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Development of Computer Vision Capability for Dexarm Robotic Arms used in an Educational Automated Manufacturing System

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Abstract

This paper presents the further development of the computer vision capability of an educational automated manufacturing system that integrates warehouse operation, material handling, and laser engraving manufacturing processes using low-cost desktop equipment. The system was initially developed by undergraduate students majoring in mechanical engineering technology (MET) and electronics and computer engineering technology (ECET) as a capstone design project. Then, it was further developed by a MET major student as an independent study project. The ultimate goal is to build an educational automated manufacturing system using low-cost, open-source desktop equipment simulating various material handling and manufacturing processes following Industry 4.0 standards. The open-source nature of the desktop equipment used to develop the system allows instructors and students to learn, improve, and expand the system creatively, allowing open-ended solutions.

The system consists of four Dexarm robotic arms, camera kits for the Dexarm, a sliding rail kit, a conveyor belt kit, and a safety enclosure offered by Rotrics Inc. The Dexarm is a three-degree-of-freedom (3-DOF) desktop robotic arm operated by a Raspberry Pi microcontroller. Depending on the modular tools equipped, it can perform various functions, such as laser engraving and material handling. The sliding rail moves a Dexarm on a base sliding on the rail with up to 1000mm travel. The conveyor belt kit moves material along its 700mm belt, and the safety enclosure ensures a safe laser engraving process. The system consists of three functional modules: 1) warehouse operation module: a Dexarm equipped with a pneumatic suction cup tool to pick stock material from raw material storage, transfer the stock material to the conveyor belt, retrieve the engraved material from the conveyor belt, and then place it in finished material storage; 2) material handling module: a Dexarm equipped with a pneumatic suction cup tool to pick up stock material that is moved to the engraving station by the conveyor belt, feed the stock material to the engraving station, retrieve the engraved material, and place it on the conveyor belt which sends it back to the warehouse operation module; 3) engraving station, a Dexarm equipped with a custom designed tool to open and close the safety enclosure door, a second Dexarm equipped with a laser engraving tool to engrave the stock material.

This paper focuses on developing the computer vision capability for the Dexarm to identify materials' shape and color, allowing the system to operate based on image analysis and communication between the Dexarm robots.

Introduction

With increasing concerns about supply chain security and rising costs associated with outsourcing, the US manufacturing industry is experiencing strong growth. According to the data published by the US Bureau of Labor Statistics (BLS), manufacturing-related jobs have grown from the lowest 11.419 million in April 2020 during the pandemic to 12.913 million as of September 2024, surpassing the pre-pandemic 12.828 million peak value in January 2019. Analysis conducted by Deloitte in April 2024 using quarterly census of employment and wages data from BLS also indicated that there are approximately 393,000 manufacturing entities in the US by the second quarter of 2023, an 11% growth from that of the first quarter of 2019. The analysis also shows a record-high $225 billion in construction yearly spending in the US manufacturing sector in January 2024, indicating a 37% annual increase since June 2020. The 2024 Deloitte and the Manufacturing Institute Talent Study, the sixth US manufacturing workforce study involving more than 200 US manufacturers and interviews with more than 10 senior executives, also reports that up to 3.8 million new employees are needed in the US manufacturing sector between 2024 and 2033. As the manufacturing industry continues to adopt Industry 4.0, knowledge and skills such as digital skills required to work with automated systems, analytical skills for virtual reality, and problem-solving skills are essential for these new positions. As Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoTs) are being widely applied and adopted in warehouse operations, material handling, quality control, assembly, and more and more other manufacturing processes, there is a pressing need for qualified employees with these high-level skills. The talent study indicates that the gap between the skills needed for modern manufacturing facilities and the skills the current workforce possesses still exists, which could result in more than 1.9 million (half of the projected new positions) of the new positions remaining unfilled. In addition, the quickly evolving manufacturing technologies and a tight labor market result in a shortage of applicants, further widening the manufacturing skill gaps.

