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From Industry to Academic Laboratory: Lab-Scaled Industrial Web Handling System for Vision Evaluation and Detection of Wrinkles

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From Industry to Academic Laboratory: Lab-Scaled Industrial Web Handling System for Vision Evaluation and Detection of Wrinkles

Abstract

We are presenting a capstone Senior Design project proposed, developed and implemented by a team of undergraduate students in Drexel University's Engineering Technology program (a four year Bachelor of Science degree). This system will reduce the cost of manufacturing of continuous-web products by eliminating the operator based wrinkle detection currently used in industry. Using vision technology combined with the known physical properties of the product the system can recognize and react to waves in the web that lead to these wrinkle formations, using a laser line generator to highlight the waves in the web, and then using the angle relationship between the laser, the camera and the web to measure the wavelength and amplitude of the wave. To develop and test this theory the students built a prototype system that mimics a real continuous web machine allowing for tensioning and intentionally wrinkling the product. This model of a real web system allows for measurements in a controlled environment. This project is a combination of educational laboratory set-up as well as an innovative approach to solve an existing industrial problem. This prototype is developed as laboratory teaching equipment, allowing students to visualize, monitor and control, and also improve a real industrial manufacturing process, giving them the opportunity to grasp the complexity and the interdisciplinary nature of those processes.

Introduction

In a fast changing industrial environment, educational laboratory activities need to keep pace with new and emerging technologies that are implemented, in order to provide students with the required skills consistent with the newest technologies available. Real life industrial settings are often too expensive and complex to implement at laboratory level. The fundamental challenging problems in manufacturing education are related to: (a) Improving the student–instructional technologies interface to incorporate the required learning tools; (b) Improving teaching and learning effectiveness. On the other hand, the advancement of increasing efficiency and reducing the cost of manufacturing is contingent on innovation. Contemporary manufacturers have the option of selecting optimum technologies or processes to suit their manufacturing environment. When these technologies are judiciously combined to address a specific manufacturing challenge such as the one presented in the paper, it will produce suitable results in terms of cost, quality, and time.

In manufacturing industry oftentimes defects in products are identified by operators examining the product. In the manufacturing of sheet products the material is typically a very long or continuous sheet, which is referred to as a web. Continuous web applications often encounter wrinkles and creases as defects in the product; these first show themselves as waves in the sheet. Products in continuous web applications can wrinkle for many reasons and when wrinkles form the product is damaged. Operators cannot always detect these wrinkle defects or maybe preoccupied when they form. An automatic method of detecting wrinkle defects in web material would allow for operators to focus on other processes in web manufacturing. Using vision technology combined with the known physical properties of the product we can recognize and react to waves in the web that lead to these wrinkle formations.

The paper presents a capstone project developed by a team of students in our Engineering Technology (ET) program within Drexel University's College of Engineering. **We would like to emphasize that the project was proposed entirely by the students based on a real product and technology request form the sponsoring company** (Mannington Inc., a Pennsylvania based company). Based on the success of the project and the funds availability, the company will decide upon full implementation of this system within their production system. This project is based on an innovative system that will reduce the cost of manufacturing of continuous-web products by eliminating the operator based wrinkle detection currently used in industry. Using vision technology combined with the physical properties of the product the scaled system developed by our students can recognize and react to waves in the web that lead to these wrinkle formations, using a laser line generator to highlight the waves in the web, and then using the angle relationship between the laser, the camera and the web to measure the wavelength and amplitude of the wave. To develop and test this theory, students built a fully automated prototype system that mimics a real continuous web machine allowing for automatic tensioning and intentionally wrinkling the product and removing wrinkle defects based on vision system feedback. The developed model of a real web system allows for measurements in a controlled environment, being a combination of educational laboratory set-up and an innovative approach to solve an existing industrial problem. **This prototype is developed also as laboratory teaching equipment, allowing students to visualize, monitor, control, and improve a real industrial manufacturing process, giving them the opportunity to grasp the complexity and the interdisciplinary nature of those processes.** This project is an innovative approach towards solving an existing industrial problem, as well as a novel instructional and research tool. Several courses in our ET curricula, ranging from manufacturing to measurements and instrumentations as well as quality control are scheduled to be impacted by this type of trans-disciplinary capstone projects. The paper aims mainly to emphasize the impact of this type of *inter and multidisciplinary student-led industry sponsored project* in our curricula as well as in student learning outcomes as a whole.

Objectives

Although the manufacturing industry is rapidly evolving, little progress is being reported, with very few notable exceptions, on the role of educational institutions in either keeping pace with this growth or addressing the importance of introducing new emerging engineering technologies, applications, and effective classroom and laboratory instruction. Preparing our students for post-graduation success must be the paramount of engineering and engineering technology education. However, it is critical for engineering/technology to transition from theoretical work in the classroom towards experiential learning with applications of technology and design. The main objective of senior design courses in engineering and engineering technology curricula is to bridge the gap between academic theory and real world practice. Accordingly, the proposed senior projects should include elements of both credible analysis and experimental proofing as discussed in ABETs criteria[6]. The senior design project can serve as an excellent culminating experience in the program of study when it focuses on research and design projects that have practical value to consumers or to industry. For the Drexel's College of Engineering's ET program at our university, the senior design course is a year-long educational journey (three quarters) that takes an idea generated by a student team or an industrial sponsor and culminates in a product or project. *This course is an excellent capstone experience, which requires both teamwork and individual skills in solving a modern industrial problem.* Senior design projects seminars in fall and spring quarters bring the students, faculty, and industrial partners together to see the student's results and to give them the additional experience of public presentation of their work.

The importance of project work in the curriculum of our undergraduate engineering programs is well understood. Students want and need to know the best industrial practices also. An engineer should be a designer, thinker, innovator and systems integrator. Hence, the educational system should inculcate into its students various aspects such as engineering principles, standards and practices, design methodologies, modeling and optimization capabilities, systems analysis and integration techniques and new technologies and research areas. An engineer can become a thinker, a creative person or an innovator only if he is allowed to independently put together all aspects of learning to solve a practical problem and look at alternatives. While regular coursework allow students to acquire engineering and scientific knowledge, only project work gives them the opportunity to become a problem solver or an innovator. Hence, project work is a very important constituent of our engineering technology curriculum.

