Industry sponsored Capstone Project for Smart Manufacturing and Industry 4.0

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Irina Ciobanescu Husanu, Ph. D. is Associate Clinical Professor and Director of the Engineering Technology Program, Drexel University, Philadelphia, PA. She received her PhD degree in mechanical engineering from College of Engineering at Drexel University and her BS/MS in Aeronautical Engineering from Aerospace Engineering College at Polytechnic University of Bucharest, Romania. Dr. Husanu' s educational background is in propulsion systems and combustion. Dr. Husanu has more than a decade of industrial experience in aerospace engineering that encompasses extensive experimental investigations related to energy projects such as development of a novel method of shale natural gas extraction using repurposed aircraft engines powered on natural gas. As chair of the Engineering Technology Curriculum Committee, she is actively engaged in aligning the curricular changes and SLO to the industry driven student competencies. Her main current research interest is in engineering pedagogy, focusing on development of integrated mechanical engineering technology curricula for enhanced student learning experience. While her expertise encompasses thermo-fluid sciences with applications in micro-combined heat and power systems, recently, her research included educational investigations in Virtual and Extended Reality for engineering systems, renewable energy systems and energy conversion, social and sustainable engineering. During the past 8 years she led several overarching educational projects in green energy and sustainability in manufacturing environment and experiential learning modules for manufacturing related courses. Her current research is focused on investigating potential applications of CO2 separation and sequestration from either flue gases (as product of natural gas combustion) or biomass byproducts. As the Senior Design Project Coordinator (a capstone design sequence of courses), she is fostering industry-academia collaborative undergraduate research.

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Abstract:

Engineering design challenges are inherently complex, demanding interdisciplinary knowledge and collaboration. In response to this need, the student design team's Engineering Technology (ET) program developed a capstone model that forms multidisciplinary teams to tackle industry-sponsored projects. These capstone projects not only offer students crucial educational advantages but also prepare them for future career demands by simulating real-world scenarios. This paper presents the student design team's systematic approach to soliciting industry-sponsored projects and guiding students in forming diverse teams to work on these challenges. It also highlights a specific industry-sponsored project in collaboration with IFM efector, Inc., which focuses on optimizing the assembly process through cutting-edge technologies like industrial PCs, Human Machine Interface Controllers, Various sensing and tracking devices and vision cameras.

This paper emphasizes the growing significance of project-based learning, noting its alignment with new technological trends such as Industry 4.0 and smart manufacturing and assembly. The integration of smart and sustainable manufacturing in capstone topics mirrors this shift, contributing to the development of leadership skills, creativity, and innovation among students. With over 65% of capstone projects focused on manufacturing, energy, and sustainability, students engage with open-ended projects that reflect real-world uncertainties and require them to determine optimal solutions. Through this model, we assess students' competencies and skills as they navigate the challenges of interdisciplinary collaboration and technological innovation.

In addition, the paper delves into the supervision and evaluation methods employed in these projects, as well as the final presentations and reports that showcase student accomplishments. By analyzing the integrative approach used in these capstone projects, we demonstrate how industry collaboration and multidisciplinary education foster sustainable, innovative solutions in engineering design as it relates to manufacturing and assembly of products.

Background

In Drexel University's (DU) Engineering Technology program, many courses related to robotics, design, and materials are offered to students. Courses such as Robotics and Mechatronics, Quality Control, Manufacturing Materials and Processes, Microcontrollers, and Applied Mechanics can benefit from the laboratory experience in applications of mechatronics and automation, robotics, and manufacturing and assembly processes. As well as helping in the teaching of various topics, such experience benefits students who are pursuing degrees in the engineering field. Students in Mechanical-manufacturing, Electrical, and Robotics and Automation concentrations along with many others can learn many new skills from multi-disciplinary projects such as developing a smart manual manufacturing assembly cell integrated with vision sensors, RFID tags and industrial PLCs.

Students in the Engineering Technology programs are required to complete a year long three series of capstone course that is MET 4XX Senior Design Project. This three-quarter sequence aims to train the students in identifying projects of relevance to society, in planning and scheduling a solution, and in entrepreneurial activities that may result from the project. This course is worth three credits per quarter every offering. The course is also intended to cover an industrial project starting from the proposal writing and conceptual design to final prototype building and concept realization steps. The senior design course sequence goals aim to (1) integrate experience that develops and illustrates student competencies in applying both -technical and non-technical skills in successfully solving engineering technology problems, ideally multidisciplinary in nature; (2) implement Project-Based Learning that includes formal design, implementation, and test processes; (3) significantly improve students' skills in the areas of system analysis and design, technical writing, public speaking, teamwork, and project management; (4) ensure that students gain experience and expertise in solving real-world design problems.

