A 2.4 GHz radio transmitter is used to control the vehicle, while video feed and camera control are managed via the PI. The system is designed to have independently operated navigation and image processing functions, allowing modular design for future upgrades, such as autonomous navigation or integration of other sensors. The main objective is to apply theoretical knowledge to design and develop a functional prototype, and thus gain experience in embedded system design, image processing, and wireless communication, by combining mechanical, electrical, and software components into an integrated system, a proof-of-concept for applications in remote surveillance in hazardous regions, and an educational platform for computer vision.

Commercially available RC vehicles today are either designed for single functions, such as obstacle avoidance or simple video streaming, or equipped with advanced sensors, such as Light Detection and Ranging (LiDAR), for 3D mapping, often making them cost-prohibitive and too complex for educational or budget-limited applications [3]. The proposed RC vehicle provides real-time situational awareness in a modular and affordable form. Vision-based simultaneous localization and mapping techniques demonstrate that visual inputs alone, when processed efficiently, can be used for navigation and environment recognition. Techniques such as two-stage image matching and image saliency methods dramatically improve recognition speed and accuracy while minimizing processing demands [4]. The role of computer vision, specifically YOLO-based object detection models, has been transformative, enabling real-time scene understanding on compact platforms. YOLO models prioritize speed and single-pass detection, making them ideal for embedded systems like the Raspberry Pi 4. Studies show that YOLO’s efficient architecture enables practical object detection even under hardware constraints, balancing detection accuracy and computational time, which are critical for the proposed RC vehicle [5].

SolidWorks computer-aided design (CAD) software is used to design components, assemblies, and motion analysis models for the vehicle's body with a focus on providing structural support and durability for unstructured terrain. The design adopts modular concepts so that the vehicle can be easily prototyped and changed for other applications, such as incorporating additional sensors. A Fused Deposition Modeling (FDM)- based 3D printer and Polyethylene Terephthalate Glycol and Polylactic Acid filaments are used to fabricate the prototype, with consideration for load-bearing capacity, impact resistance, and wear due to friction. Reinforced internal mounting structures are designed to securely house the battery, driving motors, servo motor for the camera module, and other electronics and accessories. Bash scripts are downloaded and installed on the Raspbian operating system (OS) running the PI so that the 'libcamera' library for the ArduCam 64MP Hawkeye camera can be used for video streaming, object detection, and object tracking. OpenCV and YOLO through Ultralytics are downloaded and installed on Raspbian as well. Figure 1 shows the CAD model without electronics and the prototype of the RC vehicle with all electronics assembled.