For an engineer in industry, a project is a sequence of tasks required to reach an objective. Typically, the objective is to design a device or process that has value to a customer (user). The project begins by defining a performance problem associated with an application and ends with a design solution. The problem drives the learning required to complete the project. Managing the project requires the engineer to demonstrate effective teamwork, clear communication and the ability to balance the social, economic and environmental impacts of the project. Project-based learning (PBL) is based on the practice of solving problems. Traditionally, the educational process involves students first learning the fundamentals and then utilizing "total recall" to apply these facts to solve a problem; learning objectives are set by the instructor and principles are presented to the students through lectures[1-4]. Moreover, this approach provides a context that makes learning the fundamentals more relevant and, hence, results in better retention by students[1-3]. For clarity, we view problem-based learning as pertaining to the development of knowledge based on the fundamental principles of science and mathematics and project-based learning to include mastering the engineering skills required to implement a design solution. Therefore, the multi and inter-disciplinary aspects of the senior design projects are obvious. When a topic, such the one presented here, combines and integrates a solution to an industrial need with an educational platform and experiential module, the projects is even more valuable.

The purpose of this paper is to describe the development of the wrinkle detection system involved in our capstone senior design project. The lessons learned are presented and the ways that the experiential framework may impact our ET curricula are discussed. Department of Engineering Technology's senior design project course is a 3-term core course usually taken by the students during their terminal year in the ET program.

Project Overview, Design Selection and Solution

This project is an underway project for capstone Senior Design Project, performed by a team of three students. Senior Design Project is a sequence of three-quarter capstone project design courses required for all the BSET majors. The course focuses on planning, development, and implementation of an engineering design project, which includes formal report writing, project documentation, group presentations, and project demonstrations. The goal of these courses is to demonstrate the ability to manage a major project involving the design and implementation of products with a mixture of electrical and mechanical elements as a member of a product innovation and/or development team. In these project-based courses, the students are expected to effectively manage their time and team efforts to produce a working prototype of a product in three ten-week quarters. Progress and formal reports, and oral presentations constitute integral components of this course sequence. Before beginning the projects, student teams are provided adequate training in project formulation and resource analysis, performance goals and team expectations, public presentations of project work, and individual project supervision.

ABET defines Engineering Design as: “The process of devising a system, component, or process to meet the desired needs[5, 6]. It is a decision making process, in which the basic sciences, mathematics, and engineering sciences are applied to optimally convert resources to meet stated objective[1]. The fundamental elements of the design process are: the establishment of the objectives and criteria, synthesis, analysis, construction, testing and evaluation”. In our senior design classes we have placed this definition at the core of our courses. First we focus on objectives and ask the student to write a short proposal stating these objectives, principles, and the decisive factors to reach the stated goals. The second step is conceptualization and laying down how to achieve the stated objectives. At this junction the students are encouraged to draw a block diagram showing different components of the system they want to design. Once the students compile the answers to these questions, they are directed to perform system analysis, design, component purchase and fabrication, building and testing of the prototype, as well as the overall design improvements. This project does follow the general framework described above. However, the uniqueness if the idea proposed and developed by the student team makes it exemplary in what it concerns student learning outcomes of this project.

As is described in sections below, students developed a deep understanding not only of science and engineering concepts but of how these concepts are implemented in a real industrial setting. Another important aspect is the practicality of their solutions from both perspectives: industrial and educational. Students were permanently aware of the fact that their system must pass the ultimate approval: the sponsoring company must give them the final approval for implementation and testing of their system in the real production line. Students worked under dual supervision: faculty and industrial advisors. Moreover, they worked on a weekly basis at the company, learning about the production line and technology, about product requirement and industrial applicable standards, rules and codes. They learned so much about how all their knowledge and theoretical concepts come together and integrate into developing a final product or process and this tremendous experience cannot be imparted in a classroom setting.

Added to this overall industrial experience was the one related to scaling down their system to serve as educational set-up. Students needed to develop interactive interfaces to serve learning outcomes suitable for various courses. They instrumented the system to serve not only for process monitoring but also for further development of sensors network that will allow future students to gain knowledge with sensor implementation and networking.

On sections below, we will give a more detailed description of learning outcomes of this student endeavor.

Project Constraints and Problem Statement

Over the years, many of our projects are sponsored by industrial partners, providing our students with valuable guidance and financial support in developing their working prototypes. This project was sponsored by Mannington Inc., which is a manufacturer of vinyl flooring. One of the students was also an employee of the company dealing with particularly this type of problems. Vinyl flooring starts off as thin felt or fiberglass web that is weak and prone to wrinkles. The web at Sponsoring Company is 12 feet wide and is thousands of feet long (Figure 1). The web goes through various processes that at times introduce wrinkle defects. <u>The industrial partner is sponsoring this project in order to better understand managing wrinkle defects and also to find an automated solution to wrinkle detection. The proposed solution is considered to be fully implemented by the company.</u>

The challenge is to develop a non-intrusive system to capture wrinkles before they are formed and respond to them thus preventing defects. *Students re required also to develop a lab-scaled prototype system as proof of concept.* This proof-of-concept serves as educational laboratory setting to be used as lab equipment in various courses in ET curricula. As can be seen from the concept phase, the students gain familiarity and experience working with industrial grade project requirements and management. Also, since the proof of concept must serve as an educational set-up, they must constantly think to the learning outcomes that their solution must serve. This particular approach was also used in other capstone projects developed over the past years by other students in our program. In this way we were able to enrich our laboratories with industrial grades but lab-scaled equipments, developed as capstone projects i.e. mini desktop CNC mill, marine sensor network, renewable energy set-ups (wind turbines, solar collectors, etc.). All these equipments are serving several courses in our ET curricula, for either traditional classroom instruction and/or remotely operated laboratory activities. In the same way, this experiential set-up will be able to be remotely operated, serving as a base for projects in two graduate courses (Sensors and Measurements and Engineering Quality Methods) and also serving as laboratory equipment for Applied Quality Control course and Measurement Laboratory course. In manufacturing related courses, this project may enhance the theoretical approach with a hands-on application.

Figure 1: Image of continuous web at sponsoring company with waves that require depth perception to recognize

During the development of this project students applied their knowledge about sensors, measurement theory and practice, mechanics, control, pneumatic and hydraulic systems and logic programing. They learned about modeling industrial systems and integrating their acquired knowledge in building the prototype while meeting the industrial standards combined with laboratory and research type of setting. The learned how to mitigate the flexibility required by a research and educational type of set-up with the industrial codes and rigor.