MET 4XX is focused on proposal and project progress report writing, prototype fabrication as well as design improvement and optimization. Each quarter, student teams must submit a progress report and demonstrate a physical working prototype at the end of academic year. During the fall, winter and spring quarters, they conduct an oral presentation to faculty, practicing engineers from industry and industry sponsors for the projects. The three major assessment phases of their projects were evaluated based on ten performance criteria scored on a LIKERT scale from 0 to 5, with the option of N/A:

Table 1. Scoring scale for capstone design (interpolated scores are permitted)

Score	Qualitative Score	Explanation
5	Excellent	All areas were exceptional; nothing should be improved.
4	Very good	Very few areas require minor improvement, no important omissions.
3	Good	Some minor omissions, and some areas require additional work, or have errors that should be corrected
2	Adequate/Acceptable	Errors and/or omissions that must be corrected.
1	Marginal/Novice	Effort made, but there were major errors/omissions that must be corrected.
0	Poor/Unacceptable	Almost no effort made that was consistent with guidelines

The performance criteria assessed students on the level of mastering their abilities and skills, based on both oral presentations and written reports. (Please see reference [1] for more details on assessment rubrics and scoring) Since this is a capstone project course, many ABET Student Outcomes are assessed each quarter as indicated in Table 2. Written, oral and student contribution rubrics were developed specifically for the capstone project courses and are used during assessment and evaluation. The assessor body includes the Engineering Technology program faculty, industry advisory board members, sponsoring company engineers as well engineers from various local engineers and invited Drexel University faculty.

Table 2. ABET Students Outcomes assessed per quarter offering.

Engineering Technology Courses		**ABET Student Outcomes**
MET 421	Senior Design Project I	**1, 2, 3, 5**
MET 422	Senior Design Project II	**1, 2, 3, 5**
MET 423	Senior Design Project III	**1, 2, 3, 5**

Project Opportunity and Problem Statement

This collaborative venture with IFM entails the supply of specialized equipment vital for the success of the student design team's project, generously provided by IFM. The core issue this venture aims to solve includes the discrepancies in the manufacturing process to error-proof. In addition to reducing defects and even worse, recalls, another goal is to reduce non-additive labor which involves training and hiring apt workers. The student design team's primary objective is to transform the assembly process by seamlessly integrating machine vision with real-time hand tracking and an interface controller. To accomplish this, the capabilities of dual 3D cameras were utilized: one dedicated to inspection and the other to precise sensing, thereby optimizing the efficiency of the assembly line. Additionally, RFID technology will be utilized to ensure efficient tracking and control across the assembly workflow through passive RFID tags which can both categorize and label all parts.

Overall, the student design team’s estimated project cost for parts and materials provided has averaged $30K. The team has worked closely with support engineers at IFM to finetune the final product to ensure compliance with official standards and environmental concerns.

Student design team’s collaborative partner for this project is IFM efector, a distinguished German company specializing in industrial sensors and automation technology manufacturing and supply. IFM efector is well-regarded for its dedication to excellence, and its products and solutions play a crucial role in improving the efficiency, reliability, and safety of various manufacturing and production processes in the field of industrial automation. In this joint effort, students were set to integrate IFM's cutting-edge camera technology, visually represented in the attached image below.

Figure 1. Physical layout for IFM mate prototype

The initial 3D camera, known as the IFM mate camera, is integrated with the IFM mate, which serves as an industrial PC overseeing the workflows. These workflows act as visual instruction manuals for assembly operators, guiding them through the assembly process step by step. Student design team’s approach to optimizing part assembly involves a sophisticated system that leverages color codes. The color red serves as an alert for potential errors in the assembly process and can stop the assembly process if an error is encountered. The color blue indicates the smooth transition of a part to the subsequent stage or process in the workflow. The color green serves as the distinctive indicator for the action of picking up a part. When an operator moves to retrieve a part, the second 3D sensing camera will confirm that the operator's hand has successfully grasped the part by determining the required depth within a specified bin. To guide operators seamlessly through the assembly process, an interactive screen will be prompted for display, as shown in the initial image to the left. The screen will present visual cues based on the established color codes, directing operators on the parts to be picked in accordance with the designated workflow for each specific assembly task. This integration of IFM technology and color-coded guidance not only streamline operations but also reinforces error prevention, thereby enhancing overall productivity. The accompanying image on the right displays the strategic placement of the IFM Camera atop the work desk, ensuring an optimal operational range. While a similar system is currently in place in Germany, student design team’s goal is to enhance its functionality by incorporating multiple workflows, as detailed in the following sections.

Problem Statement

The problem at hand involves the critical need to enhance the assembly process. Particularly in the realms of error-proofing via the 3D camera system, material identification through passive RFID technology, and human hand tracking facilitated by the 3D camera system. This challenge is rooted in the intricate nature of assembly tasks, the diverse array of materials utilized, and the absence of real-time guidance for operators, all of which will be addressed through the implementation of an interactive monitor. Addressing these issues is vital to ensure the quality, efficiency, and reliability of the assembly process.

Progress Towards a Solution

By addressing the identified unmet need, the team was able to create a system map approach. Students categorized the system map into eight distinct facets, each further delineated into subcategories. The student design team's exploration of these needs led us to categorize them as follows: speed, user.

interface, types of sensors, 3D cameras, targeted error identification, IFM process, stakeholders, and the final category, parts. Under the speed category, the student design team's focus revolves around determining the average time required for part assembly. For the user-interface aspect, the team delved into considerations such as the operator's position and distinguishing between sitting and standing configurations. In the types of sensors category, student design team's analysis extends to parameters like weight and the decision-making process of using either a single sensor or multiple sensors. The 3D camera system is scrutinized based on cost, type, and weight considerations. Identifying errors becomes a nuanced task, involving the breakdown of programming logic, measurement errors, and initial points of calibration. Stakeholders in this initiative encompass a diverse group comprising operators, student design team as students leveraging technical expertise, student design team's advisors, and representatives from IFM. Lastly, the parts category encompasses the mechanical design, electrical design, and material manufacturing aspects, forming the essential building blocks of the student design team's comprehensive approach.