Educational institutions at all levels, including high school career and technical education (CTE), technical and vocational schools, community and junior colleges, and universities, as well as non-profit training organizations, are working with industrial partners and professional organizations to develop curricula leading to professional certificates and academic degrees to help close the manufacturing skill gap. Educational equipment manufacturers are developing modular small-scale training systems simulating a manufacturing environment, including warehouse operations, material handling, manufacturing processes, inspection, assembly, etc., as platforms for hands-on training. Although these systems help provide students with practical skill development, they have a few common limitations: 1) they are designed and developed with limited or no flexibility for alteration or customization. Since manufacturing technologies evolve quickly, the systems could become outdated, requiring revisions and updates that can be time-consuming and costly; 2) they are built as a ‘black box’ allowing students to learn ‘what and how’ to conduct the pre-designed hands-on activities with limited or no understandings of ‘why’ the systems work the way they do. This significantly reduced the training and development of critical thinking and problem-solving skills; 3) both the hardware and educational materials are typically high cost, limiting accessibility for the educational institutes and students with limited funding sources; 4) they are typically protected by the manufacturers with intellectual property (IP) protections, making it practically impossible to integrate existing equipment from different manufacturers.

As desktop multi-functional robotic arms, such as the DexArm by Rotrics Inc. used in this study, with practically identical functionalities but less load capacities than the industrial systems, are becoming more affordable (<$1,000) and readily available, it is practical to use these desktop robotic arms to design and develop similar training systems. Since Dexarm is controlled by a Raspberry Pi microcontroller running the Raspberry Pi OS (also called Raspbian before 2020), which is an optimized free and open-source Debian Linux distribution for Raspberry Pi and is developed based on the open-source Marlin project, the DexArm firmware and G-Code control commands are free and open-source compatible with 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, laser engraving and cutting systems, etc. This makes training systems based on Dexarm very versatile, allowing hardware integration based on the same Marlin firmware and G-Code control command, such as the autonomous navigation smart 4-wheel drive vehicle 'myAGV' developed by Elephant Robotics. Such custom-designed flexible 'open' systems also allow further development of the existing systems, which gives students the opportunity to redesign the existing systems and better understand pertaining subjects through the 'learning-by-doing' active learning experience. It helps to develop students' critical thinking and problem-solving skills.

In the previous project, a manufacturing cell involving material handling operations and laser engraving processes was developed. The goal is to build a flexible training platform integrated with various modular subsystems incorporating technologies being developed and adopted in the manufacturing industry following Industry 4.0 standards. The platform and its subsystems are developed using the low-cost DexArm multi-functional robotic arm and the open-source Application Programming Interfaces (APIs) provided by Rotrics. The students who worked on the manufacturing cell had hands-on learning experiences and reserved the interface, allowing further development and expansion. The operations of the manufacturing processes in the previous design are time-based after careful experiments and tests. Although functional, this design gives the system no error-handling capability. As a continuous effort to improve the manufacturing cell further, this paper presents the development of the computer vision capability of the DexArm. By equipping the DexArm with a digital camera and through ML and image processing-based AI, the goal is to allow the DexArm to see, recognize, and process objects in its view field automatically.

The Automated Engraving System

As described in detail in the reference, the automated engraving system presented previously is the first attempted subsystem of the proposed training platform. The first DexArm (Robot 1) equipped with a 2.5-watt laser engraving tool positioned in a laser safety enclosure is used for engraving a round-shape wood coaster blank. To support the engraving process, a second DexArm (Robot 2) equipped with a custom-designed tool is used to open and close the laser safety enclosure door when the coaster blank is to be fed to, and the engraved coaster moved away from the safety enclosure. This subsystem is called the ‘Manufacturing Process Module,’ simulating a manufacturing process applied to raw materials in a manufacturing facility. A third DexArm (Robot 3) equipped with a rotary air picker and mounted on a sliding rail is used to pick up the coaster blank from the stock material storage area in the warehouse, place it onto a conveyor belt, pick up the engraved coaster from the same conveyor belt, and place it at the engraved coaster storage area in the warehouse. This subsystem is called the ‘Warehouse Operations Module,’ simulating automated material handling in a warehouse. A fourth DexArm (Robot 4) equipped with the same rotary air picker works collaboratively with a conveyor belt, which transfers blank and engraved coasters between the manufacturing and warehouse operation modules. Robot 4 picks up the coaster blank transferred by the conveyor belt to the right side, waits for Robot 2 to open the laser safety enclosure door, and feeds the coaster blank to Robot 1 for engraving. Once the engraving is completed, Robot 4 waits for Robot 2 to open the laser safety enclosure door, picks up the engraved coaster, and places it on the conveyor belt to be transferred back to Robot 3, which will subsequently put it in the engraved coaster storage area in the warehouse. This subsystem is called the ‘Material Handling Module,’ simulating material handling within a manufacturing facility. Figure 1 shows the schematic layout and subsystems, and Figure 2 shows the prototype of the automated engraving system. The green and red chevrons in Figure 1 represent the flow of blank and engraved coasters.