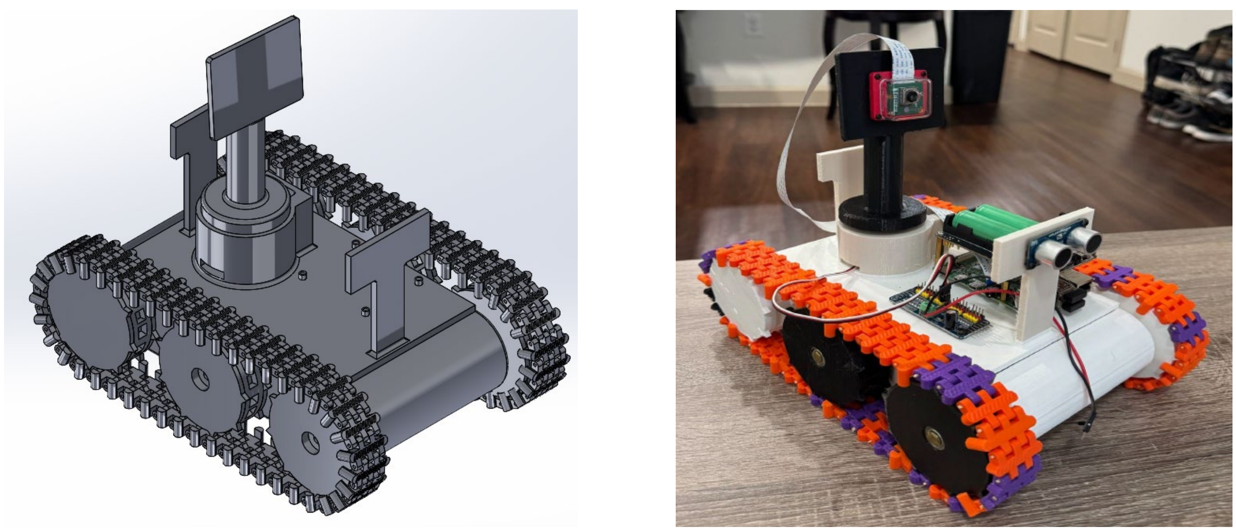


Figure 1 CAD Model and prototype of the RC vehicle

The team consists of two MET students: one focusing on CAD design, prototype fabrication, power systems, and RC hardware, and the other on PI, camera, and object detection. The team meets weekly with the faculty advisor to discuss project progress and activities to complete tasks in accordance with the proposed timeline. Although the physical prototype was successfully developed and the vehicle runs on various terrains using a 2.4 GHz remote controller as designed, the student working on the object detection function using YOLO failed to deliver a working prototype.

2. Development of an Automated Non-Lethal Projectile Launcher

This is an ongoing capstone design project focusing on the development of an automated non-lethal projectile launcher. The goal is to build an automated security system that provides real-time monitoring, detects targeted objects or individuals, and controls a non-lethal projectile launcher. The system is designed to operate autonomously to detect, recognize, and track objects and individuals. When a target is identified as unauthorized or illegal presence using object detection AI tools and face-recognition-based ML algorithms, the system will automatically adjust the launcher's orientation and then launch a non-lethal projectile at the target after sending a notification to and receiving confirmation from authorized operators. A major feature of the system is the pan-and-tilt mechanism, which allows the camera mounted in line with the launcher to rotate horizontally (pan) and vertically (tilt), automatically controlled by the AI algorithms, keeping the launcher aiming at the detected objects while waiting for instructions from authorized operators. These pan-tilt motions are driven by two servo motors that work collaboratively to reposition the camera and launcher at the detected objects.

The system incorporates a PI-compatible camera module, which captures real-time images of the surroundings. Face recognition algorithms using OpenCV and TensorFlow-based machine learning models will compare these images to a pre-trained database of allowed objects and users' data to determine the legality of the detected objects or individuals. The overall goal is to integrate mechanical systems, electronics, and AI tools into a compact, automated security system that is efficient and affordable.

Two teams, each consisting of three students (one team has one EDT, one MET, and one ECET student, and the other team has three MET students), are currently working on it. Both teams meet with their faculty advisor weekly. The team members are responsible for the three main tasks necessary to complete the project: 1) a physical model allowing pan and tilt motions of the launcher; 2) electronics and power system to operate the battery/grid hybrid power supply and the two servo motors; 3) object detection based on images from the camera to control the pan and tilt operations. The teams have completed the system design and are now working on prototype development and testing. Figure 2 shows the initial and final design of one team.