By implementing the IFM process, the team leverages workflows. A workflow serves as a visual guide displayed on the interactive monitor, guiding operators through the assembly process of the given part. The IFM Mate achieves this by defining a workspace through the IFM Mate camera, distinct from the sensing camera. The primary objective of the IFM Mate is to create diverse workflows, which can be assigned individually or in a batched production cycle. The number of workflows a station can generate determines the achievement of three key goals. To showcase this project to IFM customers, the student design team's workstation needs to produce a minimum of two workflows. Three to five workflows are necessary to serve as a training bench for new hires.

Finally, for integration into the production line and potential customer sales, the workstation should generate five workflows or more. The outlined goals evolved into a concept evaluated based on customer requirements, as detailed in Figure 2. This concept received two positive scores, zero negatives, and five neutral scores, as they lacked a direct correlation with customer needs. The positives included reducing processing time and ensuring a simple design for easy installation at other facilities, as depicted in the figure 2 above. Various design considerations were accounted for, such as system and process analysis, along with the benefit of offering easy re-programmability. Customer needs were carefully assessed, and by incorporating the concept of multiple workflows, the product gains versatility and aligns closely with customer requirements, thus increasing its value proposition.

Project title: IFM Machine Vision
Date: 1/22/2024

Design Matrix Model

	1: low, 5: high Customer	Desired direction of improvement (↑,0,↓) Concept Impact Customer Requirements	1 Multiple Workflows	2 Adjustable Table Stand	3 Power Flow Design
1	4	Reduce the processing time	+	+	0
2	4	Enchance error-proofing measures	0	0	0
3	2	Support Load scaling capabilities	0	0	0
4	3	Ensure a simple design for easy installation at other facilites	+	+	+
5	4	Ensure durability and long-lasting performance	0	+	+
6	3	Can be easily repairable/ reprogrammable	0	+	+
7	3	Allows easy replacement of worn parts	0	-	+
8	3	Enable sensitivity adjustments for indvidual operators	0	+	0
9					
		Score +	2	5	4
		Score -	0	1	0
		Score 0	5	2	4

Figure 2. Concept Impact Score

Before implementation, the human-machine interface controller must establish a connection with the IFM Mate to define the workstation and facilitate clear information flow for the operator. Once this connection is established, the concept can be realized by configuring the program for the PLC controller and establishing the necessary link between the controller and the IFM Mate. This systematic approach ensures that the concept is not only aligned with customer needs but also technically feasible and operationally effective, enhancing the overall value of the product.

Project Design Alternatives

In considering design alternatives, team evaluated the feasibility of utilizing active RFID, passive RFID, load scaling, or a combination of load scaling and passive RFID for part identification during assembly. RFID technology offers advantages such as cost-effectiveness, automation capabilities, and streamlined data collection. The student design team’s preference for passive RFID overactive RFID primarily stems from the operational range required. Passive RFID offers a maintenance-free and extended operational lifespan while eliminating the need for frequent battery replacement, commonly required in active RFID systems. Additionally, passive RFID proves highly efficient for part assembly operations. Load scaling, on the other hand, involves measuring mass or weight and is limited in its ability to identify materials based on quantity present in a specific bin. It serves a different purpose from passive RFID technology and cannot be directly compared.

Regarding alternative options to the 3D cameras provided by IFM, offerings from different manufacturers such as Cognex and Keyence were explored (Figure 3). The student design team’s key categories were considered for comparison: cost, resolution, operating distance, and ambient temperature. Keyence's camera range was priced between $1600 and $1900, Cognex's range fell between $2000 and $2300, and IFM's cameras were priced at $1735. In terms of resolution, both IFM and Cognex offered 1280 by 980 pixels, while Keyence had a resolution of 752 by 980 pixels. Concerning operating distance, IFM stood out with a range of 85-2500 mm, surpassing the 20-500 mm range offered by both Cognex and Keyence. Lastly, in terms of ambient temperature, IFM cameras operated within a range of -10 to 50 degrees Celsius, whereas the other companies' cameras functioned within the 0-50 degrees Celsius range.

O2D520	Sensing Cameras			
Specs	IFM Range	Cognex Range	Keyence Range	Units
Exposure Range	200-10,000	200-10,000	200-10,000	us
Cost	1,735.50	2000-2300	1600-1900	Dollars
Sensor Resolution	1280*980	1280*980	752 x 480	px
Ambient temp	-10-50	0-40	0-50	C
Reading Rate	40	#	#	Hz
Reading Rate	25	#	#	ms
Physical Inputs/Outputs	3/5	1/4	8/8	#
Operating Voltage	18-30	24 +/- 10%	24 +/- 10%	V
Current Consumation	<400	#	#	mA
Max V	30	24	24	V
Operating Distance	85-2500	50-500	20-500	mm
Weight	1.3	0.44	0.16	lbs
Wave Length	850	#	#	nm
Dimensions of Camera	45X45X86	61 x 60 x 52	#	mm
Material	Diecast zinc powder-coated	Painted aluminum, IP65-rated housing	Main unit case: Zinc die-casting, Front cover: Acrylic (hard coat), Operation indicator cover: TPU	N/A
Display	(2 x LED), green, yellow, green/yellow	Red, blue and IR LED ring lights and lens filters, and polarized light cover	White LEDSwitchable between pulse lighting and DC lighting	N/A