Solution

A noncontact method is preferred so that no changes are introduced to processes in manufacturing and the risk of causing further damage in minimized. A system has been developed that can measure a wave or wrinkle using a laser line projector at an angle and a vision system calibrated to examine that line. Vision systems are effective at measuring color and shapes but they lack the depth perception that is needed to identify wrinkles or waves that lead to wrinkles. Using a laser-line projector set at an angle to the sheet, a straight line can be created, which will deviate when wrinkles, waves or creases are present. A vision system can then evaluate the line and measure its straightness and then respond to the presence of deviations from the straight line. It can be measured the height of a wave in the sheet by using the angular relationship between the camera, the sheet and the laser (Figure 2). In order to test and observe the effects of sheet tension students developed a web tensioning system. The system consist a driven roller and two cylinders designed to tension the sheet. Industrial conditions did not allow for testing and research in the field. The scaled down system fits through most doorways and can be rolled through hallways. Tension developed by the two pneumatic cylinders can produce more than enough force to wrinkle the sheet. This allowed bringing the material to the point of wrinkles repeatedly while observing the effects on the sheet. In Figure 3 the web handling part of the system can be seen, it shows the rollers and tensioning cylinders before project completion.

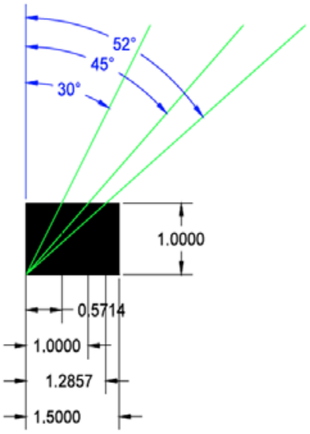


Figure 2: Verification of pattern projection technique

Figure 3: Image of web tensioning system built for lab testing

During the development of this system it was observed that wrinkles form when a wave in the sheet passes over a roller and the wave folds over. Students also observed that when placing the laser next to a roller they were able to produce a straight line that has little deviation when the sheet is flat. *As can be noticed, during the concept development phase, students took into consideration both industrial requirements (non-contact system, visibility of the waves, etc.) and* *lab-scaled set-up (being flexible and mobile, small enough to fit in a lab and big enough to capture the industrial process).*

In order to measure wrinkles in a web as it moves through a manufacturing line, students developed a web handling model system designed to allow use tension and wrinkle the web then measure these wrinkles, a scaled web handling model machine that continuously moves the sheet in a loop over two rollers that can be tensioned using pneumatic cylinders (Figure 4).

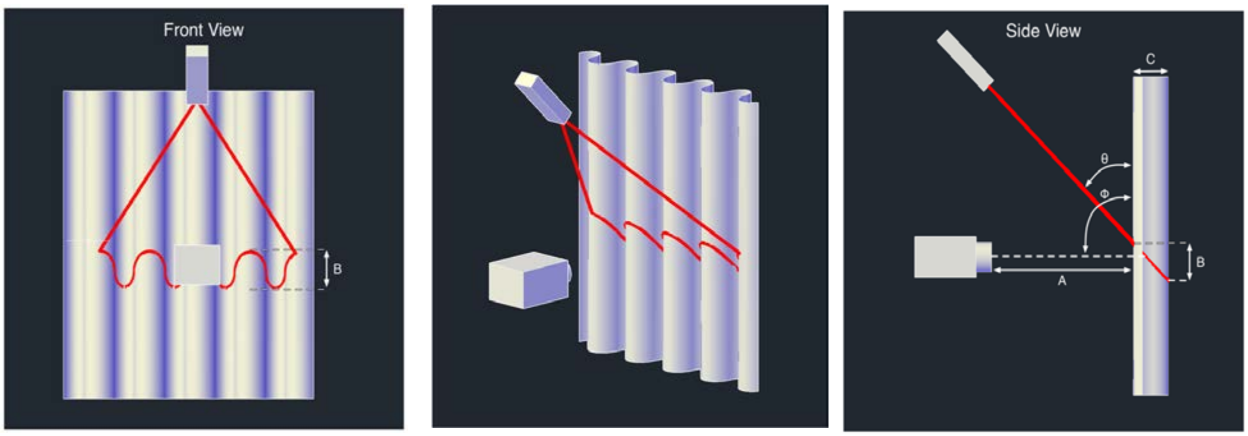


Figure 4: Front, isometric and side views of simulated pattern projection and measurement

The machine is designed to emulate the actual forces that occurred on the vinyl flooring when being passed through the accumulator. As can be seen in Figure 3, the 36" long top plate, which will be supporting the pneumatic cylinders is reinforced by two pieces of 2"x1.5" c-channel to provide the ability to hold the additional weight. This also leaves the center open for mounting the cylinder using in the center with 4" bolts. The two pieces of c-channel through the center of the frame are to hold the side pillars from bowing under the pressure of the material being pulled apart. Support straps are attached to the sides to prevent tipping of the frame. The base of the frame uses two L-beams since it will only be supporting the weight of the frame. The lower cross support is constructed in the same design as the top but have the extra feature of a mounting position for the motor. The roller design uses 3" PVC pipe for the shell and a 1" steel rod for a core. The filler is an insulation to give the PVC support through the roller. The rollers are 18" long and are held in place by two bearings. The lower roller is connected to the motor linkage to drive the webbing. The lower roller drives the webbing to create the continuous movement through the machine, while the two pneumatic cylinders pull up the upper roller. The cylinders imitate the upward movement of the accumulator, applying tension on the webbing. The force setting will be variable from a minimum of 47 lb up to a max of 264lb. The air pressure will control using an analog electronic pressure regulator that ranges from 6-30 psi. Measurement of the pneumatic cylinder forces was done in the lab with a Tinius Olsen machine. The tool was used to adapt the pneumatic cylinders to the tension measurement equipment in the lab. Students compared the calculated force values with actual forces produced in the lab.

Again, students created an additional lab set-up based on the Tinius-Olsen machine that independently can be used in Applied Mechanics courses. In developing this calibration of their pneumatic system for rollers, they used knowledge from fluid power, fluid mechanics, and applied mechanics courses combined with control notions and concepts. We would like to highlight the students' concept regarding adaptability of this system to different types of materials. They created an adaptable frame for added flexibility in researching the behavior of various materials with different properties. As it can be seen from the next sections, the control architecture is developed according to industrial standards.

Control System Architecture

The lab-based system's control architecture was modeled after Company's plant standard. In their manufacturing facility, all devices, sensors and actuators are interconnected through programmable logic controllers (PLCs). These are industrial grade computers that are designed to provide real-time control of processes while handling industrial environmental conditions. These controllers communicate with these devices via discrete input and/or output ports as well as a variety of industrial networks. In this case, it will communicate with the PLC via an Ethernet based protocol for industrial communications called EtherNet/IP. This protocol is an open standard which is adopted by many control systems and other devices. As shown in Figure 5 and 6, the PLC, machine vision camera, remote I/O and windows-based PC are all connected via the Ethernet network and communicate via EtherNet/IP.

