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Incorporating the Design and Development of an Educational Automated Manufacturing System Utilizing Desktop Equipment into Instruction of Various Courses

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Incorporating the Design and Development of an Educational Automated Manufacturing System utilizing Desktop Equipment into Instruction of Various Courses

Abstract

This paper presents the work-in-progress project to design and develop an educational automated manufacturing system that integrates warehouse operation, material handling, and laser engraving manufacturing processes using low-cost desktop equipment. The ultimate goal is to develop a modular educational manufacturing system that simulates various manufacturing processes following Industry 4.0 standards using open-source equipment. The system allows instructors to use existing modules for course instruction and students to expand and improve it.

The system presented in this paper is based on four Dexarm robotic arms, a sliding rail kit, a conveyor belt kit, and a laser safety enclosure offered by Rotrics Inc. The DexArm is a three-degree-of-freedom (DOF) universal desktop robotic arm that performs various functions depending on the tools equipped, potentially achieving the fourth DOF. The sliding rail kit provides a base for Dexarm that moves up to 1000mm along the rail. The conveyor belt kit offers a 700mm belt for material transportation, and the safety enclosure ensures a safe laser engraving process. The system performs the engraving function by picking the stock material, transferring the stock material to the conveyor belt, feeding the stock material to the engraving station, and retrieving and storing the engraved material. It consists of three function modules: 1) warehouse operation module: a Dexarm equipped with a pneumatic suction cup tool to pick stock material from raw material storage, transfer the picked 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 and place the engraved material on the conveyor belt, transfer the engraved material back to the warehouse operation module; 3) laser engraving station: a Dexarm to operate the safety enclosure door, and a second Dexarm equipped with a laser engraving tool to engrave the stock material.

This paper also discusses ongoing efforts to add computer vision to Dexarm and build a Delta robot to enhance and expand the system's functions. Students from Mechanical Engineering Technology (MET) and Electronics and Computer Engineering Technology (ECET) are working on these projects as capstone or course design projects.

Introduction

Online surveys and interviews of more than 800 US manufacturing companies and leaders performed by the Manufacturing Institute (MI) and Deloitte in 2021 indicate that the US manufacturing industry could face 2.1 million unfilled positions in the US manufacturing industry by 2030 due to the lack of skilled labor, potentially causing a trillion-dollar economic loss in 2030 alone. With the adoption of automated systems in modern manufacturing facilities, workers trained with related knowledge and skills required for these systems are and will continue to be in high demand. In large-scale automated production and operation environments, such as vehicle body welding and warehouse material handling, robotic arms are widely adopted to perform various tasks, providing high standardization in repetitive operations with excellent efficiency. In recent years, the cost of industrial robotic arms has dropped significantly to the point where small businesses can incorporate them into their operations. To work with robotic arms provided by different manufacturers typically requires special training to perform task-associated essential movements, as well as time and motion studies to assist in the layout, operation, and optimization of the entire operation for high efficiency.

Various educational institutions and universities are working with industrial partners and professional organizations to develop curricula and academic programs to address the skilled labor shortage. Educational equipment manufacturers also developed modular training systems simulating a manufacturing environment, including warehouse operations, material handling, manufacturing processes, inspection, assembly, etc., for related training. However, these training systems have a few common limitations: 1) they are designed and developed with limited or no flexibility for alteration or customization; 2) many subsystems are being built as a 'black box,' from which students will learn 'what' they will do but not 'how' and 'why' they work the way they do; 3) both the hardware and educational materials are typically expensive. Low-cost desktop multi-functional robotic arms such as the DexArm used in this study are becoming more readily available. Since Dexarm is based on the open-source Raspberry Pi microcontroller and software, it is practical to use it to design and develop similar training systems with the flexibility for open-end redesign and customization. In addition, students will also have a better understanding of pertaining subjects through the 'learning-by-doing' active learning experience.

As the first approach, this paper presents the design and development of a manufacturing system involving material handling and laser engraving processes. The ultimate goal is to develop a modular training platform incorporating technologies being developed and adopted in the manufacturing industry following Industry 4.0 standards. The system and its modules are developed using low-cost hardware and open-source software, allowing students hands-on learning experiences and opportunities for open-ended customizations and further expansions. Instructors can also create instructional materials based on this platform and integrate them into the instruction of related courses, such as manufacturing processes, industrial robotics, control systems, etc.

Conceptual Design

The manufacturing system presented in this paper is the first module of the proposed training platform. It engraves a wood coaster blank using a laser engraving tool. It consists of three functional modules: warehouse operation, material handling, and laser engraving. The process is fully automated once an engraving design is sent to the engraver Dexarm. Figure 1 shows the schematic design of the system with the three function modules.

