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Low-Cost Digital Twin Approach and Tools to Support Industry and Academia: A Case Study Connecting High-Schools with High Degree Education

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Abstract: Robotics and automation have been a growing area within K–12 educational institutions for the past decade. Across secondary educational institutions, students are introduced to robotics in classes, after-school clubs, and competition leagues through various educational platforms, vendors, and kits. Robotics was initially implemented in schools to help drive more interest in STEM through hands-on application of mechanical, electrical, structural, and computer engineering concepts. Recently, the trend of K–12 robotics has become very niche, focusing more on mobile robotics or robotics competitions. Because of this trend, students have limited exposure to emerging technological advances, such as those found in Industry 4.0. Exciting technological areas, such as digital twins, are not covered in curricula, and this lack of exposure negatively influences the direction of student interest in the "T" and "E" of STEM, with many students never pursuing computer science, technology, or robotics in higher education. The primary goal of this research is to provide a methodology to expose secondary students to Industry 4.0 technologies by leveraging accessible technologies, such as Unity and the Robot Operating System (ROS), to develop a low-cost, high-fidelity digital twin of a pick-and-place robot in a smart warehouse operation. This digital twin prototype will help students to learn about Industry 4.0 trends, such as next-generation automation systems, digital twins, digital manufacturing, intelligent automation, and additive manufacturing, using ROS–Unity integration and hardware accessible to secondary schools to simulate a pick-and-place robotic application. By harnessing the accessibility of Unity and ROS to create a low-cost digital twin prototype for a secondary school, this research has a secondary goal of improving the pipeline of students interested in pursuing STEM-related learning in higher education, thereby ensuring a future STEM workforce that can research, design, develop, operate, and maintain the systems and technologies of Industry 4.0.

Keywords: Industry 4.0; digital twin; intelligent automation; digital manufacturing; ROS; game engine; robotics; Internet of Things; ICT

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1. Introduction

Industry 4.0 seeks to create a framework for intelligent, automated manufacturing by transforming machine-to-machine interaction and human–machine interaction [1]. Industry 4.0 technology developments across robotics, artificial intelligence, digital twins, and digital manufacturing are forcing business processes to rapidly evolve [2]. This new surge in technological innovation will change labor markets, decreasing employment opportunities "in routine, intensive occupations". As Industry 4.0 continues to expand, applications of artificial intelligence, additive manufacturing, autonomous vehicles, and robotic technologies will eliminate jobs traditionally facilitated by human workers, not only in manufacturing but also in service industries [2].

The future workforce will need to develop skills that will enable it to adapt and succeed in this new technological revolution. Post-secondary educational institutions need to plan and adjust learning outcomes to support Industry 4.0 skillsets. Companies will need a workforce competent in technologies such as cloud computing, data analytics, artificial intelligence, the IoT, adaptive robotic systems, and digital manufacturing. Post-secondary students in all disciplines should be exposed to these subject areas, and STEM and engineering students should be taught more comprehensively in these subject areas [3].

The incorporation of low-cost, digital twin (DT) prototypes into secondary education curricula will expose students earlier to Industry 4.0 technologies, helping build deeper information communication technology (ICT) into the future labor force. Companies and organizations will require more workers with soft and specialized ICT skills. Some of these soft skills include complex problem solving, critical thinking, creativity, collaboration, emotional intelligence, and decision making [2]. Workers with specialized ICT skills will be required to analyze data for decision making, develop and configure systems to solve problems, and manage complex, integrated environments comprising both machines and humans. Outside of specialized skills, basic ICT skills will become a requirement for most low-skilled or service-oriented jobs, as more workers interface with automated systems, robotic technologies, and autonomous machines [2]. One of the main advantages of using Unity in digital manufacturing is the rapid prototyping and application of design thinking with iteration. A low-cost digital twin educational tool can provide students with hands-on application of both soft and specialized ICT skills. Students can create and test different versions of a digital twin to evaluate its behavior in various scenarios, practicing soft skills such as problem solving; design thinking; collaboration; and developing specialized skills with Unity, ROS, and robotic software and hardware.

With this growing need for ICT skills in the workforce, secondary educational institutions will need to expose students to the technological trends behind Industry 4.0, as well as seek ways to develop ICT skillsets earlier. This research involving digital twins based on Unity and ROS seeks to provide a low-cost methodology to expose secondary students to Industry 4.0 and ICT.

1.1. Problem Statement

In recent years, there has been a significant increase in investments in automation and robotics, leading to a highly competitive market. As companies strive to implement smart warehouse operations, multiple technologies need to be integrated. This integration complexity, combined with technological density, creates challenges for companies seeking to design more intelligence and automation into their manufacturing systems. Additionally, collaboration across various disciplines is often necessary, creating the need for a highly skilled labor workforce with both soft and specialized ICT skills. To solve these technology challenges and skill gaps, companies will need a talented, STEM workforce that can research, design, develop, operate, and maintain Industry 4.0 technologies. Therefore, there is a pressing need for an educational, cost-effective, and accessible solution for exposing students to Industry 4.0 technologies.

1.2. Research Aim

Robotics was initially implemented in schools to help drive more interest in STEM through hands-on application of mechanical, electrical, structural, and computer engineering concepts. Recently, the trend of K–12 robotics has become very niche, focusing more on mobile robots, robotic competitions, or UAVs. Because of this trend, students are developing stereotypes regarding robotics, with most students considering a robot as being made from metal, having rotational motors, and being capable of only repeating pre-programmed tasks [4]. Emerging technological advances, such as those found in Industry 4.0, are never introduced to students, thereby limiting academic exposure to the vast possibilities of robotics beyond these stereotypes. Exciting technological areas, such as digital twins and the next-generation automation system, are not covered in curricula. This lack of exposure negatively influences the direction of student interest in the "T" and "E" of STEM, with many students never pursuing computer science, technology, or robotics in post-secondary education. The primary goal of this research is to create a low-cost, digital twin of a smart warehouse operation using hardware and software that is accessible to secondary educational institutions. This approach aims to provide a cost-effective, efficient, and education-friendly solution for secondary schools to introduce students to Industry 4.0 technologies.

1.3. Research Objectives and Scope

- Developing Specialized ICT skills with ROS Integration—Establish a seamless connection between ROS and the digital twin prototype, enabling the exchange of real-time data and communication between the simulation environment and robotic systems. Working on this integration will allow students to practice specialized ICT skills and soft ICT skills.
- Fostering Critical Thinking with ROS-based Control Algorithms—Develop and integrate ROS-based control algorithms for the digital twin models, ensuring that the virtual representations accurately mimic the behavior of their real-world counterparts. This work will allow students to practice critical thinking, as well as apply science and mathematics to real-world scenarios.
- Promoting ITC skills with CAD and 3D Printing—Design virtual models using CAD and Unity software. By designing models both in CAD and Unity, students will learn about the benefits of using digital manufacturing tools. Students will also learn how Industry 4.0 incorporates additive manufacturing concepts at a lower cost and increases productivity.
- Building STEM Skills with Physical Prototype Implementation—Build or set up a physical, small-scale pick-and-place prototype using hardware and software that is accessible and cost-effective for secondary educational institutions. This robotic protype will expose students to Industry 4.0 robotic technologies, as well as allow for hands-on application of specialized ICT and engineering skills.