The PC is used to configure all of the other components as well as serve as a user interface for the system. For the user interface, the PC passes data to and from the PLC. All of the output actuators are directly controlled by the remote I/O device. This component communicates with the PLC via EtherNet/IP. It has 4 analog outputs that can output either -10-10 V or 0-20 mA. The electronic pressure regulator and drive motor relay are controlled by these outputs. The machine vision camera also communicates with the PLC via EtherNet/IP. Its register contains several bytes of data that the PLC reads over the network. This data shows the operational status of the system as well as provides feedback from the camera's programming to the PLC. This is how the camera alerts the system that it has detected an over-tension condition.

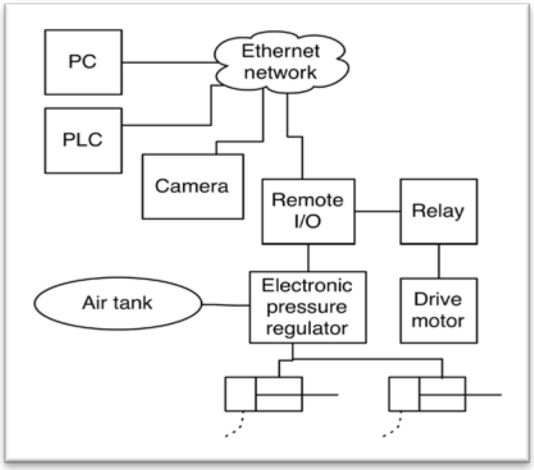


Figure 5: Control system connections

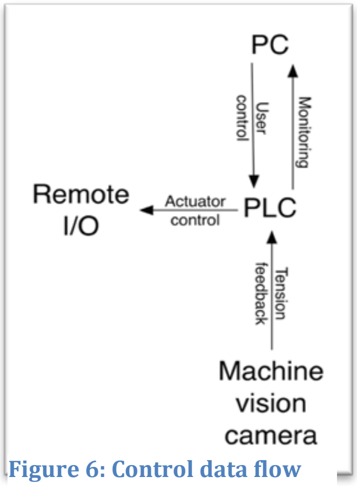


Figure 6: Control data flow

Machine vision and image processing

The system was designed to examine a straight line and divide that line into segments. Each segment is a column and in each column the edges of the line are detected. Using the edges from each column a best fit line is overlaid onto the image of the line. When an edge deviates from the best fit line over a threshold it is then measured for length, area and distance from the best fit line. From these values we then define what a "warning of an impending wrinkle" is. There were established three criteria for waves and wrinkles: the size of the deviation, the number of waves, and the overall area of the deviation. For each criterion a bit has been assigned so that when the value exceeds the threshold the bit is high. These bits have been mapped into the ControlLogix software to indicate the status of the web. The Cognex InSight programming is spreadsheet based software with specialized functions designed to evaluate images.

Programmable logic control system

The function of the programmable logic control (PLC) system in this solution is to read input data from sources such as the machine vision camera, an operator or external control system and use these inputs to control outputs such as feedback to the operator and pressure in the tension control actuator. For this application, an Allen Bradley ControlLogix PLC will be used as the controller. A connection diagram was developed based on the required inputs and outputs to and from the controller. In the final revision of the lab-scale testing machine, all data to and from the PLC was transmitted via its Ethernet connection. *This is a standard practice for modern industrial control systems.* The lab-scaled system will also use the AB ControlLogix PLC that is in the Engineering Technology mechanical lab. This controller is functionally identical to the one in use at Mannington.

The function of the PLC in the system is shown in the flowchart in Figure 7. The ladder logic code shown on the left side of Figure 7 is the program running on the PCL, which is functionally equivalent to the process described by the flowchart. The program continuously monitors the over-tension alarm state from the machine vision camera. Once this bit goes high, the controller starts a count-down timer for 5 seconds. This time delay helps to filter the alarm bit's status so that the system does not activate from a fluke reading. Once this timer has expired, the PLC program then takes action to reduce the output signal to the pressure regulator by 10%.

User interface

A user interface was developed for this system using LabVIEW. This coding language was chosen because of LabVIEW's inherent capability for interfacing between multiple systems. The purpose of the user interface of this system is to receive input and return feedback to the user. To accomplish this, it uses data manipulation, timing control and communication protocols to translate data between the user and the PLC. In LabVIEW programs, functions are wired together to pass data between their input and output terminals. This contrasts with traditional text based coding where data is stored in variables and functions read and write to these variables. This method of coding was chosen because it was designed for controlling and passing data between pieces of equipment, as it is used in this application. The front panel of the user interface is show in Figure 8. It contains the buttons and numerical controls that the operator uses to give input to the system and monitor its operating conditions. This program also provides feedback on operating parameters of the system with several charts, numerical indicators and a gauge. Some of these values such as the air pressure from the output of the regulator and the tension force in the web are calculated while other such as the motor state and percent of tension