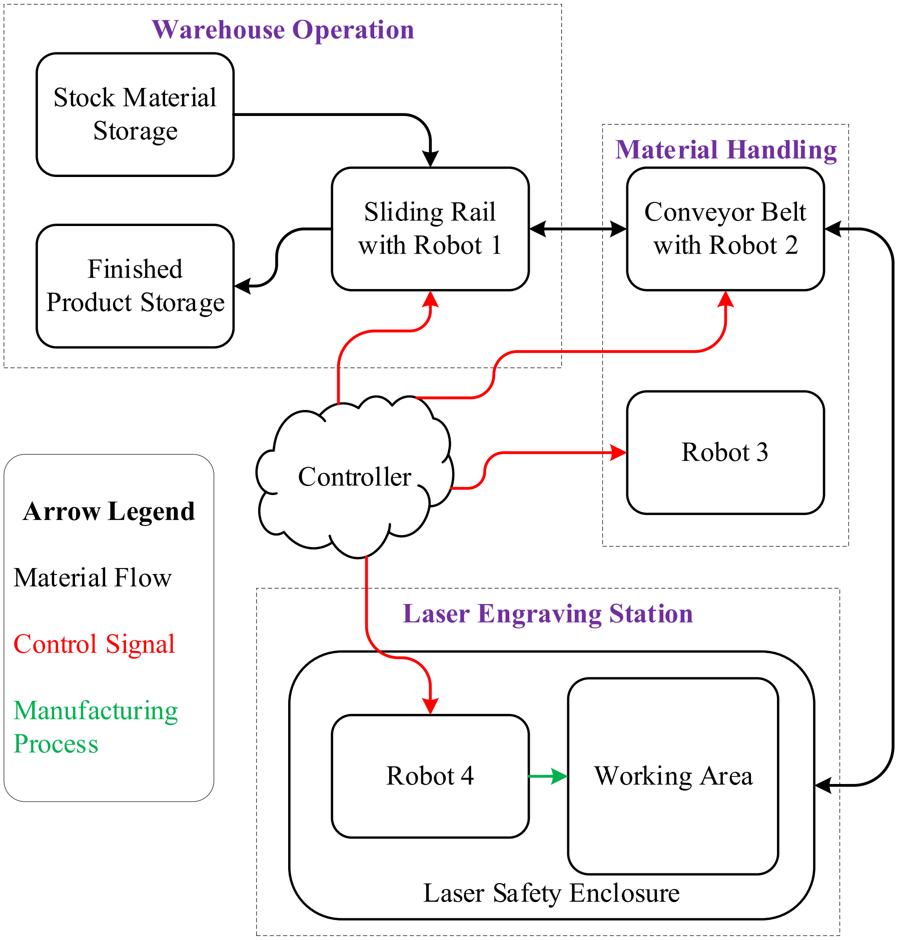


Figure 1 Schematic design of the automatic laser engraving manufacturing system

The three function modules perform the following operations in sequence to complete the laser engraving process:

The Warehouse Operation module

1. Upon starting the process, Robot 1 mounted on the sliding rail moves to the wood coaster blank storage, then picks up one blank from the storage
2. Robot 1 moves along the sliding rail to the conveyor belt in the Material Handling module, places the blank on the conveyor belt, then waits for the laser engraving process to complete
3. Once the laser-engraved coaster is sent back on the conveyor belt, Robot 1 picks it up, moves along the sliding rail to the finished product storage, and then places the laser-engraved coaster in the storage to complete the process.

The Material Handling module

1. Once Robot 1 places the wood coaster blank on the conveyor belt, the conveyor belt moves the blank to the Laser Engraving Station
2. Robot 2 picks up the blank on the conveyor belt and waits for Robot 3 to open the door of the Laser Safety Enclosure before placing the blank in the Working Area of the Laser Engraving Station

3. Robot 3 closes the door of the Laser Safety Enclosure and waits for the laser engraving process to complete
4. Once the laser-engraving process is completed, Robot 3 opens the door of the Laser Safety Enclosure, Robot 2 retrieves the laser-engraved coaster, Robot 3 closes the door of the Laser Safety Enclosure
5. Robot 2 places the laser-engraved coaster on the conveyor belt, which moves the coaster back to the warehouse.

The Laser Engraving Station

1. Once a wood coaster blank is placed in the working area and the door of the Laser Safety Enclosure is closed, Robot 4 performs the laser engraving process
2. When the laser-engraving process is completed, Robot 3 opens the door of the Laser Safety enclosure.