2. Literature Review

2.1. Robotics and Industry 4.0

In "Advances in Robotics in the Era of Industry 4.0", Bayram and İnce examined the progression of robotics and its potential role in addressing the challenges and opportunities of Industry 4.0 [5]. They provided an overview of various industrial robots, such as collaborative, mobile, and autonomous robots, emphasizing the benefits of increased efficiency, flexibility, and safety. The authors also delved into the impacts of artificial intelligence, machine learning, and advanced sensor technology on the development of robotic systems, enabling them to perform complex tasks and interact with their environments more intuitively.

Bayram and İnce further explored the challenges and opportunities of integrating robotics into Industry 4.0 production processes, including workforce impact, the need for specialized skills, and ensuring the safety and reliability of robotic systems. They proposed guidelines for adopting and integrating robotics, emphasizing risk assessment and regular maintenance and testing. The potential economic and societal impact of robotics adoption in Industry 4.0 was also discussed, including economic growth, job creation, and improved quality of life.

The Robot Operating System (ROS) is an open-source framework that has gained popularity for its flexibility, modularity, and ability to integrate various robotic hardware, such as GPU-based embedded systems, and software components, such as artificial intelligence. The ROS-Industrial (ROS-I) initiative focuses on the development of ROS-based software and applications specifically tailored for industrial applications. ROS-I fosters collaboration among researchers, developers, and industries, driving the creation of reusable software components and reducing development cycles. This collaborative approach enables industries to rapidly adapt and respond to changing market demands and technological advancements. One of the primary drawbacks is the lack of real-time capabilities in the core ROS infrastructure. Industrial environments often demand high levels of precision and real-time responsiveness, which the current version of ROS struggles to meet.

2.2. Robotic Technologies Challenges

In addition to the inherent challenge of integrating multiple, disparate technologies, there are challenges with the current state of robotic technologies required for digital twins and NGAS. More advances in robotic technologies, especially sensors, machine learning, networking, and data processing, are foundational both for digital twinning and for developing intelligence in manufacturing systems [5]. As background, the digital twin concept creates a virtual replication of a manufacturing line or asset. A digital twin is not only a virtual prototype but also a simulated instance of the physical system. The simulated instance is interconnected and continually updated with the physical system's operational and performance status [3]. The use of sensors and networks is critical to the digital twin so that it can simulate the physical environment realistically. Manufacturing or asset changes can be designed and simulated in the virtual twin, using accurate historical data. These simulations and modeling demand rich data, high computational needs, and machine learning. Digital twins are key components in the NGAS, and they provide a huge benefit in identifying opportunities to reduce cost, to increase productivity, or to be more responsive to changing demands or conditions [3].

The intelligence gap found in today's robotic manufacturing systems is caused by the current design and application of robots. Current industrial robots are preprogrammed for a predefined action and often constrained to a predetermined space. They are often disconnected and lack a digital twin. They repeat the same sequence of actions with minimal decision making or sensor feedback. These current industrial robots are also not flexible, not interconnected, and not intelligent, thereby creating challenges for companies to fix, retrofit, reconfigure, or redesign a manufacturing process. To truly realize NGAS, there needs to be a transformation of these current industrial robots into "cyber-physical systems" (CPS) that possess smart capabilities, such as sensing and networking, can learn and make real-time decisions, and have a live digital twin for simulations and modeling [5].

Advancements in robotic technologies are key to intelligent automation, especially the NGAS. In addition to the need to decrease the installation, operation, and maintenance costs, advances in sensor technology, artificial intelligence, networking, and data processing need to occur. Application of these newer robotics technologies will help to close the feedback gap that is currently limiting intelligence in today's manufacturing systems [5].

Continued advancements in sensor capabilities are critical for machines to become intelligent. Intelligent automation is realized when robotic systems can quickly process data, seamlessly communicate across the manufacturing environment, and ultimately make informed, real-time decisions. In recent years, academia and research institutions have focused on improving vision and auditory perception, as well as environmental awareness. Application of newer sensor technologies, such as laser mapping and image recognition via cameras, will help to increase overall system intelligence.

Second, as sensor technology improves, advances in machine learning and artificial intelligence are critical for NGAS. Robotic systems need to not only sense and monitor the environment but also learn, predict, and make decisions about events happening within the environment. Robotic systems operating within the NGAS will need to have environmental awareness, as well as self-awareness, to make informed decisions, such as predictive maintenance, defect avoidance, or reconfiguration for operational efficiency [5].

In addition to evolving sensors and artificial intelligence, robotic advancements in networking and data processing are required to realize the NGAS. The Internet of Things (IoT) will need to be applied to robotic systems to allow for real-time communication across multiple stakeholders: between robotic systems, between the digital and physical twins, and between human and robot counterparts. Some researchers have proposed the creation of an

"Internet of Robotic Things" (IoRT) that allows for inter- and intrarobotic communication, multiple network protocols, internet access for environmental communication, and finally a robotic cloud for leveraging cloud computing and big data analysis [5]. This IoRT will be the communication backbone that allows real-time data to flow seamlessly across the whole production system. Through the IoRT, robotic systems can become more aware of the environment beyond the range of their individual sensors. They can also be linked to their digital twins and have immediate access to big data and cloud computing resources to improve data processing and decision making.

2.3. Future Workforce Talent Development

As mentioned above, with this Industry 4.0 technological transformation, there are challenges that companies and organizations will need to overcome. To assist in meeting these new challenges, a future workforce needs to be re-tooled with skillsets appropriate to support Industry 4.0. In addition, this new workforce will need to attract and develop new talent coming from post-secondary institutions [2].

Current students will need to understand conceptually how Industry 4.0 and digital twins will apply machine learning, cloud manufacturing, the industrial Internet of Things, robotic technologies, additive manufacturing, and digital manufacturing tools. Understanding these concepts is critical to support the next-generation intelligent automation systems. Secondary and post-secondary educational institutions need not only the training but also the infrastructure to facilitate this conceptual understanding. Providing low-cost, accessible Industry 4.0 infrastructure, such as low-cost digital twin prototypes, can enable more institutions to reach more students and thereby expand the sphere of interest in Industry 4.0 technologies.

As mentioned before, Industry 4.0 has spawned new sectors and industries. With each technological trend, new roles are formed, and new skillsets are needed. Data science and machine learning have spawned new research and data analysis institutions. New business models have formed around advances in cloud computing, Big Data, and the Internet of Things. Advances in additive manufacturing, automation, robotics, and digital manufacturing are changing the labor force needs within existing companies and forming companies that never existed before Industry 4.0 [2].