Figure 3. Benchmarking Specs

Quality Function Deployment (QFD) Breakdown

A comprehensive exploration of eight customer requirements was undertaken in the analysis of quality function deployment. These requirements encompassed diverse aspects, such as reducing assembly processing time, implementing robust error-proofing measures, facilitating load scaling capabilities, and ensuring a straightforward design for easy installation across various facilities. Additionally, attention was directed towards ensuring durability and long-lasting performance, fostering easy re-programmability and repairability, facilitating the seamless replacement of worn parts, and enabling sensitivity adjustments tailored to individual operators.

Quality Function Deployment

Project title: IFM Machine Vision

Date: 11/1/2023

		Desired direction of improvement (↑,0,↓)	1	2	3	4	5
	1: low, 5: high Customer importance rating	Functional Requirements (How's) → Customer Requirements ↓	PLC Coding/Code Assist (optimizing algorithms for efficieny	RFID Vertification(providing real-time feedback to operators	Hand Tracking Technology (vie sensing Camera)	Sensor Integration(communication protocol for seamless interaction bewtween sensors)	2D Camera System(one for precise sensing, the other for inspection)
1	4	Reduce the processing time	9	8	4	4	5
2	4	Enchance error-proofing measures	9	9	7	7	6
3	2	Support Load scaling capabilities	3	2	2	2	0
4	3	Ensure a simple design for easy installation at other facilites	4	7	6	5	3
5	4	Ensure durability and long-lasting performance	5	4	5	4	3
6	3	Can be easily repairable/ reprogrammable	6	2	3	3	2
7	3	Allows easy replacement of worn parts	3	2	1	3	3
8	3	Enable sensitivity adjustments for indvidual operators	2	4	3	0	5
9							
		Technical importance score	143	133	107	97	95
		Importance %	25%	23%	19%	17%	17%
		Priorities rank	1	2	3	4	5

Figure 4. QFD Analysis

These customer requirements were efficiently distilled into five distinct functional requirements. The first entailed PLC coding, leveraging Code Assist to optimize algorithms for enhanced efficiency. The second requirement focused on RFID verification, offering real-time feedback to operators. The third involved the utilization of hand-tracking technology through a sensing camera. The student design team's requirement centered around sensor integration, emphasizing seamless communication between sensors. Lastly, the fifth requirement introduced a 3D camera system, highlighting one camera for precise sensing and another for inspection purposes.

To delve into the scoring and prioritization of these functional requirements, refer to Figure 4 above. This breakdown provides a detailed insight into how each requirement was evaluated and ranked, contributing to the overall understanding of the quality function deployment process.

Project Design

The integration of specialized sensing technology, encoders, RFID tags, and IO-Link with 3D cameras in industrial assembly environments entails an in-depth analysis of industry-standard specifications and specific attributes, coupled with implications and integration considerations. The specified power output range (450-800W) must align with industry standards to ensure efficient power supply support and operational reliability in industrial assembly environments. Adherence to industry standard benchmarks for the reading rate (40Hz) is essential to enable efficient real-time monitoring and response to assembly line activities, ensuring swift and accurate data exchange. Aligning the resolution (1254400 pixels) and wavelength (850nm) specifications with industry standards is critical to maintaining consistent image quality and precision, crucial for accurate part inspection and quality control. Ensuring compatibility with industry-standard temperature tolerances (-60°C) and exposure range (200-10,000µs) is essential for resilience against extreme environmental conditions in industrial settings, optimizing the functionality of integrated components. The specified operational range (85-2500mm) and field of view (FOV) (1-5m) necessitate alignment with industry standards to ensure comprehensive spatial monitoring and visibility within industrial assembly environments, contributing to effective data capture and part identification.

The seamless integration of 3D cameras in industrial assembly environments calls for meticulous adherence to industry-standard specifications and integration implications, optimizing precision, reliability, and operational efficiency. Achieving optimal integration requires the positioning of 3D cameras and specialized sensing cameras to capture precise and detailed images, ensuring accurate identification of components and guided assembly cues based on the 1254400-pixel resolution. The integration necessitates a robust power supply to support the specific power output range and operational voltage (18-30V) of the O2D520 and O2I501 IFM cameras, aligning with industry standards for efficient functionality. Considerations of the operational range and FOV of the cameras are vital to ensure effective capture and monitoring of assembly processes, accommodating diverse assembly tasks within industrial settings. Adhering to industry-standard specifications for ambient temperature and exposure range is essential to optimize performance and prevent operational issues in varying environmental conditions.