Prototype Development

The DexArm robotic arm, sliding rail, conveyor belt, laser safety enclosure, and other accessories and tools developed by Rotrics Inc. are used for the prototype development since they are low-cost with open-source software. DexArm is an all-in-one desktop three-DOF robotic arm, and the modular design allows tools such as a laser engraver and a pneumatic suction cup to perform various tasks. It has a 220-degree angular and 220 x 220 x 270 mm volumetric workspace with 0.05mm location repeatability and a 500-gram payload. The sliding rail has a 1250x30x10mm footprint and 1000 mm effective moving length, 0.1mm precision, and up to 250mm/s moving speed. The conveyor belt has a dimension of 750x220x82mm, 700mm effective belt length, 0.2mm precision, and up to 120mm/s moving speed. The laser safety enclosure has a 518x358x358mm dimension, allowing the safe operation of the laser tool with a ventilation function.

For this design, a DexArm (Robot 1) equipped with a portable air pump and a pneumatic suction cup is mounted on the base of the sliding rail that slides along the rail, as shown in Figure 2. The second DexArm (Robot 2), equipped with the same air pump and pneumatic suction cup, is mounted on a stationary foundation by the conveyor belt, as shown in Figure 3. The third DexArm (Robot 3), equipped with a simple rod tool, is mounted by the door of the laser safety enclosure to work coordinately with Robot 2 to feed a blank and retrieve laser engraved wood coaster, which is processed by the fourth DexArm (Robot 4) equipped with a 2.5W laser engraving tool mounted within the enclosure as shown in Figure 4. Figure 5 shows the schematic layout and material flow and Figure 6 shows the prototype of the manufacturing system.

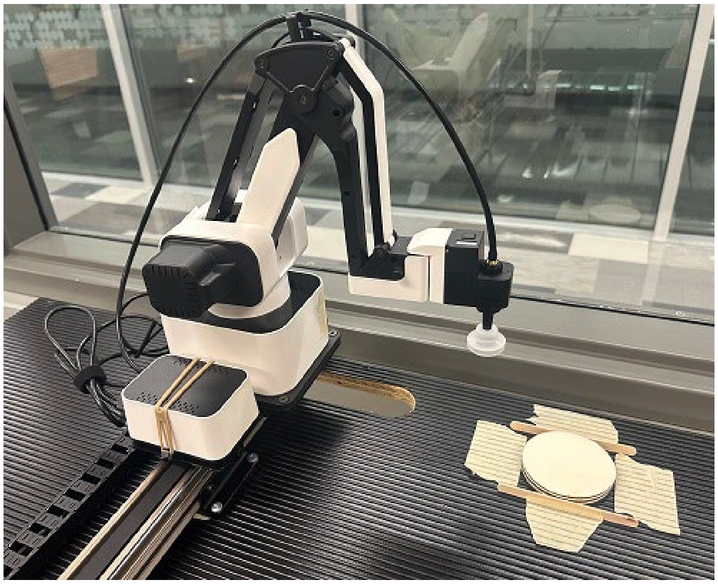


Figure 2 Robot 1 mounted on the sliding rail located at the stock material storage