With both the creation of new and the transformation of old industries, companies are demanding skillsets that can support the technological trends behind Industry 4.0. In addition, current occupations are at risk for being automated, especially within service industries or roles that are repetitive in nature. Machine intelligence is allowing for higher cognitive tasks, such as language and voice recognition. Developments in computing and robotics are driving automation of labor tasks previously completed only with human labor. Robotic technologies combined with machine learning are introducing decision-making capabilities, eliminating the need for human labor [2]. As these Industry 4.0 technologies continue to develop, industry-wide applications of artificial intelligence, additive manufacturing, autonomous vehicles, cloud computing, and Big Data will replace the jobs performed by humans. Industries such as manufacturing, financial, transportation, service, and retail will be impacted by Industry 4.0, and their respective workforces will need to transform existing skillsets, as well as develop new skillsets [2].

While the existing labor force needs to be re-skilled, the future workforce (our students in secondary and post-secondary educational institutions) need to be educated for the skills and jobs of the future, especially in the technologies and processes that will be transformed by Industry 4.0. The future workforce will need both basic and specialized skills for information and communication technologies (ICT) [2]. Workers with specialized ICT skills will be required to analyze data for decision making, develop and configure systems to solve problems, and manage complex, integrated environments comprising both machines and humans. Outside of specialized skills, basic ICT skills will become a requirement for most low-skilled or service-oriented jobs, as more workers interface with automated systems, robotic technologies, and autonomous machines. In addition to ICT skills, interdisciplinary skills will be in demand. These soft skills include complex problem solving, critical thinking, creativity, collaboration, emotional intelligence, and decision making [2]. These ICT and soft interdisciplinary skills can be developed and promoted in secondary institutions through STEAM, through project-based learning, and other pedagogical methods.

In addition to ICT and soft skills, science, technology, engineering, and math competencies will be required across all occupations and industries, especially as Industry 4.0 starts to enter different sectors. Technological innovation has led to an increased demand for STEM competencies across all occupations and industries. Increased automation and digitalization have increased the need for a future workforce competent in STEM concepts, subject areas, and skills. STEM education, in both secondary and post-secondary educational institutions, will be paramount for generating the talent pipelines needed for Industry 4.0.

In summary, Industry 4.0 is dramatically changing the future labor landscape. As these technologies advance and become more pervasive, the labor forces across multiple industries will need to adopt new skillsets. Basic ICT skills for workers will be required for all industries, including lower-skilled occupations, as well as service-oriented and retail industries. More specialized ICT skills for workers will be required in industries seeking to automate or implement digital processes, such as the next-generation automation system. As machine learning, artificial intelligence, and automation become more pervasive, having interdisciplinary, soft skills, such as critical thinking, emotional intelligence, problem solving, collaboration, and creativity, will also become more vital for workers. Finally, to overcome the technological challenges with Industry 4.0, companies and organizations will need to develop and promote more STEM competencies. Secondary and post-secondary institutions are critical enablers in building this talent development pipeline to ensure the success of Industry 4.0.

2.4. Literature Gaps

In recent years, there has been a growing number of publications on digital twins. This model enables real-time communication and data exchange between the virtual and physical environment, allowing for monitoring of performance, testing of scenarios, and capturing data and insights to support decision making. Despite the increasing number of articles on this topic, there are still many unexplored opportunities and gaps in this field, offering a vast landscape for experimentation. In their systematic review, Cruz and Tonin highlighted the need to create digital twins with free and/or open-source software [6]. Given the requirements of a digital twin, they focused on analyzing software that can create 3D models, write scripts, and serve as a build platform. The game engines analyzed are listed in Table 1. The preferred technologies in each category were listed as Blender, Visual Studio, and Unity, respectively. This research suggested that future studies could focus on developing digital twins in Unity, adapting to the physical environment and generating data to enhance digital twin capabilities.

Table 1. Game Engines Evaluation [6].

Criteria	CryEngine	Godot	Unity	Unreal Engine
Ease of Use	Quite complete software, but with a high degree of complexity in terms of its interface and use	Very simple and intuitive interface and use	Very simple and intuitive interface and use	Relatively complex interface and usage
Availability of resources	Average amount of content (assets and ready-made materials) available on the internet	Large amount of content (assets and ready-made materials) available on the internet	Large amount of content (assets and ready-made materials) available on the internet	Large amount of content (assets and ready-made materials) available on the internet

Table 1. *Cont.*

Criteria	CryEngine	Godot	Unity	Unreal Engine
Documentation	Available on the website	Available on the website	Available on the website	Available on the website
User community	Forum with up-to-date discussions, but with an average number of active members	Forum with up-to-date discussions, and a large number of active members	Forum with up-to-date discussions, and a large number of active members	Forum with up-to-date discussions, and a large number of active members
Importing Data	Compatible	Compatible	Compatible	Compatible
Importing 3D files	Compatible	Compatible	Compatible	Compatible
Importing images	Compatible	Compatible	Compatible	Compatible
Importing sounds	Compatible	Compatible	Compatible	Compatible
Creation of Cameras	Compatible	Compatible	Compatible	Compatible
Creation of Animations	Compatible	Compatible	Compatible	Compatible
Trigger of Events	Compatible	Compatible	Compatible	Compatible
Physics Elements	Compatible	Compatible	Compatible	Compatible
Use of code language	C++	Own language, GDScript	C++	C#

Some digital twin research has been conducted with game engines; however, they do not assume a manufacturing setting. Sørensen, Ma, and Jørgensen found that game engines have great potential for simulations that require a high degree of realism [7]. They used Unreal Engine to create digital twins of wind turbines to model wind power and estimate power production. In another similar project, Clausen, Ma, and Sørensen, used Unreal Engine to create digital twins of photovoltaic cells to model sunlight and estimate power production [8]. In both case studies, they found that game engines have the potential to generate meaningful real-time data. Game engines have also been known to assist in creating digital twin models for autonomous vehicles [9]. Yun and Park tested self-driving algorithms on these digital twins to verify object detection, obstacle avoidance, and lane recognition. These simulation results were then verified in a real-life environment using an RC car. All three of these case studies demonstrated the utility of using a game engine for digital creation in their respective research topics.

3. Methodology

The authors propose a methodology that will exposing secondary school students to Industry 4.0 technologies, develop important ICT skills, and provide a hands-on, project-based learning environment using a low-cost, educationally focused digital twin prototype. This methodology incorporates the following implementations.

3.1. Unity–ROS Integration for Digital Twin Prototype

Integrating Unity and ROS is a crucial step in the development of digital twins for smart warehouse operations. Unity, a powerful game engine, excels at rendering 3D environments and simulating physics, while ROS is a robust middleware for developing robot software. To achieve seamless integration, a communication bridge must be established between Unity and ROS, enabling real-time data exchange between the simulation environment and robotic systems. The data-exchange process should be efficient and accessible, allowing students to develop, test, and deploy simple control algorithms.