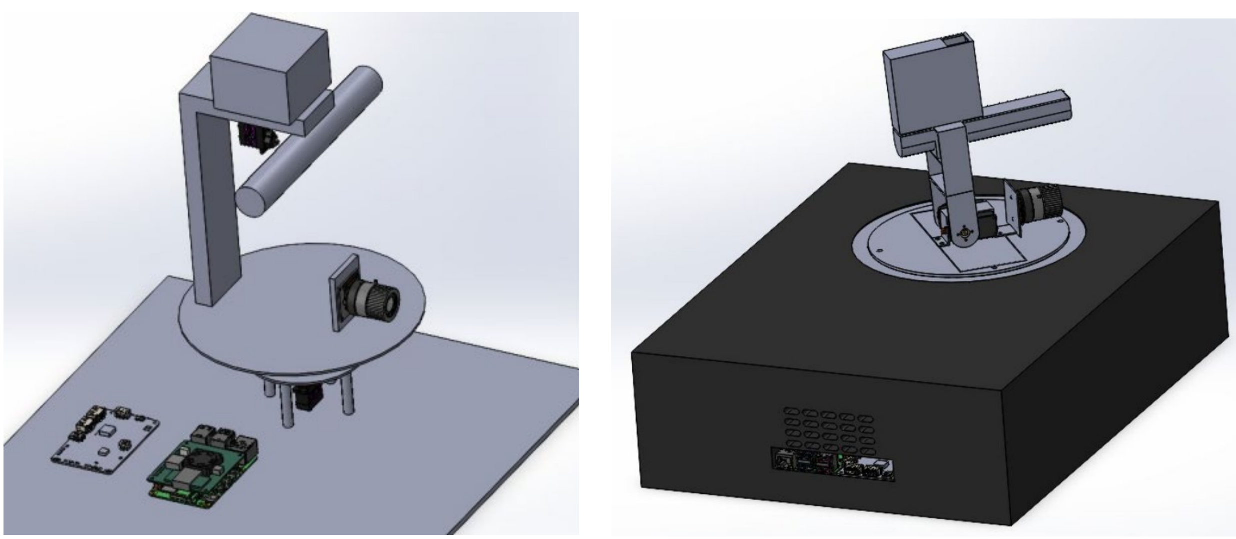


Figure 2 Initial and final design of the launcher

3. Development of a Handheld Device for Rapid Detection of Parasitic Nematodes

Parasitic nematodes, slender roundworms that are typically 0.5~1.5mm long, are problematic pests of numerous crops, causing significant issues within the nursery industry due to the industry's need to continuously obtain maximum seedling and plant production, typically with the same or similar stock plants, and in proximity to one another[6]. Their penetration of host tissues, primarily through root systems, can disrupt water and nutrient uptake and flow, resulting in underdeveloped plants and major agricultural losses. Parasitic nematode diagnostics are achieved via visual inspection of host plant roots' morphological features and microscopy or molecular techniques. However, these techniques are time-consuming and expensive and may destroy healthy plants and/or plant tissue [7]. The need to develop new innovative ways and equipment to detect these nematodes is crucial. This USDA-sponsored research project focuses on the development of an innovative handheld device for rapid in-situ detection of parasitic nematodes by integrating imaging and ML-based imaging analysis into a minirhizotron design.

The root systems of parasitic nematode-infected plants typically show abnormal morphological characteristics, such as tiny (~0.5mm) lemon-shaped cysts attached to or large knots on the host plant root systems. This character enables non-destructive detection by using a minirhizotron to image the root systems of infection-suspected plants. By developing and applying ML and object detection algorithms to train and analyze these images, it is feasible to detect the presence and species of parasitic nematode infections. A comprehensive literature review is conducted to identify potential solutions for developing this device. SolidWorks CAD software is used to design the prototype, which is fabricated using FDM 3D printing methods. Open-source software tools, including Pytorch [8], an ML library integrated within Python for computer vision applications, Detecto [9], an image analysis-based object detection and inference, LabelImg [10], a tool used for image annotations and labeling, and finally Matplotlib[11], a tool used to display the results of analysis results graphically, are used to develop the software and graphic user interface for the device. A web-based remote-control interface is also developed, allowing authorized users to log in and remotely access multiple such devices deployed in the fields.

A team of 15 undergraduate students, including EDT, MET, ECET, and CS majors, worked on the project over the 2020~2024 academic years. Typically, among the three to four undergraduate students working simultaneously, there is always a CS major leading AI-related tasks, an ECET student leading electronics-related tasks, and an EDT and/or MET student leading physical design and experimental testing-related tasks. A group meeting, including both undergraduate students and faculty members with MET, ECET, EDT, and Agricultural Science (AG) backgrounds, is held weekly throughout the entire process. Figure 3 shows a section view of the fully assembled CAD model and a prototype minirhizotron (with a different length than the CAD model minirhizotron) being used in a field test. Figure 4 shows an image of the cyst nematode-infected tomato plant root system, captured by the minirhizotron, transferred to cloud storage, processed by detection algorithms, and displayed in a web browser-based user interface. Figure 5 shows the detection and identification of cyst and root-knot nematodes with the suspected infected location highlighted, identified species labeled, and accuracy values displayed in a graphical user interface designed for the minirhizotron.