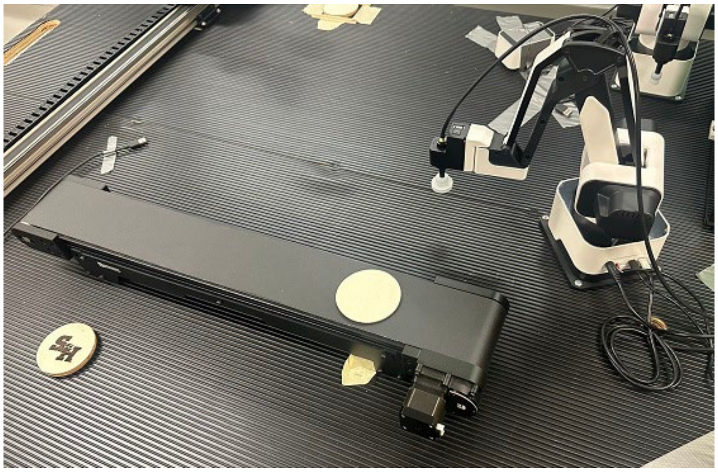


Figure 3 Robot 2 mounted on the stationary base by the conveyor belt

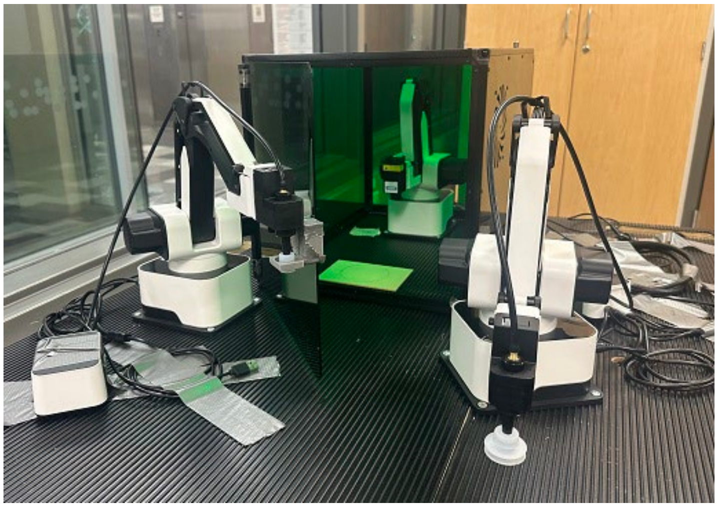


Figure 4 Robot 2 and 3 mounted near the safety enclosure, with Robot 4 inside the enclosure

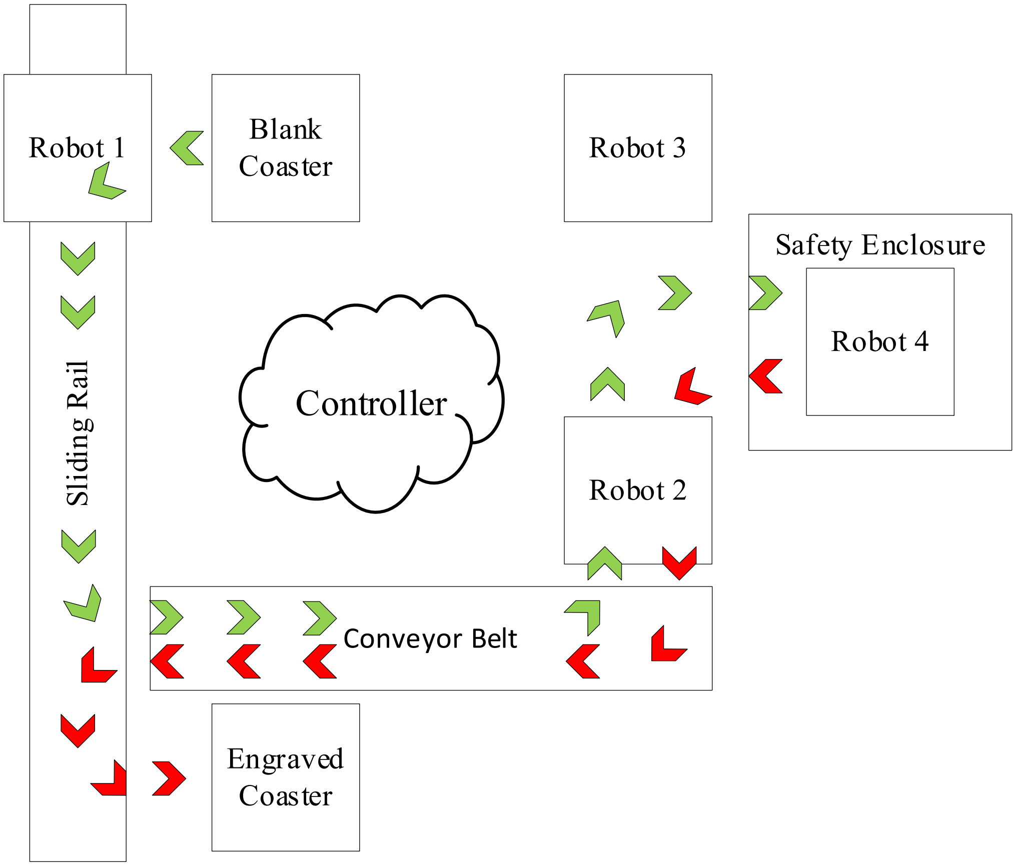
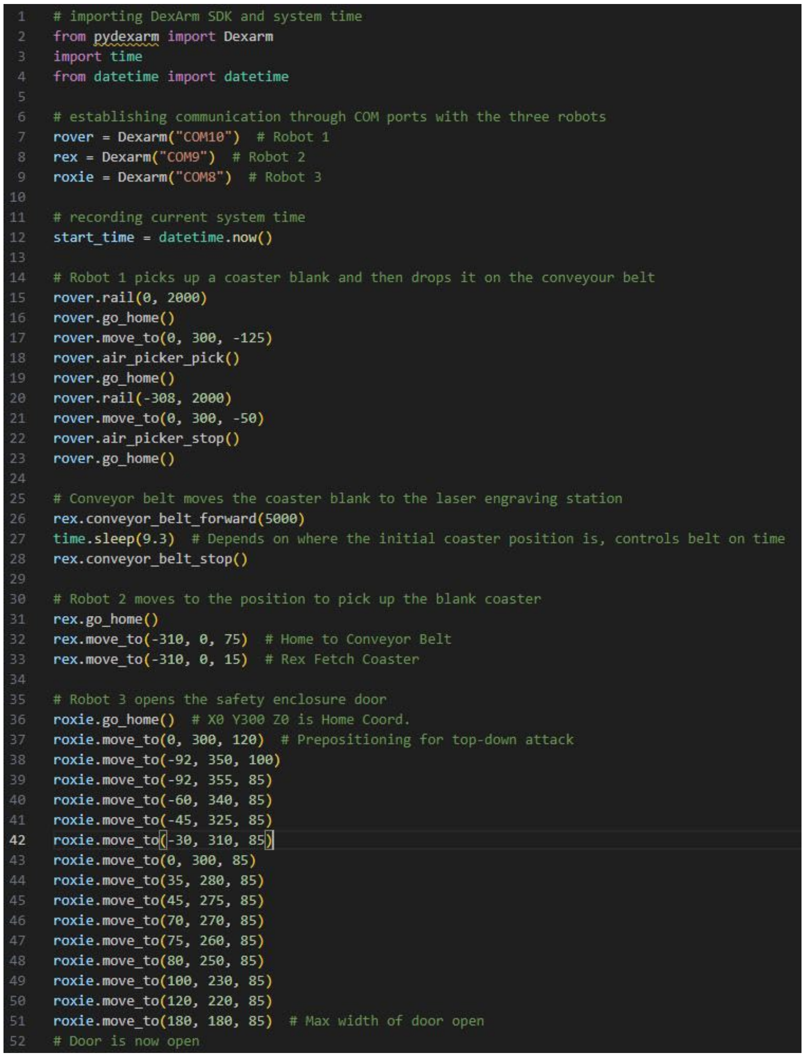