Precise handling of reading rates and response times is crucial to ensure efficient communication and integration between the IO-Link, controllers, and the 3D cameras, facilitating real-time notification of discrepancies and efficient data exchange. This feature facilitates the selection of required materials for specific assemblies based on work orders retrieved from the SQL database, streamlining the assembly process by eliminating unnecessary materials. Participants in the project are recommended to possess prior experience in PLC programming. The use of Code Assist, a code-writing chatbot, is suggested to expedite progress. For a visual representation of the project design, see Figure below. Regarding electrical design, the project employs O2D520 and O2I501 IFM cameras for sensing and inspection, respectively. A robust power supply, converting the standard 120V from the wall socket into a 24V DC system, supporting all aspects of the system. PLC-ladder logic, coupled with Code Assist, will be employed for efficient and rapid code development.

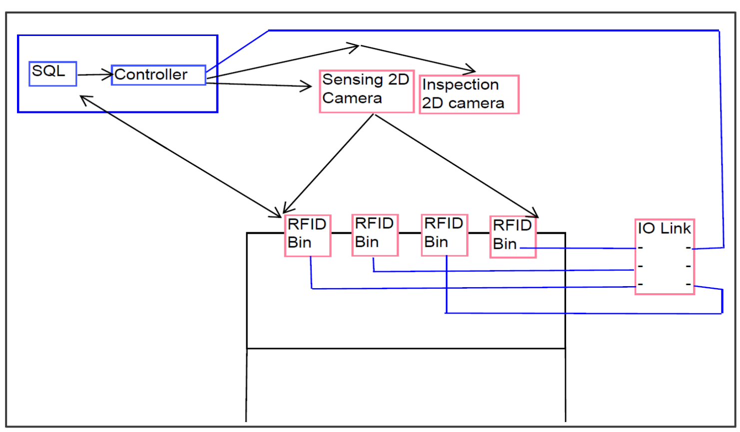


Figure 5. Process Map

Design Assembly

In the realm of design assembly and mechanical engineering, the successful integration of the IFM Mate Worker Assistance System, particularly the OXZ100 model, into the production environment hinges on critical design and customer considerations. The design layout must encompass adjustable positioning for cameras and monitors, ensuring precise and adaptable placement to facilitate optimal monitoring and assistance in the assembly process. Additionally, the use of plastic and aluminum materials for system components is crucial to guarantee durability and longevity in industrial settings. Customer-centric elements, such as user-friendly features and compatibility with IFM cameras and available monitors, play a pivotal role in the seamless integration of the system. Furthermore, prioritizing clean cable management and lightweight design contributes to ease of handling and installation, optimizing the practicality of the assembly process. A comprehensive set of instructions has been meticulously crafted to facilitate the setup of the IFM Mate Worker Assistance System, emphasizing the strategic positioning of system components and the availability of instructional videos and step-by-step guidance.

In the context of the final design involving the vertical mounting of a metal pegboard to the back of the table, additional considerations for mounting components and managing cables need to be aligned with the specific attributes and safety requirements of this configuration. It is imperative to select a metal pegboard engineered for vertical applications within industrial settings, ensuring it possesses the requisite thickness and hole size to accommodate heavy-duty usage while maximizing durability and load-bearing capacity. Incorporating a secure mounting strategy, utilizing strong screws anchored into the frame or spacers affixed to the table, is essential to provide sufficient standoff space to accommodate the hooks and facilitate ease of insertion and removal of components. Systematically organizing the mounted components based on their size and frequency of usage is crucial, ensuring that heavier tools are positioned at the lower sections of the pegboard to mitigate the risk of accidents or unanticipated falloffs.

Human Factor Considerations

The design of the interactive screen is of paramount importance, as it must be intuitive and user-friendly to minimize the likelihood of operator errors or confusion. Ethically, a well-crafted interface should recognize the diverse skills and capabilities of operators, ensuring inclusivity and ease of use for all individuals. To enhance the comfort and well-being of operators involved in part assembly, several ergonomic considerations are taken into account. Firstly, the desk is strategically positioned at elbow height to facilitate efficient part assembly by optimizing spacing. Adequate lighting is implemented to ensure clear visibility, thereby fostering a conducive working environment. Scheduled breaks are incorporated to allow individuals to stretch and move, thereby mitigating fatigue and promoting overall well-being. Additionally, careful attention is given to monitor placement, with the top positioned at or slightly below eye level. This arrangement, combined with the direct alignment of the screen in front of the operator, aims to prevent neck strain and contributes to a more ergonomically sound assembly process.

Students prioritized implementing ergonomic seating. Chairs with adjustable features such as lumbar support, seat height, and armrests are utilized to maintain proper posture and reduce the risk of musculoskeletal disorders. Furthermore, ergonomic tool design is emphasized, as tools and equipment with ergonomic handles, grips, and controls can minimize hand and wrist fatigue and reduce the risk of repetitive strain injuries. Lightweight, well-balanced, and easy-to-maneuver tools are selected to optimize operator performance and comfort.

LCA and Environmental Considerations

Expanding on the environmental consideration of total energy consumption, the group embarked on a comprehensive analysis to evaluate the energy usage of the lab bench and its components. This involved breaking down the entire system into its constituent parts and meticulously examining each component's power requirements. From power supplies to cameras, every element was examined, with calculations based on current and voltage ratings to determine power consumption accurately. To ensure optimal energy performance, the group devised a strategy to simulate a typical workflow spanning a full day. This simulation would provide real-world data reflecting the energy usage patterns of the system under normal operating conditions. By meticulously recording these results and graphing them, the team aimed to establish clear boundaries delineating acceptable energy consumption levels. These boundaries, marked as upper and lower limits on the graph, served as benchmarks against which measured data could be compared.