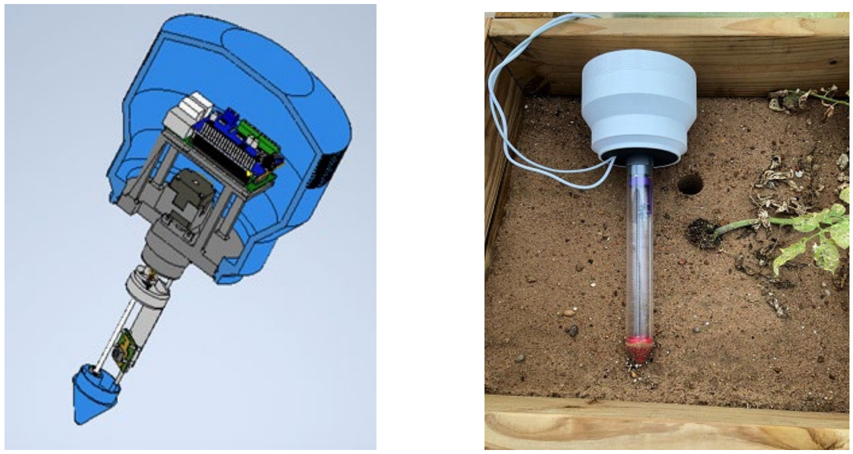


Figure 3 CAD model and prototype of the minirhizotron

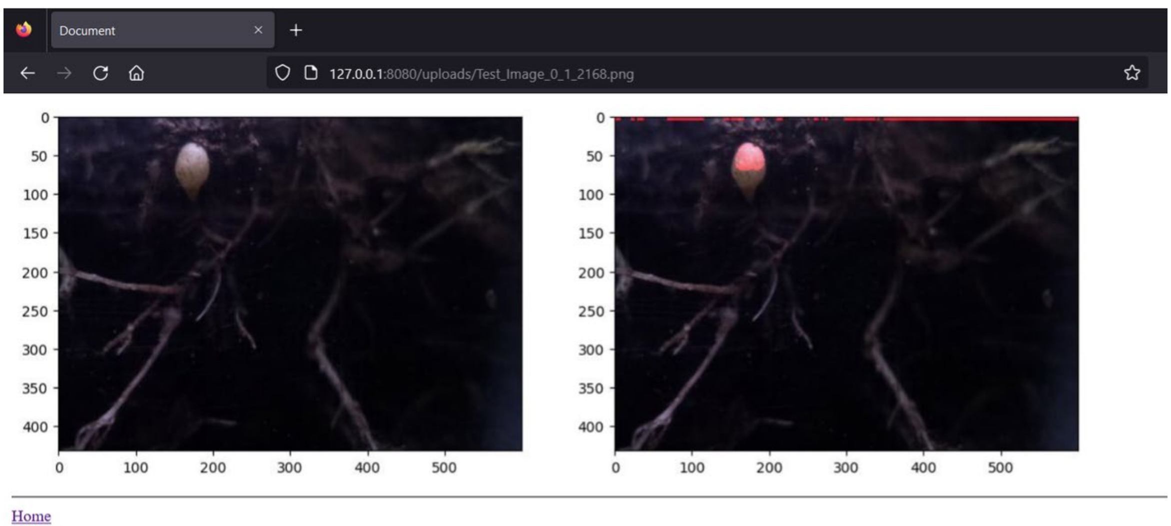
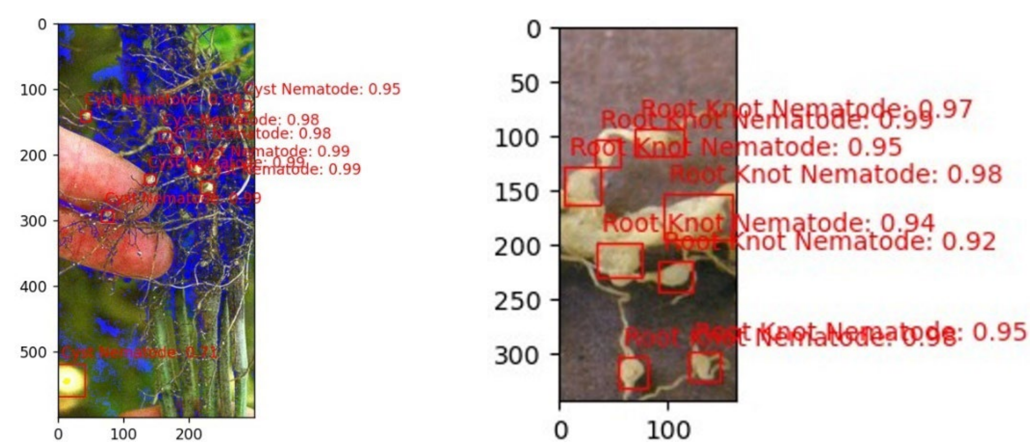