Figure 5 Schematic layout of the manufacturing cell

Figure 6 The integrated manufacturing cell

Control Software and Results

The control software functions as the 'brain' of the manufacturing system, coordinating individual components to achieve related functions. Since DexArm is based on the Marlin project (G-Code control commands) with completely open-source firmware and its software development kit (SDK), pydexarm, is based on Python programming language, Python is used in this project. In Marlin, a controller sends a command to a device to perform a particular task and waits for a reply from the device indicating the completion of the task before sending another command. This sequential operation mechanism allows the presented system to complete the designed functions in sequence. The four DexArms used in this project are connected to a controlling computer via USB cables and thus can be accessed and controlled through the serial COM port of DexArm. Figure 7 shows a sample code that first initializes communications with Robot 1, 2, and 3, controls Robot 1 mounted on the sliding rail to pick a coaster blank and then drops it on the conveyor belt, moves the conveyor belt towards the laser engraving station, moves Robot 2 to the position ready to pick up the blank on the conveyor belts, and controls Robot 3 to open the laser safety enclosure.



```python
# importing DexArm SDK and system time
from pydexarm import Dexarm
import time
from datetime import datetime

# establishing communication through COM ports with the three robots
rover = Dexarm("COM10")  # Robot 1
rex = Dexarm("COM9")  # Robot 2
roxie = Dexarm("COM8")  # Robot 3

# recording current system time
start_time = datetime.now()

# Robot 1 picks up a coaster blank and then drops it on the conveyour belt
rover.rail(0, 2000)
rover.go_home()
rover.move_to(0, 300, -125)
rover.air_picker_pick()
rover.go_home()
rover.rail(-308, 2000)
rover.move_to(0, 300, -50)
rover.air_picker_stop()
rover.go_home()

# Conveyor belt moves the coaster blank to the laser engraving station
rex.conveyor_belt_forward(5000)
time.sleep(9.3)  # Depends on where the initial coaster position is, controls belt on time
rex.conveyor_belt_stop()

# Robot 2 moves to the position to pick up the blank coaster
rex.go_home()
rex.move_to(-310, 0, 75)  # Home to Conveyor Belt
rex.move_to(-310, 0, 15)  # Rex Fetch Coaster

# Robot 3 opens the safety enclosure door
roxie.go_home()  # X0 Y300 Z0 is Home Coord.
roxie.move_to(0, 300, 120)  # Prepositioning for top-down attack
roxie.move_to(-92, 350, 100)
roxie.move_to(-92, 355, 85)
roxie.move_to(-60, 340, 85)
roxie.move_to(-45, 325, 85)
roxie.move_to(-30, 310, 85)
roxie.move_to(0, 300, 85)
roxie.move_to(35, 280, 85)
roxie.move_to(45, 275, 85)
roxie.move_to(70, 270, 85)
roxie.move_to(75, 260, 85)
roxie.move_to(80, 250, 85)
roxie.move_to(100, 230, 85)
roxie.move_to(120, 220, 85)
roxie.move_to(180, 180, 85)  # Max width of door open
# Door is now open
```

Figure 7 Sample code

Eight-centimeter diameter round-shaped plywood blanks are used to test the system. Figure 8 shows Robot 3 holding the safety enclosure door open, Robot 2 transferring an engraved coaster from the enclosure to the conveyor belt, Robot 1 waiting to pick up the engraved coaster, and then placing it in finished coaster storage. Figure 9 shows two laser-engraved coaster samples.