3.2. Physics-Based Simulation in Unity/ROS

To create accurate digital twins of smart warehouse operations, it is essential to develop realistic physics-based simulations using Unity. Unity's built-in physics engine, PhysX, provides a powerful toolset for simulating rigid body dynamics, collision detection, and other physics phenomena. By leveraging these capabilities, students can create virtual environments that closely mimic real-world conditions, enabling them to evaluate the performance of warehouse automation systems under various scenarios.

3.3. ROS-Based Control Algorithms

Developing ROS-based control algorithms for digital twins is another vital aspect of the proposed approach. These algorithms are responsible for controlling the behavior of robotic systems within the simulation environment, ensuring that they perform their tasks efficiently and safely. The ROS-based control algorithms should also consider the real-world constraints of the robotic systems, such as sensor limitations, actuator dynamics, and communication delays [10]. This consideration will ensure that the digital twins accurately represent the behavior of the physical systems and provide meaningful insights for improving their performance. By leveraging ROS's modular architecture, students can develop reusable control algorithms that can be easily integrated into different robotic systems and warehouse operations.

3.4. Virtualization, CAD Design, and 3D Printing Applications

Designing virtual models using computer-aided design software available to secondary educational institutions is another important step. The CAD step allows students to design the digital assets for the smart warehouse operations prototype. Various parts and components, such as a puck feeder or a puck-sorting container, should be designed in CAD software and then 3D printed to expose students to additive manufacturing technologies. 3D printers are now readily accessible to secondary institutions, and incorporating additive manufacturing is critical to exposing students to Industry 4.0 technologies.

3.5. Physical Prototype Engineering

Building a physical prototype of a pick-and-place smart warehouse operation allows students to engage in hands-on engineering applications. For a simple system, the sorting mechanism utilizes a color sensor triggering a servo gate. For a complex system, the sorting mechanism uses image detection via a camera, and the actual sorting is performed by a robotic manipulator. Regardless of complexity, the physical prototype should closely mirror the virtual CAD design and be integrated with Unity–ROS. All the parts should be sourced from vendors available to secondary educational institutions. The design and build of the prototype will expose students to robotic technologies that are used in intelligent manufacturing implementations.

4. Case Studies

In this case study, the authors tested the methodology with a small student population of late middle school and early high school students.

4.1. Specialized ICT Skills with ROS

The platform enabled real-time data exchange and communication between the simulation environment and robotic systems, facilitating the development, testing, and deployment of control algorithms within a unified platform. ROS and Gazebo provided students with exposure to specialized ICT skills required in the future labor workforce. The researchers used WKLATA Mirobot Manipulator to expose secondary students to the concepts of digital twins through an ROS integration [11]. The Mirobot was simulated in ROS Gazebo with the MoveIt configuration (Figure 1). Various planning trajectories were tested both in the Gazebo simulation and with the physical robot. The installation, setup, and configuration of ROS with Mirobot packages will facilitate the development of specialized ICT skills for secondary students. In addition, various types of manipulators, including a soft robotic pneumatic gripper, along with machine vision capabilities, can be explored to understand how robotic technologies will play a critical role in the future.

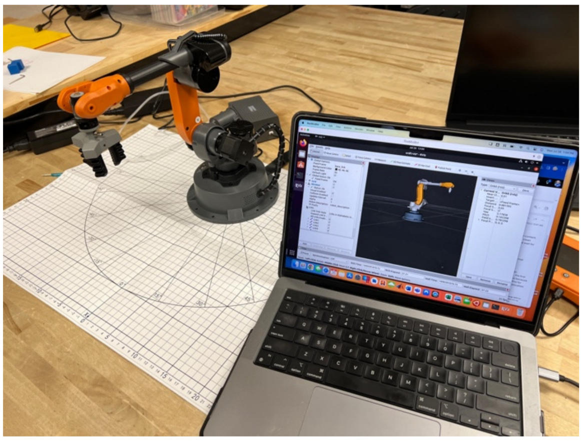


Figure 1. Mirobot Integrated with ROS MoveIt and Gazebo via USB Serial Connection.

4.2. Critical Thinking with ROS-Based Control Algorithms

The researchers developed and integrated ROS-based control algorithms for the digital twin models, ensuring that virtual representations accurately mimicked the behavior of their real-world counterparts. This integrated environment exposes students to digital twin concepts, as well as alternatives to the traditional physical build and testing methodologies (Figure 2).

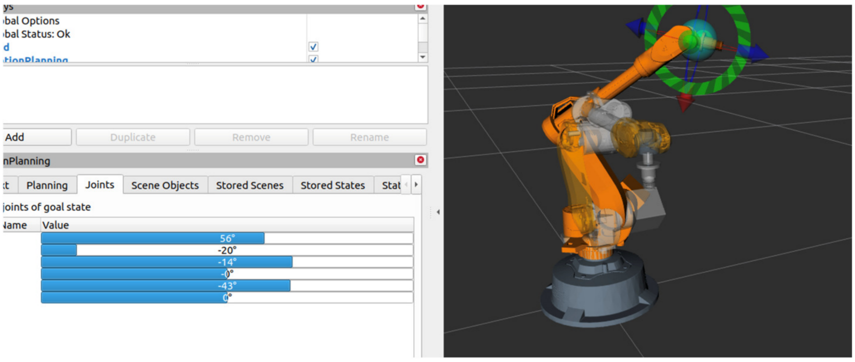
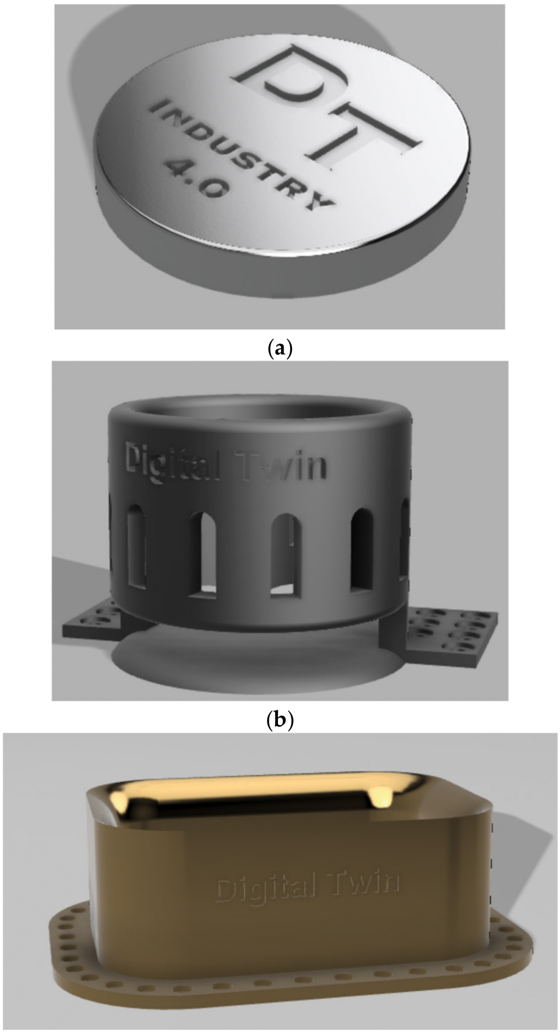


Figure 2. Mirobot Joint Movement Simulations using ROS MoveIt.