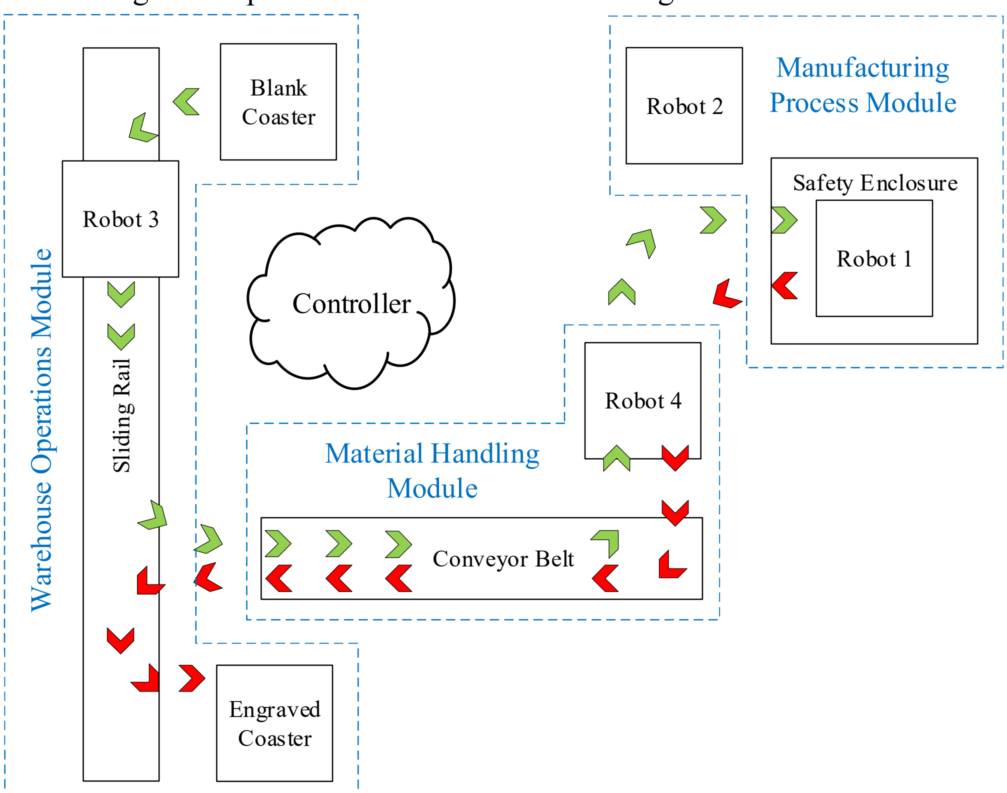

Figure 1 Schematic layout and subsystems of the automated engraving system

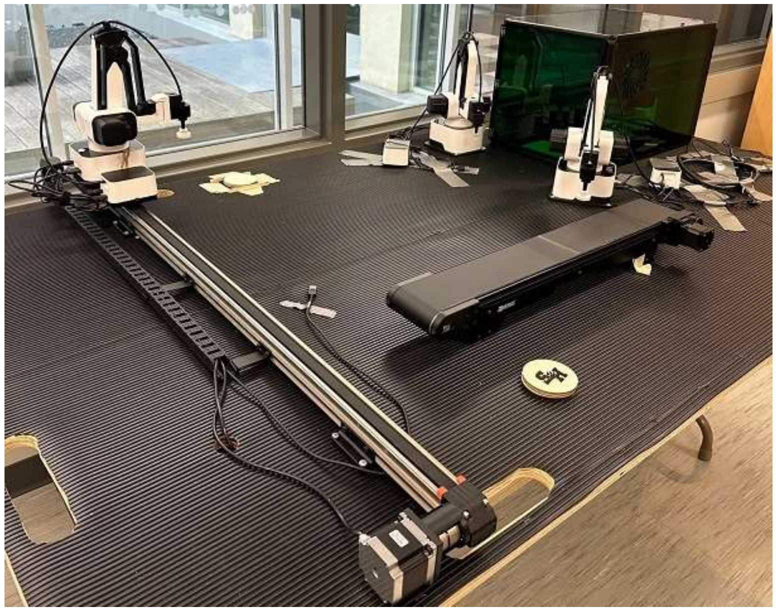

Figure 2 A prototype of the automated engraving system

The engraving process starts with Robot 3 picking up a wood blank from the blank coaster storage area. It ends with Robot 3 placing the engraved coaster in the warehouse's engraved coaster storage area, following the route represented by the chevrons. All processes the wood blank experiences are in sequence, and the controller is designed accordingly based on the time domain. Additionally, parameters such as coordinates for the positions of rotary air pickers mounted on the DexArms are determined based on experimental tests and hard-coded in the controlling software. It expects the blank or engraved coasters to be located at the predefined positions at the designated time, making the system incapable of handling any unexpected errors. In addition, the system can't perform tasks such as picking up coaster blanks in different colors or shapes stored at various locations in the blank coaster storage area or placing engraved coasters at designated locations in the engraved coaster storage area. The DexArms in the system operate based on waiting time instead of when blank or engraved coasters reach their designated position. In summary, the system has no intelligence and cannot handle out-of-sync operations or be flexible in performing different tasks based on given parameters. This project focuses on developing DexArm's computer vision capability to see the position of a targeted coaster blank based on its color and shape. The ultimate goal is to equip Robot 3 & Robot 4 with image analysis-based AI capability to perform more complex tasks by training them to recognize targeted objects.