Figure 4 Sample image processing results using the web-browser-based user interface



(a) (b)

Figure 5 Sample detection and species identification results

4. *Computer Vision for Robotic Arms*

With increasing concerns about supply chain security and rising costs associated with outsourcing, the US manufacturing industry is returning and experiencing robust growth in both revenue and employee numbers. One of the key upgrades in the US manufacturing industry is the adoption of Industry 4.0, which incorporates ML, AI, IIoT, and industrial robots in warehouse operations, material handling, quality control, assembly, and other manufacturing processes. It creates a manufacturing skills gap, demanding a workforce equipped with digital skills to work with automated systems [12].

As desktop educational robotic arms, such as the DexArm [13] and MyCobot 280 [14] units with identical functions but less load capacity compared to the industrial systems, are becoming more reliable, cheaper (<$1,000), and readily available, it is practical to use these systems for the development of education systems. Since DexArm is controlled by a PI SBC and Raspbian OS, a customized open-source Debian Linux distribution for PI developed based on the open-source Marlin project, the DexArm firmware and G-Code control commands are free and open-source, compatible with the Marlin firmware. Being the world's leading open-source project, Marlin has been widely adopted and supports many 3D printing platforms, computer numerical control (CNC) mills, and laser engraving and cutting systems.

This ongoing project, conducted by a volunteer undergraduate student majoring in ECET, focuses on integrating the vision kit for DexArm to equip the robotic arm with computer vision for more intelligent operation [15]. Based on the Vision Terminal open-source platform developed for the DexArm, using open-source PyQt5, PySerial, OpenCV-Python, and DexArm API GUI and AI libraries, it is further enhanced to allow the collaborative operations of the camera and a rotary air picker to pick, align, and place identified objects based on their color, shape, and orientation. Figure 6 shows the shape-based picking, orienting, and stacking operations of the arm.