4.3. ITC Skill Exposure with CAD and 3D Printing

The researchers developed CAD models to expose students to digital manufacturing tools. The CAD models were created using an AutoDesk Fusion 360 Educational License. Fusion 360 is free to all secondary educational institutions and can run on both Windows and Mac OS. The CAD step includes designing the digital assets of the prototype. The first model was the product (a.k.a. "puck"), which was designed by creating sketches with the required dimensions. The sketches were then extruded to form the shape, and the geometries were refined using filet, chamfer, and deboss features (Figure 3a). The model of the puck was then inserted into another model to accurately determine the correct dimensions for the puck-feeding mechanism. Sketches, extrusions, debossing, and threaded hole features were used to build the puck-feeding model (Figure 3b). The third model developed was the sorting container for the pucks (Figure 3c). Finally, the virtual model for the pick and place prototype used STEP files to model the off-the-shelf parts and components. The STEP files were provided by the vendors when purchasing the products. For this prototype, the part vendors were Gobilda, Rev Robotics, PITSCO, and ServoCity.

These STEP files were imported into Fusion 360 as components and then assembled into a digital model using rigid and revolute joints (Figure 4).



(**a**)

(**b**)

(**c**)

Figure 3. (**a**) FUSION 360 Model of Puck. (**b**) FUSION 360 Model of Puck-feeding Mechanism. (**c**) FUSION 360 Model of Puck-sorting Container.

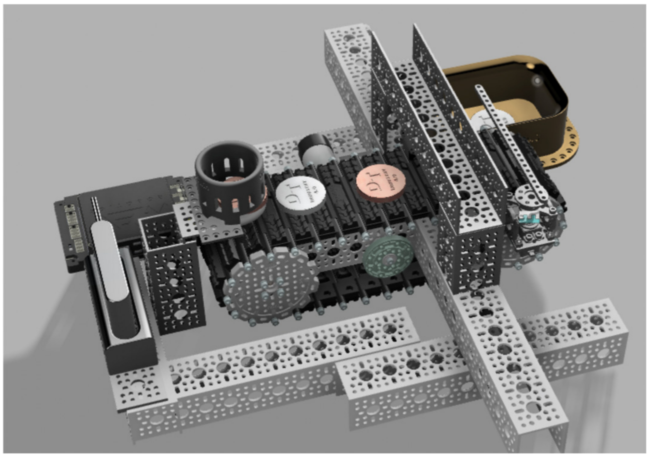


Figure 4. FUSION 360 Model of Custom Prototype.

The virtual model of the pick and place manufacturing line will need to be updated. During the physical build, component availability in the lab required different parts and components to be implemented. In addition, some components were cut or substituted or were not available as CAD files. Therefore, the virtual model was not a true virtualization of the physical prototype.

4.4. Building STEM Skills with Physical Prototype Implementation

In addition to using the Mirobot as an off-the shelf solution, the researchers built a physical pick-and-place manufacturing-line prototype. All the parts were sourced from various educational vendors available to secondary schools. Some of the educational vendors included PITSCO, GoBilda, ServoCity, and Rev Robotics. A single motor-powered conveyor belt system was used. The motor selected was a GoBilda 5203 Series Yellow Jacket Planetary Gear Motor with a 19.2:1 ratio, 24 mm in length with an 8-mm REX shaft, and 312 RPM. The conveyor belt was constructed from GoBilda rubber treads (24-mm pitch, 112-mm width) that were wrapped around 115-mm track sprockets with one idler wheel spread across the footprint. The conveyor system was belt driven using a GoBilda timing belt (9-mm width, 360-mm pitch length, 72 teeth). The support frame and structure were constructed from U-Channels of various lengths, connected using brackets, quad blocks, and M4 button head screws (Figure 5).

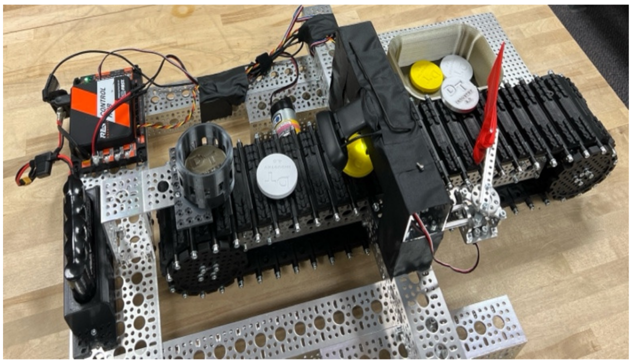


Figure 5. Physical Build of Assembly Line Prototype.

The 3D printed puck-feeding mechanism was mounted above the conveyor belt using additional channels, and L brackets. A V3 Color/Distance Sensor from Rev Robotics was mounted on a U-channel "sensor bridge", which spanned the conveyer belt. In addition, a Logitech webcam was mounted on the same "sensor bridge" for vision-tracking and image-recognition capabilities. A Rev Robotics Control Hub with a PITSCO Tetrix 12-Volt 3000-mAh NiMH battery was installed. All components were wired to the control hub (Figure 6).

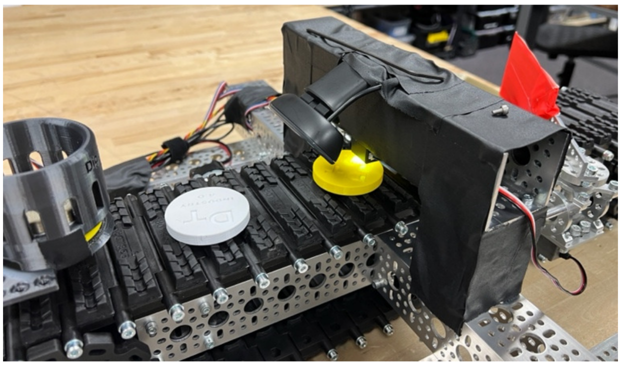


Figure 6. Sensor Bridge with Computer Vision.

For the pick and place, a Gobilda Dual Mode Servo (25-2 torque) was installed to mimic the pick and place of a robotic arm. Future implementation could replace the Servo with a robotic arm (such as the Mirobot) or vacuum to move pucks; however, for this first implementation, a standard Servo was used to sort the pucks based on material finish. The puck sorting and re-routing utilizes a beam attached to the Servo arm, which acts as a gate that can open, close, or redirect pucks. The Servo sorter was mounted using standoffs connected to a Servo block, immediately behind the sensor bridge (Figure 7).