Hardware and Development Platform

Rotrics Inc. offers a low-cost ($69) computer vision kit, which includes a compact (36×36×30 mm) with a 2.0-megapixel (1920 x 1080) resolution and a light-weight digital camera that can be mounted to the DexArm using a set of brackets provided. It is powered and interfaces with a controller easily via a standard USB cable. The scratch-based ML building block incorporated in the Rotrics Studio allows one to easily create ML and AI projects with color recognition and object tracing capability. The most critical aspect of this project is that Rotrics also provides industrial-grade computer vision APIs, allowing the development and integration of computer vision capability into DexArm for color and shape recognition. Figure 3 shows the hardware setup for developing the computer vision-related functions.

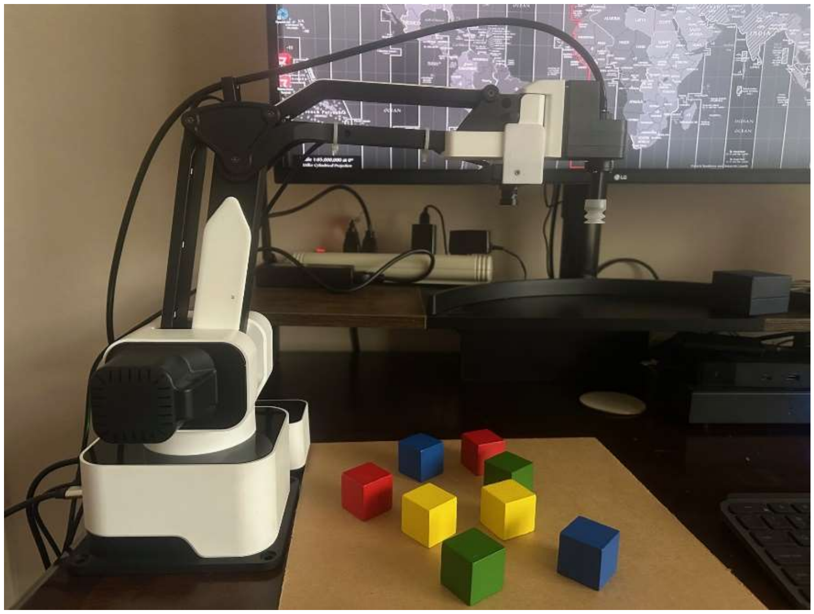

Figure 3 A DexArm equipped with a Rotrics computer vision camera and a rotary air picker

Rotrics Inc. also provided an open-source Vision Terminal as a platform for developing and deploying computer vision projects. This platform offers a graphic user interface (GUI), as shown in Figure 4, allowing: 1) connection to various DexArms by selecting the serial COM port and cameras connected to the select DexArm; 2) definition of the three pre-defined colors; 3) adjustment of range of color based on HSV model; 4) color selection and recognition results with the center coordinates of high-lighted areas of identification; 5) adjustment of end effector position allowing corresponding movements and operations; 6) demonstration examples.