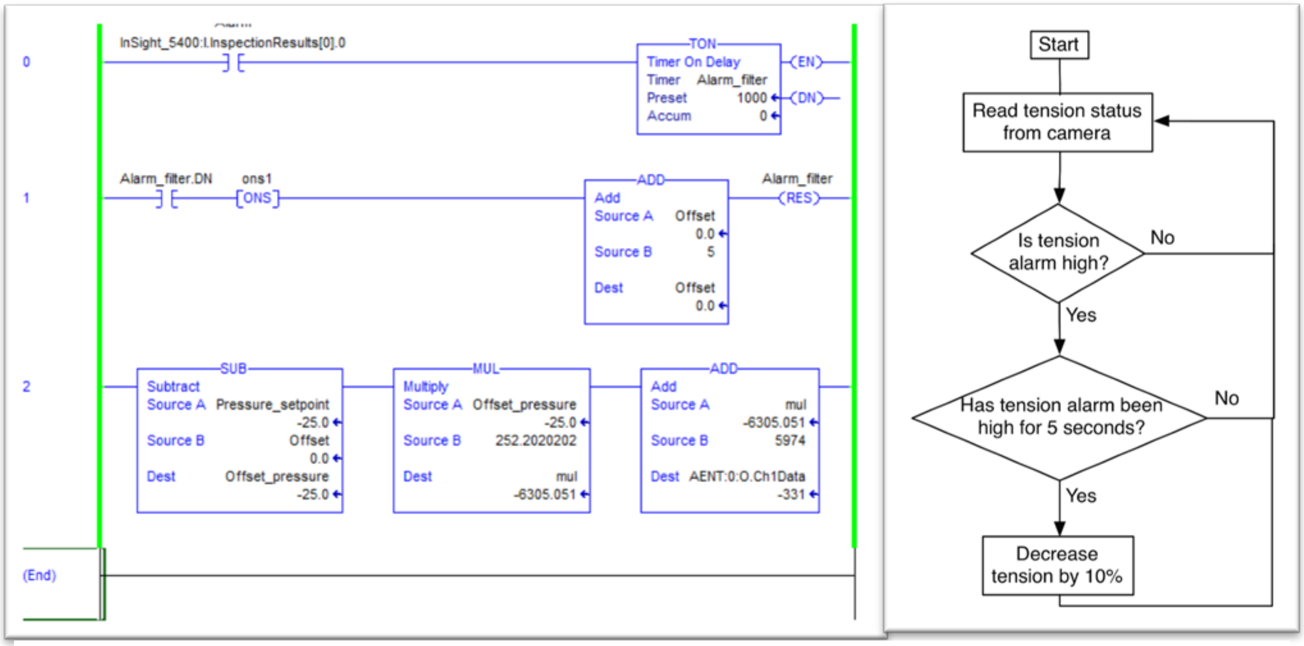


Figure 7: PLC ladder logic code and equivalent flowchart

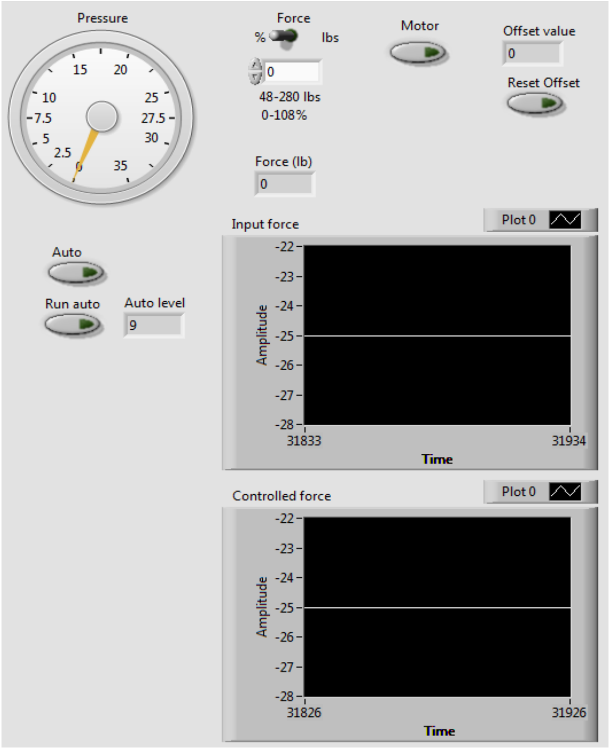


Figure 8: User interface developed in LabVIEW

force are directly measured from the system. Figure 7 and 9 shows the block diagram code that was developed for this system. This is the code that LabVIEW runs to facilitate the operation of the user interface. The sections of the block diagram code are explained below:

Automated tension increase

This part of the code was developed to facilitate the testing of the lab-scaled system. Its function is to increase the tension in the web by 1% per second. This simulates a worst-case scenario in the process where an external influence other than the tension control system is causing an increase in the tension of the web being monitored. For simplicity in the lab system, the actuator causing this "external" tension increase will be the same as the one controlled by the feedback from the camera. This section of the code is only activated for the development and testing of the system.

Motor control

This part of the code controls the operation of the web motor. It is necessary to have the web moving in order to accurately simulate normal

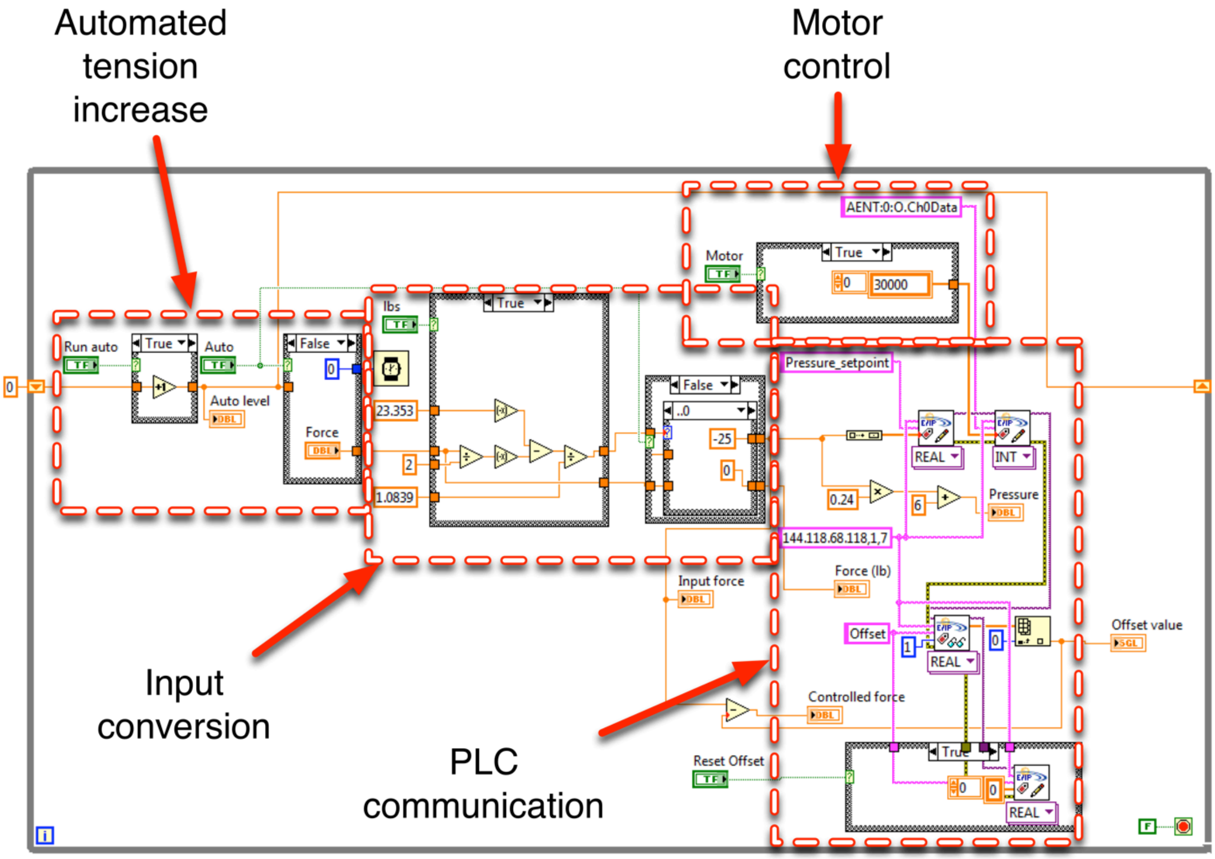


Figure 9: LabVIEW block diagram

operating conditions, so the bottom roller in the system is driven by an AC gear-motor. This motor is controlled by switching its power supply with a solid-state relay. While the relay is a binary device that can only be on an on or off state, it is controlled via an analog output signal from the PLC. This is because the remote I/O connected to the PLC from the system only has 4 analog outputs and no digital ones. Therefore, the Boolean signal from the user control is the condition for a case structure that switches the output to either 10v or 0v.