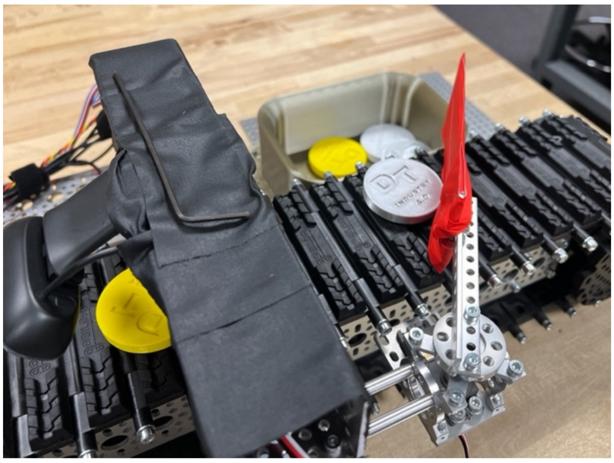


Figure 7. Pick-and-place Sorting Gate (No Manipulator).

In addition to the pick-and-place robotic system, the products (small pucks), the puck-feeding mechanism, and puck-sorting container were manufactured using 3D Prusa printers. For the 3D printed parts, Autodesk Fusion 360 was used to export both the models into a standard tessellation language (STL) format. PrusaSlicer software, version 2.5.0, was used to create a geometry code (gcode) format from these STL files. The models were then printed on a Prusa i3 MK3S+ printer using eSun PLA+ filament. The printing time was about 18 h for all the models. Different filaments were used to change the puck color and material finish to better facilitate the sorting process (Figure 8).

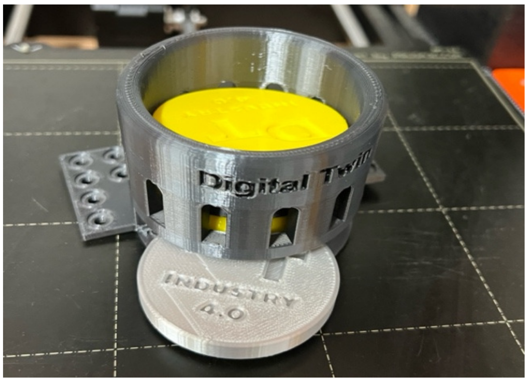


Figure 8. 3D Printed Pucks and Feeding Mechanism.

Due to constraints with both part and component availability at the time of building, the physical model did not reflect the initial CAD model. Additional time will be required to rework both the CAD model and the physical prototype to have complete virtualization of the environment. With more part availability, a smoother and quieter conveyor belt system could have been implemented. In addition to the structural build, for the first generation, only the color sensor and the camera were installed. Additional sensors and IoT devices (such as MicroBits) need to be added to show students the capabilities with the Internet of Things.

A final consideration from the case study would be to explore integrating off-the-shelf, out-of-the-box implementations, such as the Mirobot, with student-built prototypes, allowing students to work with advance technologies such as the Mirobot but still have hands-on, project-based learning opportunities to design, built, and test robotic technologies (Figure 9).

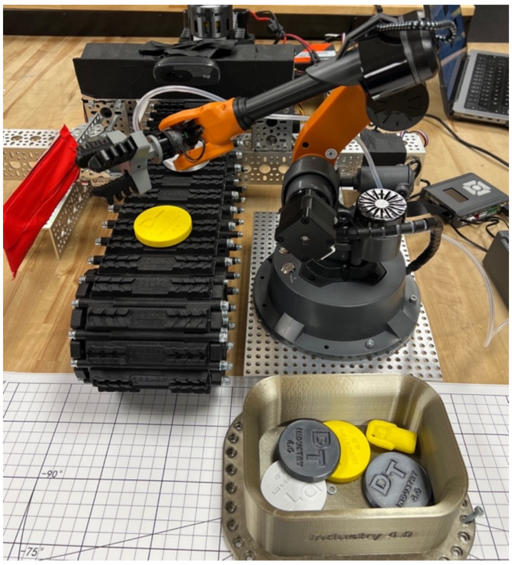


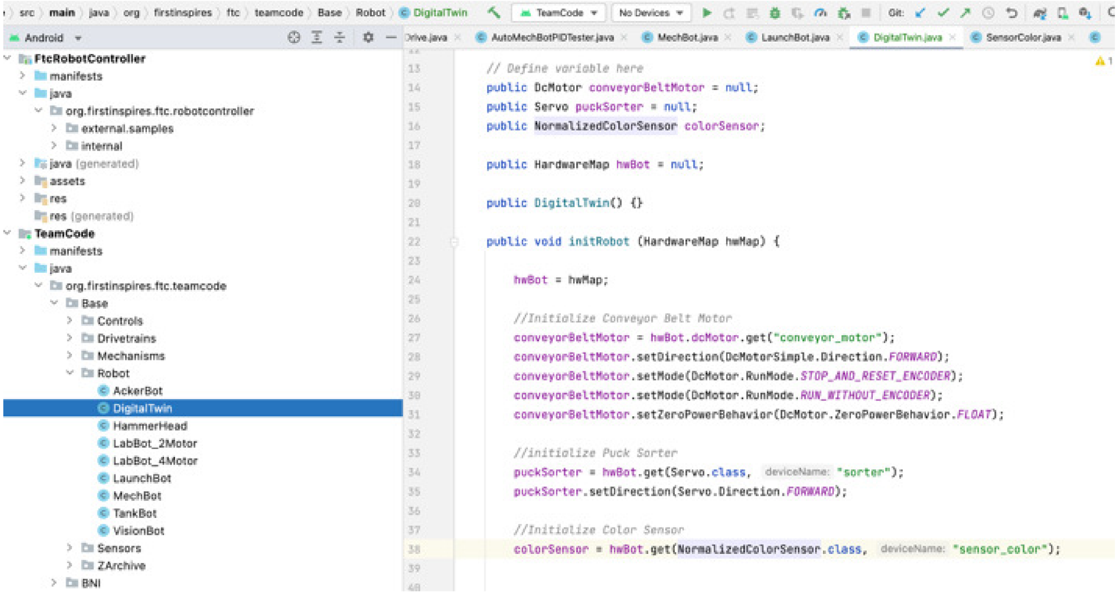
Figure 9. Mirobot and Student-built prototype Integrated for Pick-and-Place Manipulator.

4.5. Exploring Automation Limitations without ROS/Unity Integration

The researchers explored automating without using ROS and Unity to understand the feasibility of other options, especially for secondary schools without Unity or ROS expertise. Java was selected as the programming language, and Android Studio was chosen as the integrated development environment (IDE). The Software Development Kit (SDK) provided by FIRST Tech Challenge was installed since it contains multiple libraries to control various actuators and sensors. The SDK also helps with building intelligence into the system through libraries of different sensors and cameras.