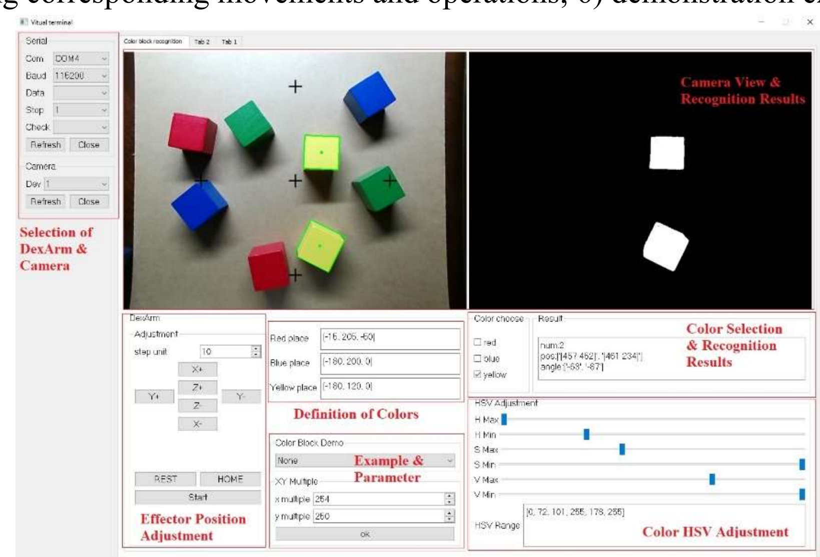

Figure 4 Vision Terminal computer vision development platform

Control Software and Results

Based on the Vision Terminal open-source materials provided by Rotrics, control software is further developed to allow the collaborative operations of the camera and a rotary air picker to pick and place a yellow wood block and a round wood coaster blank. The following open-source development tools are used to develop the control software.

- PyQt5: a library of functions allowing GUI development using Python
- PySerial 3.5: a library of functions allowing Python serial port access
- OpenCV-Python 4.9.0.80: a library of functions for real-time computer vision
- DexArm API: a library of functions controlling the movement of DexArm and operations of end effectors (tools) attached to the DexArm
- Microsoft Visual Studio Code: an integrated development environment (IDE) with a built-in Python 3.11.8 interpreter

The purpose of the control software is to perform the following functions through the GUI: 1) use the camera attached to the DexArm to identify the targeted object(s) in the view field based on predefined color/shape; 2) highlight the identified object(s) and calculate the coordinates at the center of the highlighted area; 3) control the rotary air picker attached to the DexArm to pick up the and place the identified object(s) at the designated location. Figure 4 shows the GUI of the control software, in which two yellow blocks mixed with other colored blocks placed in the view field of the camera are identified and highlighted and Figure 5 shows the air picker is picking up one of the two yellow blocks. Figure 6 shows the GUI of the control software with a round coaster blank mixed with other colored blocks is identified and highlighted, and Figure 7 shows the air picker is picking it up. The results show that DexArm equipped with a camera can identify objects based on color or shape. Further development is underway to incorporate these functions into the operations of Robot 3 to select blanks based on their color, shape, or both. Robot 4 will also be reprogrammed to handle objects on the conveyor belt when it sees them.