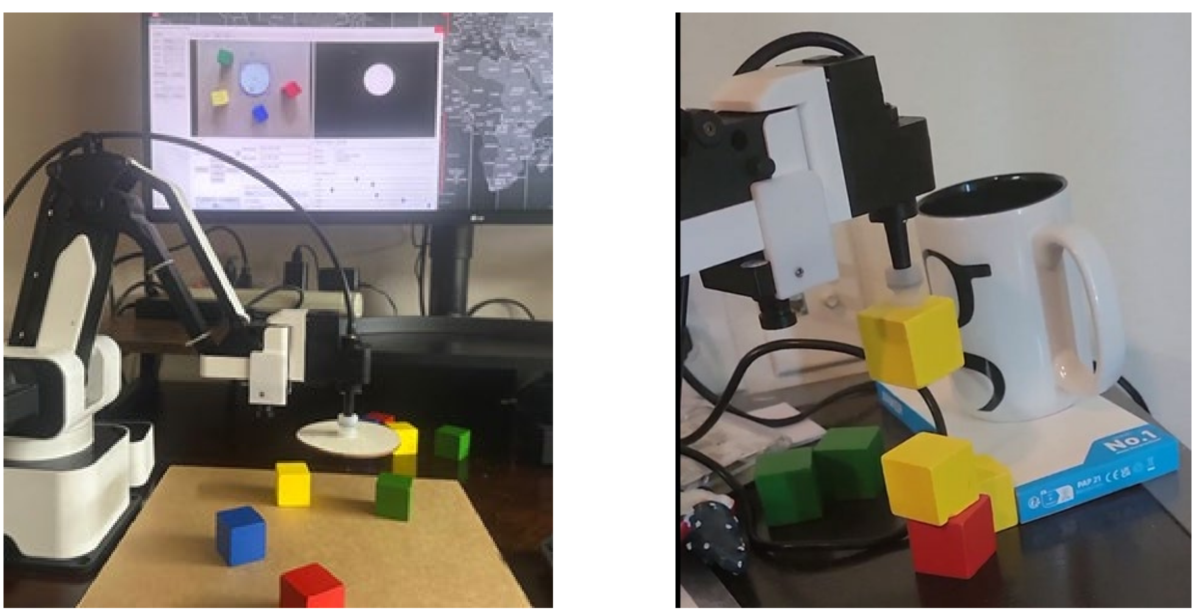


Figure 6 Picking and stacking based on the shape of objects

Assessment
Students' performance in the two senior design courses is assessed using similar instruments with different requirements.

4XXX Senior Design I:

1. Project identification and pre-proposal: students review a list of available projects provided by industrial sponsors and faculty or propose a project with sufficient engineering design, analysis, prototype development, and technical writing components to identify a capstone design project. Teams of two to three students with the required educational backgrounds for the project are formed, and faculty mentors for each team are identified. A pre-proposal, including the project title, team members, faculty mentor, problem definition, project objectives, and potential solutions, will be submitted.
2. Midterm project proposal: teams submit a report detailing their selected solution and design approach, including technical details such as specifications, block diagrams, graphs, references, a proposed timeline with benchmarks, and other documents used to address the problem.
3. Final technical report: teams submit a final design-phase technical report showing detailed block diagrams, graphs, CAD models, and engineering drawings of the initial design, analysis, and simulation results; achievements based on the timeline and benchmarks; a bill of materials; a cost analysis; and a plan for prototype fabrication and testing.

4XXX Senior Design II:

1. Finalized design phase report: teams submit a report containing finalized designs ready for prototype fabrication and testing.
2. Midterm project proposal: teams submit a report documenting prototype development, experimental test, iteration of design changes, and testing results.
3. Poster presentation: teams submit posters for presentation at the XXXX University Undergraduate Research Symposium, held annually in late April.
4. Final technical report: teams submit a final technical report showing detailed design documents as described above.

Teams present their reports to the class to solicit feedback, and the final technical report will be presented to the class, faculty, industrial sponsors, and members of the department's industrial advising board. The reports and presentations will be graded using the rubric shown in Table 1.

A final report summarizing design requirements, design options and criteria for selection of the final design, CAD models and engineering drawings, analysis such as motion studies and strength analysis, bill of materials, project timeline with benchmarks, prototype building, testing, and redesigning iterations, is to be submitted. As a minimum requirement, a partially functional prototype, a poster presented at the annual URS event, and other project documents (meeting logs) are to be submitted for assessment purposes. Table 2 shows assessment breakdown with different associated weights.