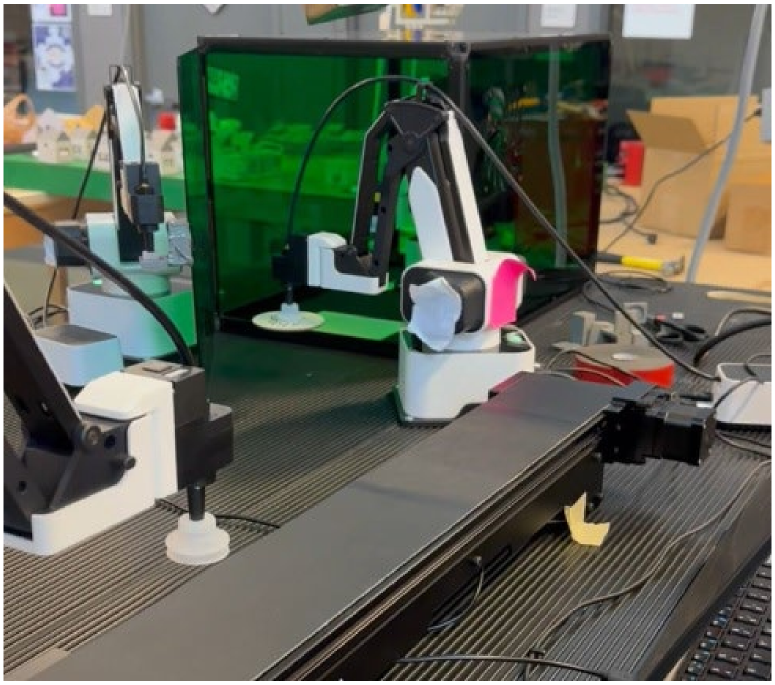


Figure 8 Robot 2 transferring an engraved coaster from the safety enclosure to the conveyor belt

Figure 9 Samples of laser-engraved coaster

Student Assessment

A group of four undergraduate students majoring in mechanical engineering technology (MET), electronics and computer engineering technology (ECET, two students), and engineering design technology (EDT) completed this project to satisfy the Senior Design course requirement for their degree program during the 2022~2023 academic year. The online Individual Development & Educational Assessment (IDEA) evaluation system is used to assess students learning. Table 1 shows the evaluations of the Senior Design course, which the group of four students enrolled in Spring 2023.

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)	4.6	0	93
Developing knowledge and understanding of diverse perspectives, global awareness, or other cultures	4.3	7	79
Learning to apply course material (to improve thinking, problem solving, and decisions)	4.4	7	93
Developing specific skills, competencies, and points of view needed by professionals in the field most closely related to this course	4.4	7	93
Acquiring skills in working with others as a member of a team	4.4	7	79
Developing creative capacities (inventing, designing, writing, performing in art, music, drama, etc.)	4.0	21	79
Gaining a broader understanding and appreciation of intellectual/ cultural activity (music, science, literature, etc.)	3.9	21	64
Developing skills in expressing myself orally or in writing	4.5	7	86
Learning how to find, evaluate, and use resources to explore a topic in depth	4.5	0	86
Developing ethical reasoning and/or ethical decision-making	4.4	0	79
Learning to analyze and critically evaluate ideas, arguments, and points of view	4.3	7	79
Learning to apply knowledge and skills to benefit others or serve the public good	4.4	7	93
Learning appropriate methods for collecting, analyzing, and interpreting numerical information	4.6	0	93

Table 1 Student Ratings of Learning on Relevant Objectives

The majority of students (93%) agree that they gained a basic understanding of the subject and learned to apply course material, which aligns with the first and second student outcomes (SOs) of the Engineering Technology Accreditation Commission (ETAC) accreditation criteria of the Accreditation Board for Engineering and Technology (ABET). The Senior Design course was administered as a one-credit course in Fall 2022, during which the students form a team, identify a project, define a project timeline and benchmarks, complete initial engineering design and analysis, and develop a bill of materials for the project. It was offered as a three-credit hour course in Spring 2023, and the students are required to build and test a prototype following the design-analysis-build-test iterative process. The students are teamed up based on their interests and majors. Each team is required to present initial and final project proposals in Fall 2022 and progress and final reports in Spring 2023, documenting the entire design and prototype development process in written and oral presentation forms. The teams must also identify and meet with a faculty advisor weekly to discuss project progress. These educational components assess the third and fifth SOs of the ETAC general criteria of ABET.