Input conversion

This section of the code handles the conversion to and from percent and force values. The pressure regulator is controlled by an analog 4-20mA signal from the remote I/O. This is controlled in the PLC's program as a percentage value where 0% is 4 mA and 100% is 20 mA. This section contains a user control to allow input in either percent of maximum tension force or actual pounds of tension force. This input is then either passed through if it is inputted as percent or converted from pounds force to percent force. The percent force is then filtered to an allowable maximum and minimum that is appropriate for the system.

PLC communication

This section handles the communication between the PC that is running the LabVIEW VI and the PLC. This is done over an Ethernet network using a protocol called EtherNet/IP. This is a protocol specifically designed to facilitate the communication of real-time control systems over an Ethernet network. While it is possible for the VI to communicate directly with the machine vision camera and remote I/O, this communication is routed through the PLC per Mannington's standards for control system architecture.

Pneumatic circuit

The pneumatic system, shown in Figure 10, provides the power to apply tension force to the web. Energy for this system is stored in a refillable air tank. This allows the system to be more portable and not necessarily tethered to a compressed air source in the lab. Gauges monitor the tank pressure and pressure after the regulator that provides the tension force to the web. The regulator is controlled by an analog current output from the remote I/O device mounted on the lab setup. Air pressure is only applied to the annular area of the piston while the other side is vented to the atmosphere. The weight of the top roller returns the cylinders to their extended positions when the pressure on the annular side is removed.

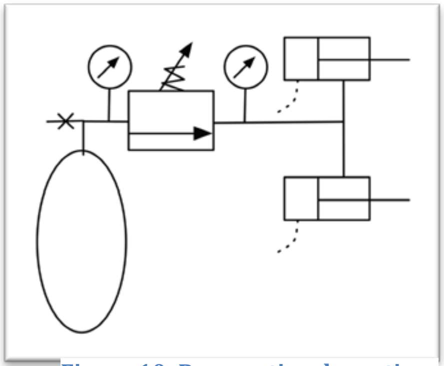


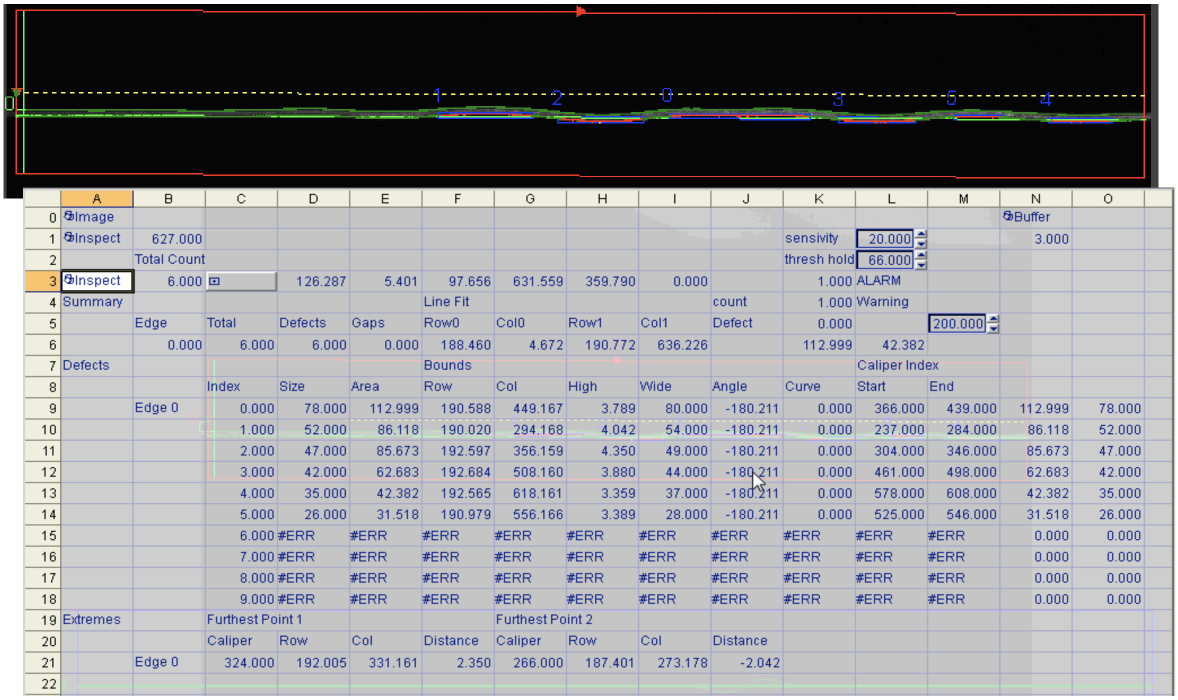
Figure 10: Pneumatic schematic of lab-scaled system

Experimental Results and Capstone Project Conclusions

A procedure to evaluate the success of the wrinkle detection and prevention system was developed. This was done using the vision system evaluation of the line projected onto the sheet. Below in Figures 11 and 12 is an image of the line from the line projector inside the InSight examination window. Students designed the software to examine straight lines and evaluate them on their straightness. They found that they could easily wrinkle the sheet when they maintained high tension on the sheet. Students only focused on the percent of tension our system produced and its correlation to waves and wrinkles. Using the data they developed from experiments on the force of the system this comes out to 133.4 lbf total over a 17 inch wide sheet or 7.85 lbf/inch of tension on the sheet.