A Rev Robotics Control Hub was used as the system controller instead of a PLC. FIRST Tech Challenge hardware and software components are readily accessible to secondary educational institutions. PLC is more expensive and less intuitive for students. In addition, the Java and Python programming languages are sponsored languages for the AP College Board, allowing students to gain hands-on learning with computer science while preparing for college at the same time. In addition, the FIRST Tech challenge SDK provides a predefined library of classes and methods to make programming of the robotic system simpler for secondary education students.

The programming architecture included a system hardware class, an autonomous mode class, and a tele-operation (TeleOP) mode class for human control. The system hardware class contained all the hardware configuration and hardware methods required to run the prototype. This class also contained reusable methods for the actuator and sensors. EasyOpenCV was set up for vision tracking and image recognition using the camera hardware. The autonomous classes contained the automated operation of the conveyor belt system without human control. The TeleOp classes allowed for a human operator to control the prototype during the testing and configuration phases (Figure 10).



```java
    // Define variable here
    public DcMotor conveyorBeltMotor = null;
    public Servo puckSorter = null;
    public NormalizedColorSensor colorSensor;

    public HardwareMap hwBot = null;

    public DigitalTwin() {}

    public void initRobot (HardwareMap hwMap) {

        hwBot = hwMap;

        //Initialize Conveyor Belt Motor
        conveyorBeltMotor = hwBot.dcMotor.get("conveyor_motor");
        conveyorBeltMotor.setDirection(DcMotorSimple.Direction.FORWARD);
        conveyorBeltMotor.setMode(DcMotor.RunMode.STOP_AND_RESET_ENCODER);
        conveyorBeltMotor.setMode(DcMotor.RunMode.RUN_WITHOUT_ENCODER);
        conveyorBeltMotor.setZeroPowerBehavior(DcMotor.ZeroPowerBehavior.FLOAT);

        //initialize Puck Sorter
        puckSorter = hwBot.get(Servo.class, deviceName: "sorter");
        puckSorter.setDirection(Servo.Direction.FORWARD);

        //Initialize Color Sensor
        colorSensor = hwBot.get(NormalizedColorSensor.class, deviceName: "sensor_color");
```

Figure 10. Java Code Example.

There were some issues with the automation. The color sensor could only detect large contrast in colors (e.g., white versus yellow pucks). Some pucks (silver and bronze metallic) were more difficult to detect in the current lighting environment. The EasyOpenCV programming for vision tracking and image recognition did not fully detect the color of pucks in this first generation. More configuration and training will be required to leverage image detection between the different pucks by the camera.

4.6. *Exploring Communication Limitation without ROS/Unity Integration*

The researchers explored creating a real-time, continuous communication link between the virtual environment and the physical environment without using ROS or Unity. Once again, the goal was to understand the feasibility of other options, especially for secondary schools without Unity or ROS expertise. The communication link explored leveraged Acme Robotics' FTC Dashboard [12]. However, there were a few challenges with using this off-the-shelf software. The standard FTC Dashboard assumes creating a digital version of a mobile robot moving on a FIRST Tech Challenge game field, not necessarily a pick-and-place manipulator. Therefore, true virtualization of the physical prototype could not be achieved using the FTC Dashboard out of the box. Customization and reconfiguration of the FTC Dashboard, especially the graphical interface, would need to happen to simulate digital twins in a smart warehouse operation.

Once these gaps were identified, the original Fusion 360 model was exported into Autodesk Inventor 2023 software. Inventor was used to export the model in JT file format. The JT file format was then imported into the Siemens Process Simulate Standalone version. The model successfully rendered in Technomatix; however, there were some issues with the whole model being imported as a single component (Figure 11). With proper importing of individual components and assembling them in Process Simulate, a realistic simulation could be created. Further work could improve virtualization with an integration with the Rev Robotics Control Hub or the installation of a refurbished or lower-cost PLC controller. In summary, a communication link was established as part of this case study, but this link was not properly configured for true connectivity and virtualization of the digital twin prototype with either the FTC Dashboard or the Tecnomatix Process Simulate model.

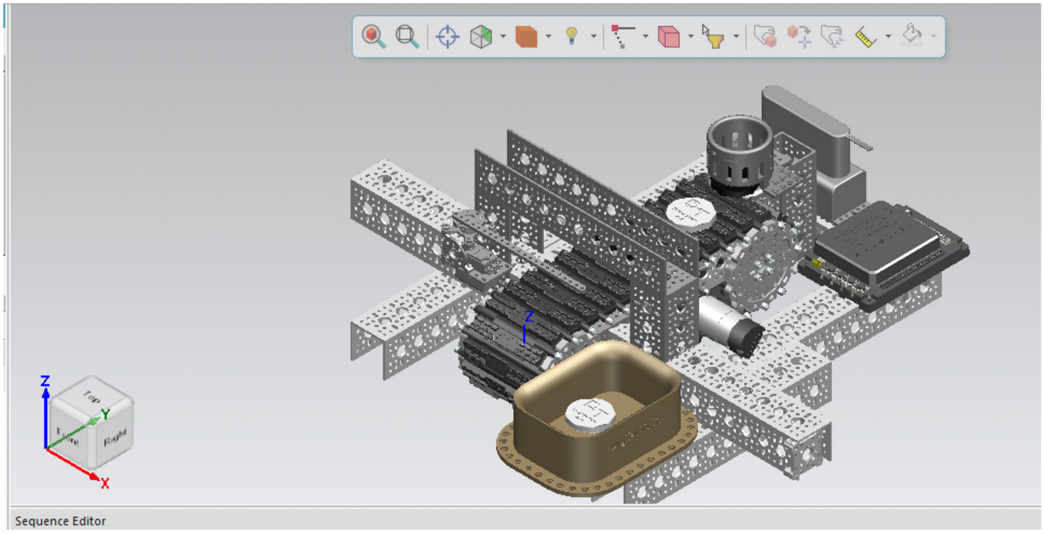


Figure 11. Process Simulate Model of Digital Twin.

5. Results

The primary goal of this research was to provide a methodology to expose secondary students to Industry 4.0 by implementing a low-cost digital twin prototype that changes student perceptions of robotic technologies and shows the benefit of these technologies outside of current student stereotypes. Although the final prototype was not fully operational by the definition of a digital twin, exposure to the various technologies behind Industry 4.0 was achieved. Both quantitative and qualitative results were gathered.