Score	1 (poor)	2	3	4(best)
Grammar / Mechanics	more than five spelling or grammar errors throughout the documentation.	three or four spelling or grammar errors throughout the documentation.	more than two spelling or grammar errors throughout the documentation	no spelling or grammar errors.
Graphics	figures, tables, schematics, or graphics are not incorporated into the presentation and documentation.	misuse graphics, inappropriately captioned, or included irrelevant information.	uses graphics that relate to the subject and the text.	uses advanced graphics and/or other software tools to enhance presentations and documents.
Appearance	Personal appearance is inappropriate for the occasion and audience. (T-shirt)	Personal appearance is inappropriate for the occasion and audience. (Business casual)	Personal appearance is appropriate for the occasion and audience. (Business attire)	Personal appearance is completely appropriate for the occasion and audience.
Preparedness	The student is not prepared to present.	The student is somewhat prepared but has not yet rehearsed.	The student is prepared but could use more rehearsal	The student is prepared and well-rehearsed.
Delivery	The student reads all the information from the electronic presentation or cue cards, making no eye contact with the audience.	The student frequently uses electronic presentations or cue cards but maintains some eye contact with the audience.	The student refers to bullet items in the presentation or cue card and maintains eye contact with the audience.	Students rarely refer to electronic presentations or cue cards and maintain eye contact with the audience.
Elocution *(distinct pronunciation and articulation)*	The student speaks unclearly and incorrectly pronounces words.	The student speaks softly and pronounces most words correctly.	The student speaks clearly and pronounces words correctly.	The student speaks clearly, projects, and pronounces words correctly.
Demonstration	No Demonstration *(project failed at the last minute)*	Partially functioning demonstration	Fully functioning demonstration.	Fully functional demonstration of all project aspects.

Table 1 Rubric for grading report and presentation

Assessment Breakdown	
Team and class participation; attendance (group meetings with/without faculty mentor)	20%
Initial project proposal (10%), project progress report (10%), final project report (20%), and associated presentations, as well as prototype demonstration (10%)	60%
Meeting minutes, testing notes, peer review & grading on presentations	10%
Poster presentation at annual Undergraduate Research Sympodium	10%

Table 2 Assessment items with different associated weights

The online Individual Development & Educational Assessment (IDEA) evaluation system, administered by XXXX University, collects student ratings of learning for relevant objectives. Table 3 shows the student ratings for ETEC4399 Senior Design II in Spring 2025, in which the students in the first case study enrolled (ETEC4199 is not assessed using this tool since it is a one-credit-hour course). The majority of the students (87%) agree that they have learned to apply course material, aligning with the first SO of the ETAC general criteria. Although 83% of the students agree that they have acquired skills in a team-working environment, which aligns with the fifth SO of the ETAC general criteria, 10% still disagree, indicating potential to improve the team-forming process and management further to foster a more effective team-learning environment. 87% of the students agree that they have developed skills in expressing themselves orally or in writing, aligning with the third SO of the ETAC general criteria. For students who participated in research projects, a weekly meeting and quarterly progress reports are required. They also expressed similar agreements, especially the development of skills in researching, evaluating, and developing practical solutions to research problems, and working in a team environment.

Student Ratings of Learning on Relevant Objectives (1: strongly disagree; 2: disagree; 3: neutral; 4: agree; 5: strongly agree)		**Students Rating (%)**	
	Score	**1 or 2**	**4 or 5**
Gaining a basic understanding of the subject (e.g., factual knowledge, methods, principles, generalizations, theories)	4.5	0	90
Developing knowledge and understanding of diverse perspectives, global awareness, or other cultures	4.4	10	73
Learning to apply course material (to improve thinking, problem solving, and decisions)	4.5	7	87

Developing specific skills, competencies, and points of view needed by professionals in the field most closely related to this course	4.5	7	93
Acquiring skills in working with others as a member of a team	4.4	10	83
Developing creative capacities (inventing, designing, writing, performing in art, music, drama, etc.)	4.0	20	73
Gaining a broader understanding and appreciation of intellectual/ cultural activity (music, science, literature, etc.)	4.0	17	60
Developing skills in expressing myself orally or in writing	4.6	7	87
Learning how to find, evaluate, and use resources to explore a topic in depth	4.5	3	87
Developing ethical reasoning and/or ethical decision-making	4.2	3	83
Learning to analyze and critically evaluate ideas, arguments, and points of view	4.4	7	80
Learning to apply knowledge and skills to benefit others or serve the public good	4.2	7	90
Learning appropriate methods for collecting, analyzing, and interpreting numerical information	4.5	0	87