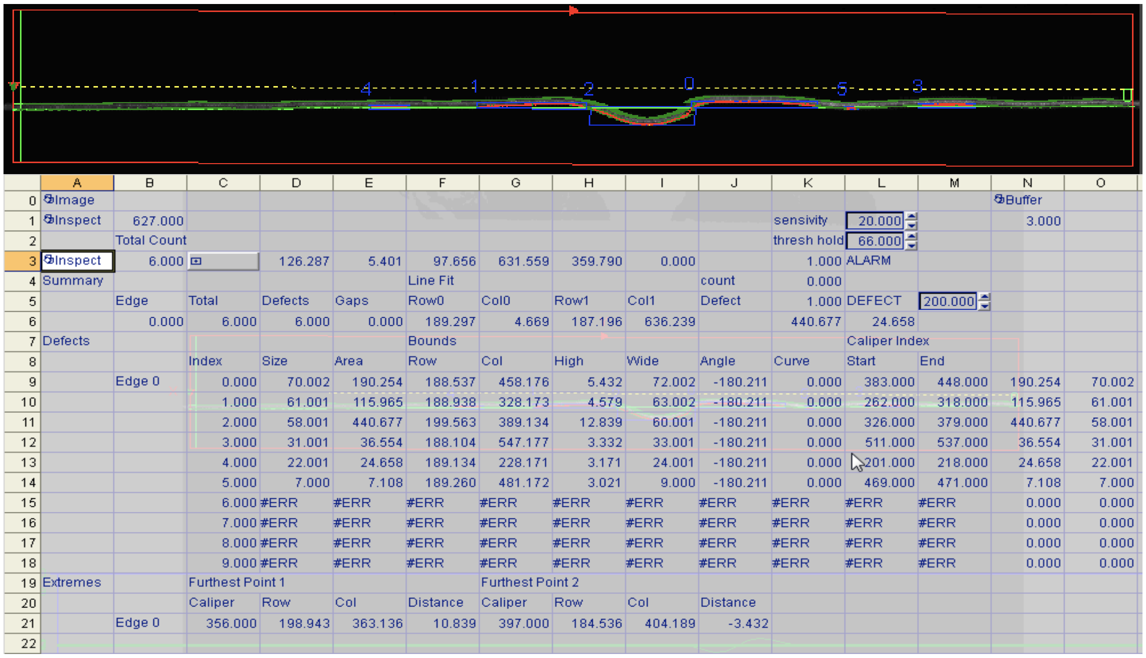
Figure 11 depicts data obtained from a web tensioned at 70% of the system pressure and at this point the web is at risk of wrinkles. It can be seen that there are still six points identified as defects in the index array but the size and area of the defects have exceeded the threshold. This sets the values in cells K3 & 4 to high and thus indicates there is a potential risk of wrinkles. The change in the image from the not at risk to this at risk state is subtle to our eye. The vision system can measure very slight changes and measure them reliably. They sort the defects by size in the inspection array and the size of the largest defect has grown from 56 to 78 pixels. This has crossed the defined threshold to the point where the control system is alarmed that the web as at risk of wrinkling and that it should respond. These values as mentioned before were found through evaluation of the sheet under tension and can be easily changed to fit the material under evaluation. The force on the sheet at this point is 198.2 lbf or 11.66 lbf/inch of tension on the sheet. The effect that high tension has on the sheet is that the material creeps towards the center of the web. As it is drawn to the center waves develop and are clearly seen on the rollers as the sheet rolls over the roller. Once the waves become large enough they fold over and crease causing permanent damage to the sheet.

Detecting the onset of wrinkles allows the manufacturer to adjust and correct the wrinkle condition. We can create control loops to prevent the tension or other conditions from causing wrinkles. This can reduce wrinkle defects and allow for a reduction in defects. But in the case where a wrinkle has formed and the defect has already happened we are also able to detect these



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	Image													Buffer	
1	Inspect	627.000									sensivity	20.000		3.000	
2		Total Count									thresh hold	66.000			
3	Inspect	6.000	⊡	126.287	5.401	97.656	631.559	359.790	0.000		1.000	ALARM			
4	Summary					Line Fit				count	1.000	Warning			
5		Edge	Total	Defects	Gaps	Row0	Col0	Row1	Col1	Defect	0.000		200.000		
6		0.000	6.000	6.000	0.000	188.460	4.672	190.772	636.226		112.999	42.382			
7	Defects					Bounds						Caliper Index			
8			Index	Size	Area	Row	Col	High	Wide	Angle	Curve	Start	End		
9		Edge 0	0.000	78.000	112.999	190.588	449.167	3.789	80.000	-180.211	0.000	366.000	439.000	112.999	78.000
10			1.000	52.000	86.118	190.020	294.168	4.042	54.000	-180.211	0.000	237.000	284.000	86.118	52.000
11			2.000	47.000	85.673	192.597	356.159	4.350	49.000	-180.211	0.000	304.000	346.000	85.673	47.000
12			3.000	42.000	62.683	192.684	508.160	3.880	44.000	-180.211	0.000	461.000	498.000	62.683	42.000
13			4.000	35.000	42.382	192.565	618.161	3.359	37.000	-180.211	0.000	578.000	608.000	42.382	35.000
14			5.000	26.000	31.518	190.979	556.166	3.389	28.000	-180.211	0.000	525.000	546.000	31.518	26.000
15			6.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
16			7.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
17			8.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
18			9.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
19	Extremes		Furthest Point 1				Furthest Point 2								
20			Caliper	Row	Col	Distance	Caliper	Row	Col	Distance					
21		Edge 0	324.000	192.005	331.161	2.350	266.000	187.401	273.178	-2.042					
22															

Figure 11: Image of sheet with waves that lead to wrinkles. In the defect array the size of the largest defect has exceeded the threshold for defect size



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
0	Image													Buffer	
1	Inspect	627.000									sensivity	20.000		3.000	
2		Total Count									thresh hold	66.000			
3	Inspect	6.000	⊡	126.287	5.401	97.656	631.559	359.790	0.000		1.000	ALARM			
4	Summary					Line Fit				count	0.000				
5		Edge	Total	Defects	Gaps	Row0	Col0	Row1	Col1	Defect	1.000	DEFECT	200.000		
6		0.000	6.000	6.000	0.000	189.297	4.669	187.196	636.239		440.677	24.658			
7	Defects					Bounds						Caliper Index			
8			Index	Size	Area	Row	Col	High	Wide	Angle	Curve	Start	End		
9		Edge 0	0.000	70.002	190.254	188.537	458.176	5.432	72.002	-180.211	0.000	383.000	448.000	190.254	70.002
10			1.000	61.001	115.965	188.938	328.173	4.579	63.002	-180.211	0.000	262.000	318.000	115.965	61.001
11			2.000	58.001	440.677	199.563	389.134	12.839	60.001	-180.211	0.000	326.000	379.000	440.677	58.001
12			3.000	31.001	36.554	188.104	547.177	3.332	33.001	-180.211	0.000	511.000	537.000	36.554	31.001
13			4.000	22.001	24.658	189.134	228.171	3.171	24.001	-180.211	0.000	201.000	218.000	24.658	22.001
14			5.000	7.000	7.108	189.260	481.172	3.021	9.000	-180.211	0.000	469.000	471.000	7.108	7.000
15			6.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
16			7.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
17			8.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
18			9.000	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	#ERR	0.000	0.000
19	Extremes		Furthest Point 1				Furthest Point 2								
20			Caliper	Row	Col	Distance	Caliper	Row	Col	Distance					
21		Edge 0	356.000	198.943	363.136	10.839	397.000	184.536	404.189	-3.432					
22															