Further Developments

A team of undergraduate students has been designing and building a Delta robot as an addition to the manufacturing cell for material handling that will be integrated into future expansion, which allows the selection and storage of various blank materials and shapes. A Delta robot consists of three parallel arms, and the arm can be 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) holding a tool. The team has completed the engineering design using SolidWorks for all required components, conducted a stress analysis of the structure, designed the schematic of the servo motor control, and is currently building the prototype. Figure 10 shows the CAD model and Figure 11 shows the strength analysis results of the Delta robot developed using SolidWorks.

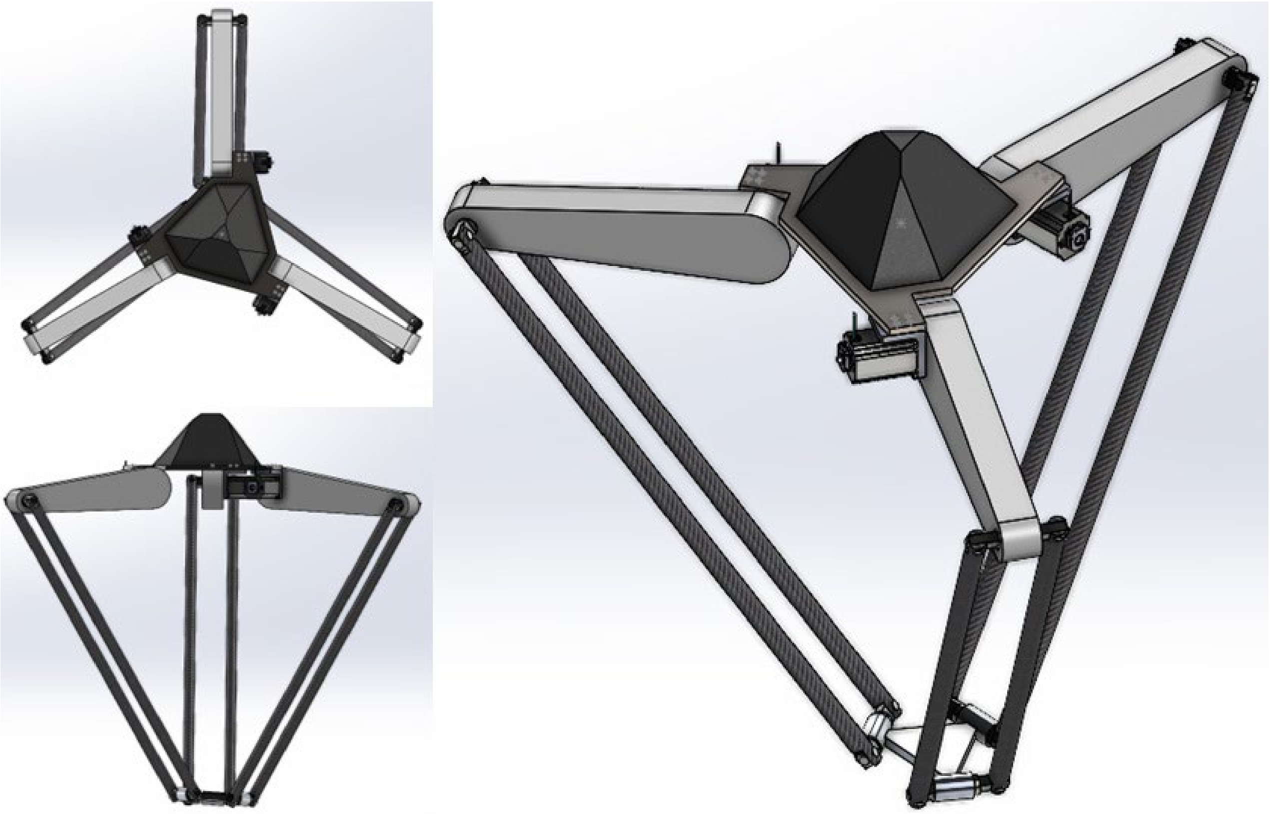


Figure 10 CAD model of the Delta Robot

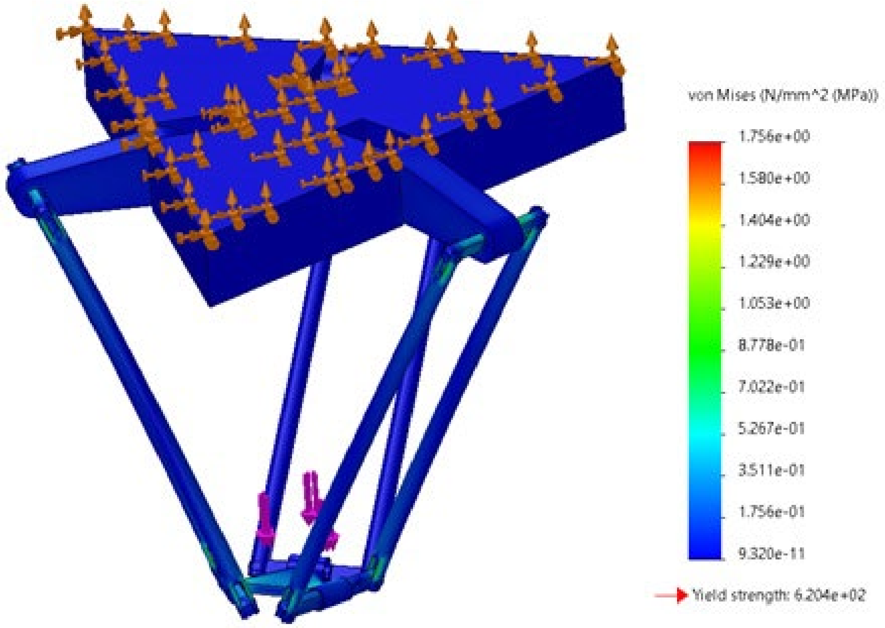


Figure 11 Stress analysis of the Delta robot structure

Rotrics also offers a computer vision kit with a USB digital camera with a 1920 x 1080 (2 Mb) resolution, a built-in microphone, and mounting brackets for DexArm. The camera operates on a Python API, allowing DexArm to perform tasks such as color and shape recognition based on machine learning and image processing. Another team of undergraduate students is working on integrating the kit into the manufacturing cell to perform tasks in a 'smarter' way using computer vision. Figure 12 shows the DexArm mounted on the sliding rail, fitted with a camera and a pneumatic suction tool to recognize the round wood and rectangular black aluminum stock materials, allowing stock material selection.