Upon analysis, if the recorded energy consumption exceeded the established limits, indicating excessive energy usage, the team would pivot to devise necessary adjustments to the system's design. These adjustments might involve optimizing component configurations, fine-tuning operational parameters, or exploring alternative energy-efficient technologies. The goal was to rectify any energy inefficiencies and bring the system's consumption within acceptable bounds.

Conversely, if the measured data fell within the expected range or even below average, indicating satisfactory energy performance, the group would still explore avenues for improvement. While not an immediate priority, continuous enhancement remained a key objective, reflecting the team's commitment to sustainability and efficiency. This approach ensured that even if the energy consumption levels were deemed acceptable initially, ongoing efforts would be made to further refine and optimize energy usage wherever feasible. In essence, by prioritizing the assessment of energy consumption and implementing proactive measures to regulate and optimize it, the group demonstrated a commitment to environmental responsibility and efficiency in the design and operation of the lab bench system.

While considering energy efficiency, the reusability of each component was evaluated. To assess their potential for reuse, the student design team conducted a comprehensive life cycle analysis. This analysis aimed to identify components containing parts that could be disassembled and repurposed in the manufacturing process of new components by IFM.

Figure 5 below illustrates the flow of this process, starting with the production of a component and concluding with its end-of-life stage. Upon reaching the end of its usable lifespan, the quality and performance of each component were assessed to determine which parts are suitable for reuse. These reusable parts are then integrated into producing new components, contributing to student design team’s conservation and sustainability efforts. Any parts deemed unsuitable for reuse are responsibly disposed of

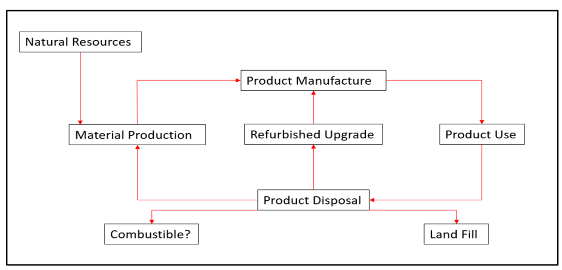


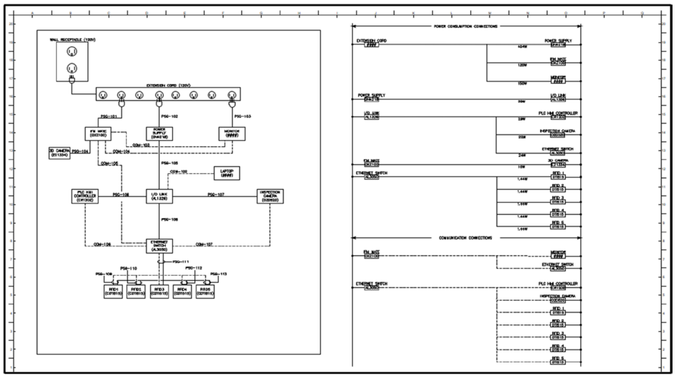
Figure 5. Life Cycle Analysis

Power and Consumption Considerations

An important concept that was explored, was the power distribution and modeling of the student design team’s entire setup. During the trial stages of assembling student design team’s prototype, initial power readings, such as voltage and current, by referencing spec sheets for each part and utilizing the IFM website were gathered. Although IFM’s website provided a thorough analysis of each part, the student design team’s project scope focused solely on power metrics.

A model of power distribution and network connections is mapped out in student design team’s Power Distribution drawing in Figure 6. On the left side of the drawing, it displays the power flow from part to part and indicate which parts are connected via Ethernet. With numerous cables involved, organizing them is essential for reproducibility. With the gathered measured data, along with the maximum and minimum power readings, the group will generate a graph accurately tracking the measured power. The graph will display upper and lower boundaries, along with live metering of power across an average industrial workday to simulate full-day usage. All power measurements will be converted to energy by multiplying each power for each component by the runtime in student design teams for one day.

A visual representation of Power Consumption Estimates can be seen in Figure 6 below with a table that breaks down energy consumption per part and total energy. It illustrates the daily average of power consumption. A low energy slope indicates system efficiency without needing much improvement. Conversely, a high slope raises flags, prompting student design team's group to consider more efficient parts and potentially altering student design team's design to yield the most efficient energy output.