Figure 5 The air picker picks up the identified object (yellow block)

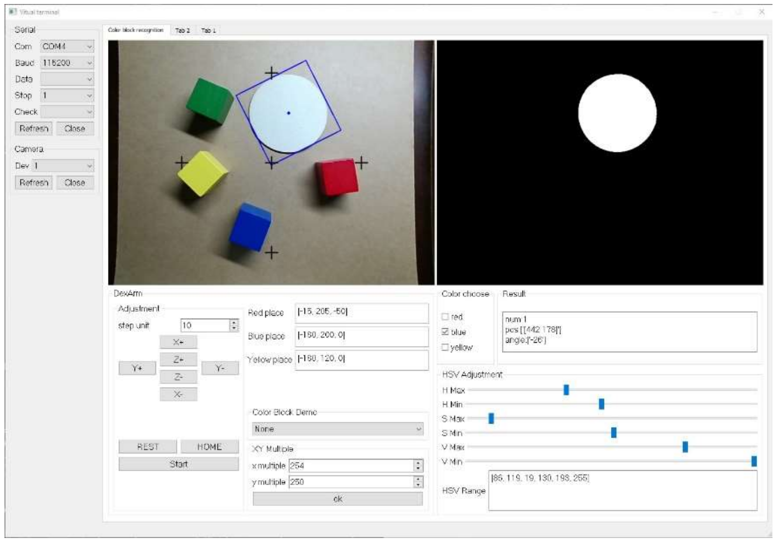

Figure 6 The control software identifies the round coaster blank

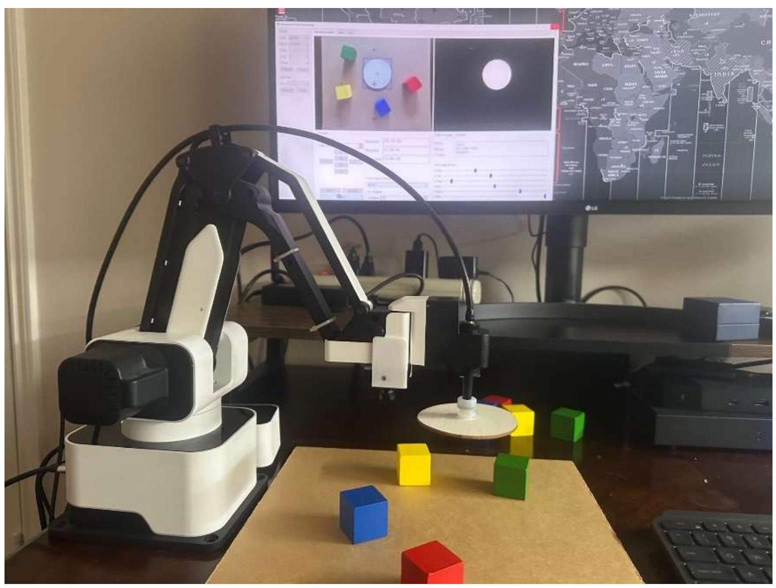

Figure 7 The air picker picks up the identified object (round coaster blank)

Future Plan

A team of undergraduate students has been developing a Delta robot as an alternative to the DexArm for material handling of the engraving system, allowing much faster material handling operations. A Delta robot consists of three arms, each considered a four-member linkage with two long and two short parallel members connected via various universal joints. Each of the three parallel arms is connected to a servo motor mounted on a stationary base (positioned on the top of the robot) through a connecting rod and a movable end effector (generally below the base) connected to the other end of the arms, holding a tool. The team successfully developed a prototype, which was tested to be functional. Figure 8 shows the team presenting the prototype at the 2024 annual undergraduate research symposium. The feasibility of incorporating the same computer vision camera used in this project and the image recognition and end effector operation functions developed will be explored.

Figure 8 Prototype of a Delta robot

Since DexArm is based on the Marlin open-source project, it also supports OpenMV cameras, which are low-cost, compact, and expandable computer vision modules operated using Python. The integrated microcontroller allows on-board processing, and built-in pins and USB ports enable easy communication with and control of other devices, such as DexArm.

Conclusions

Using the low-cost Computer Vision Kit for the desktop DexArm robotic arm and the Vision Terminal GUI interface from Rotrics Inc., object recognition based on color/shape through image processing and picking and placing the object based on the results are successfully developed. The open-source Marlin project-based firmware of the DexArm allows the development of Python-based control software. It provides possibilities of endless computer vision solutions using other hardware and software based on the same framework, such as the OpenMV. This example of a 'learning-by-doing' active learning approach with open-ended solutions is an excellent opportunity for students to develop problem-solving skills. Instructional material based on this project will be developed and integrated into the instruction of the newly developed Mechatronics course.

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