Table 3 Student ratings of learning on relevant objectives

Future Plan

Currently, as a research project, a team of two undergraduate students with ECET and MET majors are developing computer vision equipped mobile robotic arm using a camera flange [16] for a MyCobot 280 robotic arm controlled by a PI and mounted on the top of a mobile LIMO Cobot [17] equipped with LiDAR and other vicinity sensors and controlled by a Nvidia Orin Nano SBC as shown in Figure 7. The goal is to integrate it together with the DexArm, as shown in Figure 6, into the educational automated manufacturing system [18].

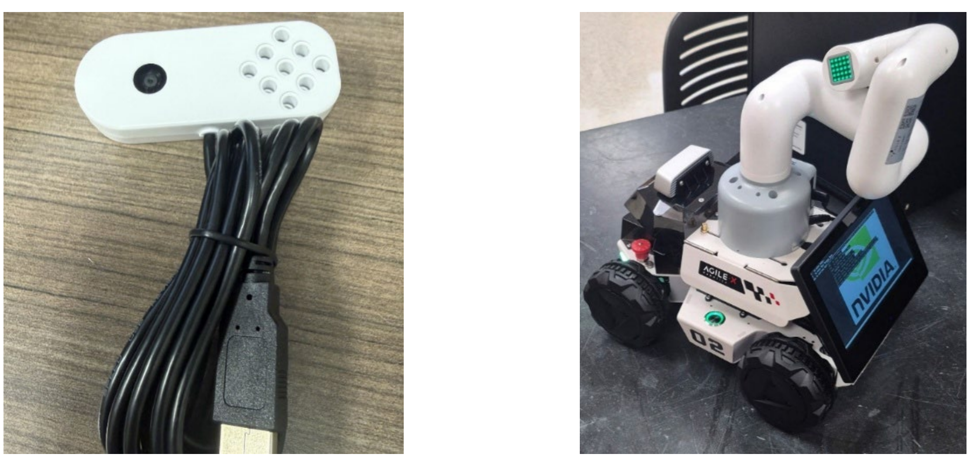


Figure 7 Camera Flange for the Mycobot 280 mounted on top of a LIMO Cobot

It is observed that, for capstone design projects with AI-related components, despite strong interest from students in EDT, MET, or ECET majors, they are not confident in tackling the challenges associated with SBC-based AI tools and the programming required. The fact that the MET student failed to build functional YOLO models for object detection in the first case study and the success achieved in the USDA research project with the involvement of the CS major undergraduate students indicates that further training in the subject for the non CS major students is necessary for them to develop knowledge and skills to work with smart systems. However, the success of the ECET major student working on case study four and the progress of the ECET and MET major students working on the LIMO Cobot show potential for their success with further training. While the curricula of the EDT, MET, and ECET majors include programming and electronics courses with a focus on CAD modeling and simulation, mechanical system design and analysis, and electronic hardware, respectively, they all lack training in AI tools running on SBCs. The author plans to discuss with faculty in these programs the feasibility of developing a new course focusing on this subject for interested students as a technical elective.

Conclusions

Integrating open-source AI tools into capstone design and undergraduate research projects provides an excellent opportunity for students to develop problem-definition, research, critical thinking, and problem-solving skills, with open-ended solutions that satisfy requirements and constraints. From successful and, more importantly, failed cases, as well as different learning curves observed among students with various backgrounds and levels of dedication, it is necessary to offer further training in SBC-based AI tools to help students be more confident when taking on similar tasks, especially for non-CS majors. It is also observed that a team's performance depends on the educational backgrounds of its members, how tasks associated with the projects are managed among them, and their level of dedication. Forming and managing an effective team for capstone design projects remains a challenging process.

Acknowledgement

The author would like to thank the 26 undergraduate students who worked on or are currently working on various capstone design and research projects mentioned above. The support of industrial sponsors, industrial advisor board members, faculty mentors, and lab technicians and staff is also highly appreciated.

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