Variable Electricity Costs at $0.0769 per kWh (Industrial Average)			
Part	Power (W)	16 Hrs/Day kWh	Rate($/kWh)
Power Supply	404	6.464	$0.497
IFM Mate	120	1.920	$0.148
Monitor	150	2.400	$0.185
HMI Controller	29	0.464	$0.036
Inspection Cam	22	0.352	$0.027
3D Camera	10	0.160	$0.012
I/O Link	29	0.464	$0.036
Ethernet Switch	24	0.384	$0.030
RFIDs (5)	7.2	0.115	$0.009
1 Day Total		12.723	$0.98
1 Week Total		63.616	**$4.89**

Figure 6. Power Distribution Diagram (L), Power Consumption Estimates (R)

Failure Modes and Effects Analysis

The Failure Mode & Effect Analysis (FMEA) diagram seen in Figure 14 provides a systematic approach to identifying potential failure modes in a process, analyzing their causes and effects, and suggesting preventive measures. The first potential failure mode identified is "Loss of Power." This issue is attributed to an unstable connection between components. The severity of this failure mode is rated at 5, indicating a significant impact if it occurs, but it has a low occurrence rate of 1, suggesting it is unlikely to happen frequently. To address this issue, the proposed solution is to check the upstream power. This involves ensuring that the power and its delivery to the system are reliable and free from interruptions. The second potential failure mode is an "Unstable Connection Between Components." This problem arises due to malfunctioning parts. The severity of this issue is rated at 3, indicating a moderate impact, and it has an occurrence rate of 3, meaning it is relatively likely to happen. To mitigate this failure mode, it is recommended to fasten the connection correctly. This involves checking and securing all connections to ensure they are tight and properly aligned, reducing the risk of instability. The third potential failure mode is "Malfunctioning Parts." This issue can be caused by the overheating of the surrounding temperature. The severity of this failure mode is rated at 4, indicating a high impact on the system, while its occurrence rate is 2, suggesting a moderate likelihood of occurrence. To address this issue, the proposed solution is to disassemble and diagnose the malfunctioning parts. This involves taking apart the affected components, inspecting them for defects or wear, and performing necessary repairs or replacements. The potential failure mode is the "Overheating of Surrounding Temperature." This can be a result of the end of part life, where components have reached the end of their useful lifespan. The severity of this issue is rated at 3, indicating a moderate impact, and it has an occurrence rate of 1, suggesting it is unlikely to occur frequently. To mitigate this issue, it is recommended to change the temperature of the production room. This involves adjusting the environmental conditions to ensure that components operate within their optimal temperature range, preventing overheating. The final potential failure mode is the "End of Part Life." This occurs when components have reached the end of their designed lifespan and are no longer functioning effectively. The severity of this issue is rated at 2, indicating a lower impact compared to other failure modes, and it has an occurrence rate of 1, indicating it is rare. The proposed solution for this issue is to replace the part with a new one. This involves regularly monitoring the condition of components and replacing them before they fail to ensure the system continues to operate smoothly.

Economic Analysis

The integration of IFM's cutting-edge camera technology into the student design team's part assembly process involves a comprehensive economic analysis, including detailed cost assessments and budget considerations. The initial investment encompasses the procurement of IFM's camera technology, interactive screens, and essential hardware for seamless integration, along with software development costs for creating the PLC program and software driving the interactive screen.

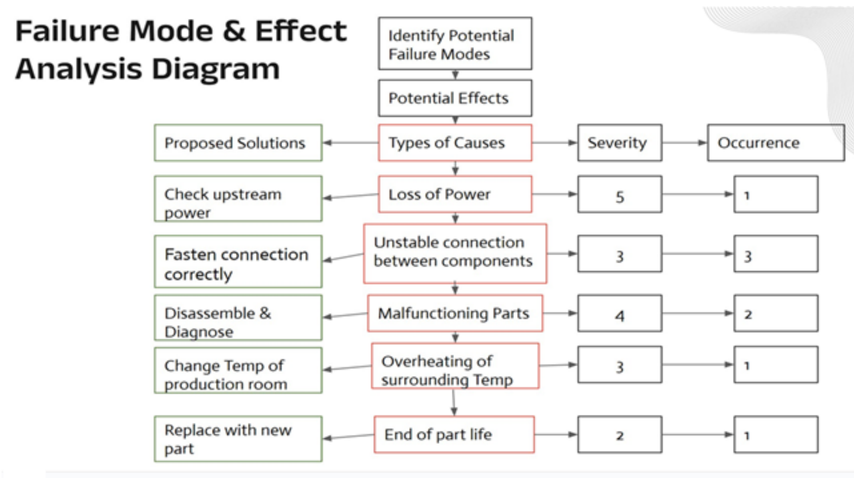


Figure 7. Failure Modes and Effect Analysis Diagram

Additionally, installation and integration costs are factored into the initial financial outlay. On the operational side, significant cost savings are anticipated, driven by streamlined workflows and error prevention mechanisms inherent in IFM's technology.

These efficiencies are expected to lead to notable reductions in labor costs and fewer scrapped or reworked parts, contributing to overall cost efficiency. Moreover, productivity gains, including faster assembly times, reduced downtime, and heightened throughput, are key economic drivers. The impact of error prevention on the cost of quality is substantial, translating to lower rework costs and heightened customer satisfaction. The economic analysis also involves calculating the return on investment (ROI) by weighing the expected benefits against the total investment and conducting an in-depth risk analysis to identify potential challenges or unforeseen expenses that could influence economic outcomes. This holistic perspective aims to ensure informed decision-making and successful implementation.

The economic blueprint for incorporating IFM's advanced camera systems into the student design team's part assembly process is anchored by a calculated initial capital outlay. In detailing the target cost and budget, the cornerstone is the procurement of sophisticated IFM hardware that includes interactive screens, cameras, and ancillary equipment necessary for comprehensive system integration. The initial production cost per station stands at $24,791.70. This cost encompasses a variety of components, such as cables, touchscreens, inspection cameras, power distribution blocks, Ethernet switches, and RFID sensor kits, among other required parts.