5.1. Qualitative Results

- The application of computer-aided design with the low-cost digital twin prototype exposed students to digital manufacturing concepts. Digital manufacturing is a foundational component of Industry 4.0. [13]. Through the virtual CAD design of the digital twin prototype, students started to understand how these digital tools create more intelligent and automated manufacturing systems. Exposure to digital tools under the umbrella of computer-aided manufacturing generated discussions about various career opportunities that may not have been introduced or discussed otherwise.
- The application of additive manufacturing (3D printing), sensors, robotic components, and vision tracking in the low-cost digital twin prototype introduced the concepts of intelligent automation. By students learning how to work with and apply these various technologies with a hands-on, working prototype, students gained more exposure to these technologies and transformed their own perceptions, social norms, and stereotypes regarding robotic applications. Some students were excited to see robotic technologies without "wheels," focusing substantial time and attention on machine vision, robotic manipulators, and soft grippers.
- Working with the programming and communication connectivity behind the low-cost digital twin prototype helped students to build the skills necessary for Industry 4.0. By having to program, configure, and virtualize the digital twin prototype, students developed their information communication technology (ICT) skills. Some students deepened their ICT skills through programming; however, all students broadened their ICT skills and more importantly practiced interdisciplinary skills, such as complex problem solving, critical thinking, creativity, collaboration, emotional intelligence, and decision making. The building of the prototype and the challenge of causing the manipulator to pick up an object fostered teamwork and collaboration in the student groups.

- Through the process of implementing a low-cost, digital twin prototype, students were exposed to exciting technological areas, such as digital manufacturing, digital twins, and intelligent automation. More importantly, they learned about potential roles in the future workforce and the skills required to be successful in the industrial revolution of Industry 4.0. Whether the digital twin prototype is fully or partially operational, the process of designing, building, and operating the digital twin prototype exposed students to the vast career potential found in the "T" and "E" of STEM.

5.2. Quantitative Results

A short student survey was conducted to collect some preliminary data. For this research, the student population consisted of 25 students enrolled in engineering, technology, or robotics classes in grades 7–10 (middle and high school) [Table 2].

Table 2. Student Survey Results conducted by authors.

Learning Objectives and Outcomes	**Responses**
Prior Industry 4.0 knowledge	4 out of 25
Change in perception of future career opportunities	18 out of 25
Change in perception of robotics and its applications	17 out of 25
Positive feedback on learning about digital twins	19 out of 25
Positive feedback on learning about additive manufacturing	22 out of 25
Positive feedback on learning about CAD/virtual simulations	20 out of 25
Positive feedback on learning about ROS	23 out of 25
Positive feedback on additional lessons about Industry 4.0	20 out of 25
Positive feedback on benefits of learning Industry 4.0 trends	21 out of 25
Positive feedback on this form of robotic technologies versus mobile robotics or robotic competitions	24 out of 25

6. Conclusions

To implement Industry 4.0, there needs to be more advancement and innovation in multiple technologies, one of those being robotic technologies [14]. To help advance these robotic technologies, as well as overcome other technological challenges related to Industry 4.0, secondary and higher educational institutions need to work together to improve the pipeline of students interested in pursuing STEM-related learning and developing ICT skills, thereby ensuring a future workforce that can research, design, develop, operate, and maintain the systems and technologies of Industry 4.0. Outside of specialized STEM roles, a majority of the future workforce will need to work alongside or at least interact with advanced systems; therefore, the future workforce will need to be versed in ICT skills and possess strong interdisciplinary soft skills, such as problem solving, critical thinking, and quick decision making, to be successful.

Because of the expanding technology penetration across all industries, broad and specialized STEM and ICT skills will be required for all occupations and most levels of employment. To help prepare this future workforce, secondary institutions need to expose students to the wide variety of technologies that comprise Industry 4.0. The low-cost digital twin approach using Unity and ROS has shown great potential in helping secondary schools to expose students to key aspects of smart warehouse operations. First, the seamless integration of Unity and ROS allows for real-time communication and data exchange, enabling a learning environment in which students can practice soft and specialized ICT skills within a unified platform that includes rapid development, testing, and deployment of control algorithms. Second, students can practice applying science, mathematics, and critical thinking through the development of physics-based simulations using Unity's advanced capabilities to render realistic representations of warehouse operations. This process exposes students to how Industry 4.0 technologies can evaluate automation systems' performance and identify potential issues before implementation, reducing the risks associated with costly errors and system downtime. Finally, through CAD, 3D printing, and robotic pick-and-place prototypes, student can gain exposure to and learn about how digital manufacturing, additive manufacturing, and robotic technologies are integral to Industry 4.0.

Overall, the digital twin methodology leveraging Unity and ROS offers a cost-effective, efficient, and user-friendly solution for students in secondary schools to learn about Industry 4.0 technologies. Through these project-based learning opportunities, secondary students can be introduced to Industry 4.0 and subsequently learn about and apply the concepts behind digital manufacturing, intelligent automation, robotic technologies, additive manufacturing, digital twins, the Internet of Things, and machine learning. These secondary students can start to make career connections with Industry 4.0 and understand the importance of learning these technologies for future success. By exposing students to Industry 4.0, secondary educational institutions can start to develop a pipeline for a future workforce that possesses the STEM, ICT, and interdisciplinary skills required to design, build, maintain, and operate the technologies of Industry 4.0. With a strong STEM and ICT future workforce, companies will be able to realize the efficiency, productivity, and profitability benefits of Industry 4.0 [3].

7. Further Work

There is substantial opportunity to improve this low-cost digital twin prototype for secondary educational institutions. Further work and additional case studies can be conducted. In the realm of further work, the exploration of cost-effective and accessible software suites for digital twin modeling, such as Unity and ROS, needs to be expanded upon. While the physical and simulation aspects of digital twin modeling are well established in the commercial industry, harnessing these affordable tools in an educational setting requires additional exploration. The WKLATA Mirobot's educational platforms, such the AI Vision kit, the Fruit Picking Line kit, the conveyor kit, and the Assembly Line Training Cells, can offer hands-on application for students to work with a small-scale Industry 4.0 manufacturing or smart warehouse operations (Figure 12) Other educational kits to explore include the VEX V5 Workcell [15,16]. Custom solutions combining both a Mirobot manipulator and student-built assembly line prototypes can also be further explored (Figure 13).

Figure 12. Off-the-shelf WKLATA AI Automatic Sorting Line Training Cell [11].

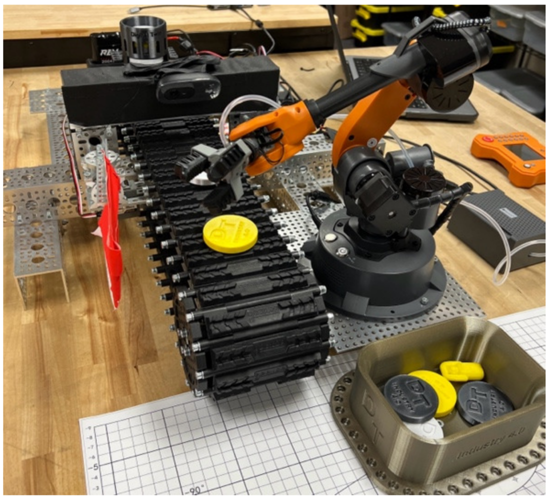


Figure 13. Mirobot Integrated with Researcher-built Assembly Line.

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