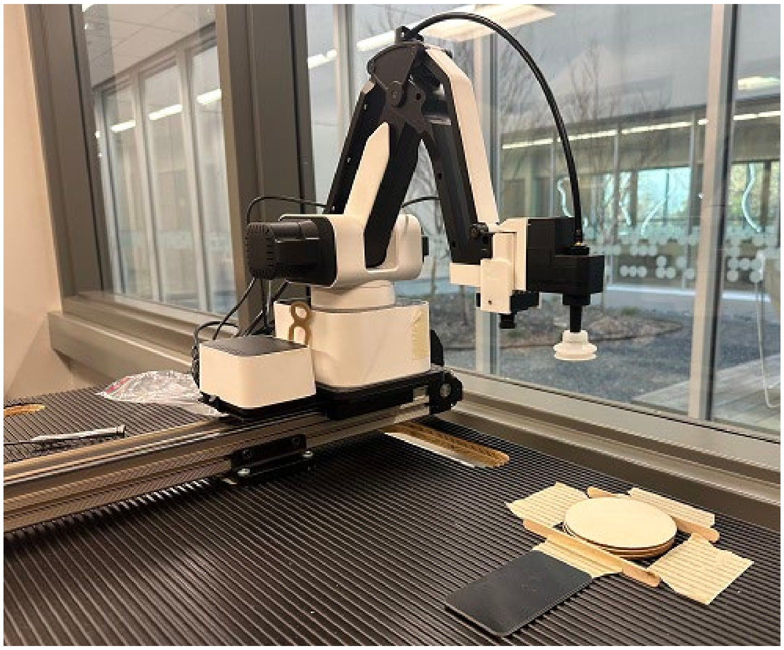


Figure 12 A Dexarm equipped with a digital camera for computer vision

The feasibility of integrating management information systems such as radio frequency or QR code-based inventory management database and voice command-based DexArm operations based on machine learning into the existing system will also be explored.

Conclusions

Using the low-cost DexArm robotic arm, sliding rail, conveyor belt, and various tools for the DexArm from Rotrics Inc., a group of four undergraduate students successfully developed an automated laser engraving system. The open-source firmware for the hardware used in this project allows the development of Python-based control software with endless possibilities for further expansions and integration of other open-source hardware.

Learning modules, such as laser processing, time and motion study, industrial robots, etc., are being developed using the presented manufacturing system. Motor control educational materials will also be designed and developed based on the ongoing Delta robot project. The learning-by-doing pedagogical method integrated into these educational materials will be incorporated into the instruction of 3D Parametric Design, Applied Numerical Analysis, and Control Systems Technology courses.

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