Student Performance Assessment

The student team working on the IFM Machine Vision project demonstrated consistent improvement throughout the academic year, with performance scores reflecting increasing proficiency in technical and analytical competencies. Scores collected on a LIKERT scale from faculty and industry mentors and summarized below.

Fall (Proposal Phase)

• Scores ranged between 3.06 and 4.30, indicating Good to Very Good performance.

• Strong performance in defining the problem and initial research (4.44), but lower scores in system modeling and experimentation (2.93).

• The team faced challenges with early-stage clarity, system modeling, and initial technical development.

Winter (Progress Phase)

• Scores improved across most criteria, with a range of 3.40 to 4.59.

• Higher scores in design specification and iterative refinement (4.40, 4.22).

• Continued refinement of alternative concepts and stakeholder engagement (3.94, 4.58).

• Moderate improvements in engineering modeling and judgment (4.09, 8: 4.14).

Spring (Final Phase)

• Final scores indicated notable growth, with values between 3.95 and 4.80, signifying Very Good to Excellent performance.

• Highest achievement in final solution clarity and documentation (4.80, 9: 4.59).

• Improvements in technical feasibility and design decisions (4.63).

• Engineering judgment and final project conclusions were well-developed (4.41).

The student team excelled in defining project needs, research, and solution development, with steady progress toward achieving a high-functioning assembly line enhancement. Early challenges in system modeling and alternative concept refinement were successfully addressed through iterative improvements. By the final phase, the team demonstrated strong problem-solving, decision-making, and engineering judgment, leading to a well-structured and effective final product. For a more detailed analysis of the assessment data please refer to [1].

Conclusion

The collaboration with IFM has provided a valuable opportunity to revolutionize the assembly process by integrating advanced technologies. The use of cutting-edge equipment, such as dual 3D cameras, industrial PCs, and Human Machine Interface Controllers, has paved the way for a more efficient and innovative approach to assembly line operations. Through careful analysis, students identified key areas for improvement, including error-proofing mechanisms, material identification systems, and real-time human hand tracking. By directly addressing these challenges, they were able to streamline operations, enhance operator guidance, and ultimately improve the quality and reliability of the assembly line.

The student design team followed a systematic approach, from concept evaluation to technical implementation, ensuring that their solution met both customer needs and technical feasibility. By incorporating multiple workflows and prioritizing easy programmability and versatility, they enhanced the value and adaptability of their product, making it suitable for a diverse range of requirements.

Through this experience, students gained valuable hands-on exposure to real-world challenges by applying theoretical knowledge in practical settings. With the support of mentorship and collaboration, they developed essential competencies in critical thinking, problem-solving, and teamwork—skills that will serve them well in their future professional endeavors.

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Bibliography

1. Husanu I., Ertekin Y., Fehlinger D., "Integrating Research Experience into Industry Sponsored Capstone Design Projects in Mechanical and Manufacturing Engineering Technology", 2025 ASEE Annual Conference & Exposition, Montreal, Canada.
2. IFM. *Instructions for set-up OXZ100*. IFM. Retrieved December 05,2023, from https://www.ifm.com/mounting/80301694UK.pdf
3. Keyence. *Vision System overview*. Keyence. Retrieved December 05,2023, from https://www.keyence.com/products/vision/vision-sys/vs/
4. Cognex. *DataMan 470 Specifications*.Cognex. Retrieved December 05,2023, from https://www.cognex.com/products/barcode-readers/fixed-mount-barcode-readers/dataman-470-series/specifications
5. Taleghani, M., Ansari, H. R., Jennings, P., Renewable energy education in sustainable architecture: lessons from developed and developing countries. Energy Education Science and Technology Part B-Social and Educational Studies, 2010. 2(3-4): p. 111-131.
6. Sirinterlikci, A. (2014, June), "Interdisciplinary Capstone Projects", 2014 ASEE Annual Conference & Exposition, Indianapolis, Indiana. 10.18260/1-2—20691
7. Manufacturing USA Annual Report, Fiscal Year 2016, https://www.manufacturingusa.com/sites/prod/files/Manufacturing%20USA-Annual%20Report-FY%202016-web.pdf
8. Davis, J. & Swink D, Smart Manufacturing as a Real-Time Networked Enterprise and a Market-Driven Innovation Platform, https://smartmanufacturingcoalition.org/sites/default/files/smlc_sm-real-time_networked_enterprise_1.pdf
9. http://www.engineeringchallenges.org/challenges/16091.aspx
10. S. A. Ambrose, M. W. Bridges, M. DiPietro, M. C. Lovett, and M. K. Norman, How learning works: Seven research-based principles for smart teaching. John Wiley & Sons, 2010.
11. V. Braun and V. Clarke, "Using thematic analysis in psychology," Qualitative research in psychology, vol. 3, no. 2, pp. 77-101, 2006.
12. Bosman, L., & Shirey, K. (2022, August). Using Bio-Inspired Design and STEAM to Teach the Entrepreneurial Mindset to Engineers. In *2022 ASEE Annual Conference & Exposition*.