Figure 12: Image of defect wrinkle and evaluation spreadsheet with a defect at index 2 having an area of 440 pixels

defects in the sheet. Figure 12 is the image of the sheet after a wrinkle has formed and the sheet is damaged. In this case we can still respond by trying to correct the over tension conditions but we can also identify this area of the sheet as defective. In this scenario if a foot counter was used to identify the location in the sheet where the damage was it could be marked as defective and a manufacturer could use this information when taking their product to completion.

In Figure 12 as in previous images there are six defects captured and their size has not increased it has in fact decreased. The largest size defect in the defect array is 70 pixels. To capture damaged or wrinkled material students evaluated the area and in the defect array defect number two has an area of 440 pixels. This defect has a substantially larger area than the others. The defect bit is also set high in cell K5 this bit is controlled by examining the area column and capturing the max value. We observed that once the wrinkle is formed and a crease is in the web the damage is done. We also observed that when the tension is lowered and the wrinkle is relieved the sheet will appear flat. The vision system as it is now cannot see creases so it is critical to capture the wrinkle as it is formed.

From the three conditions captured in the images above we have shown the wrinkling with proper laser-line placement and line evaluation we can determine if the sheet is at risk of wrinkling. For our experiments the actual tension on the sheet is not critical for evaluation but the effects of that tension are measured as it deforms the sheet.

Project Conclusions

Lab studies of different types of wrinkles and sources of these wrinkles would allow for more control loops than just tension. The system was designed specifically for wrinkles formed by excess tension. Other causes of tension could be misaligned rolls, uneven thickness profile of the web, heating or uneven heating. All of these could be evaluated using same system with slight modifications that will enhance the educational value of this set-up. The system may be equipped with appropriate sensors to detect misalignments, web thickness profile and temperature profile of the web during manufacturing. Application of the vision system and line projector in an industrial environment would require a stationary roll with enough room to set-up the line projector and camera in front of the roll. Ideally located in a spot where wrinkles often form. Depending on the width of the web the camera may need to be located further from the web or maybe limited to a cross section of the web where wrinkles are more likely to form. Testing on the threshold of wrinkling even of the same materials we used might not correlate to the exact same lbf/inch of web values we found. Students' results should be close to what can be expected in the manufacturing environment at Sponsoring Company. The application of this system will provide an increase in efficiency by reducing the percent off goods. This could increase efficiency and increase attention to detail of non-automated processes. Human interaction would not be eliminated while processing web material just refocused onto other areas.

From educational standpoint, this system can be used in various courses in our curricula, from illustrating the industrial usage and setting of various sensors to data collection regarding quality manufacturing processes and analysis. It is also a valuable tool in bridging the gap between theory and practice in manufacturing classes.

Assessment and Conclusions

The project was assessed formative during the fall and winter quarter. Students are required to submit a written report for the proposal phase (fall term) and a progress report at the conclusion of the winter term. Also, the team is required to present their proposal at the end of fall term. The presentation is public and is held in front of an evaluation panel consisting of faculty and industry experts. Also, the presentations are open to students' participation. At the conclusion of the spring term, each project is formally assessed. Teams are required to hold a final presentation, including a demonstration of their working prototype, and to submit a written final report. Both oral presentation and written report are evaluated by faculty from our ET program and also guests from other departments and affiliated colleges and by external evaluators from industry. Most of our external evaluators are also members of our Industrial Advisory Committee and/or sponsors and collaborators of Department of Engineering Technology. Our senior design evaluation criteria are based on a-k ABET-ETAC student learning outcomes and on our specifically formulated performance indicators. At the final evaluation, the project scored for the written report an average of 4.3 to 4.9 out of 5 and for oral presentation an average of 4.5 - 4.6 out of 5 for objective a: demonstrates ability to apply knowledge and techniques of the discipline; demonstrates mastery of the techniques and skills of the discipline; demonstrates mastery of modern tools used in the discipline.

Also for the outcome b: demonstrates an ability to apply knowledge of mathematics, science and engineering to engineering technology problems, team scored an average of 4.7 out of 5 for oral presentation and 4.3 out of 5 for written report. Students demonstrated an ability to define an optimal, realistic, and technical approach that meets requirements in terms of technical, economic and societal criteria with realistic deadlines, identifying problems that are suited for technical solution and produces practical solutions based on meeting requirements of analyzed problem components. For these outcomes (d and f), team scored average scores of 4.3 to 5.0 out of 5 possible, for both written report and oral presentation. Similar scores were given for remaining outcomes, regarding societal and environmental aspects of the project. The project was awarded the best senior design project (at tie with another project) for AY 2012-2013, by both student and faculty and external evaluators' panels.

The development and implementation of a project of this scale and also creating lab-scaled educational equipment in our senior project design course is described here. During this endeavor, students learn, verify, and reinforce theoretical concepts by performing experiments through the project experience. In our approach we adopted the principles of the problem-learning methodology. The design experience develops the students' lifelong learning skills, self-evaluations, self-discovery, and peer instruction in the design's creation, critique, and justification. Students learn to understand the manufacturer data sheets, application notes, and technical manuals. The experience, which would be difficult to complete individually, gives the students a sense of satisfaction and the accomplishment that is often lacking in many engineering courses, using traditional teaching approaches. Furthermore, the design experience motivates student learning and develops skills required in industry. The project is used to allow students to apply fundamental engineering concepts as well as principles of engineering design. The societal impact of the project also makes students more aware of what engineering can do to address current manufacturing issues worldwide, such as reducing waste, and off goods.

From inter-disciplinary standpoint, this project may serve as experiential basis for two of our undergraduate core curriculum courses: “Measurement and Instrumentation Laboratory” and “Applied Quality Control”. While for the former one, we will develop laboratory activities related to sensors, measurement and instrumentation, which can be easily spun-off, for the later, the set-up is mainly used to exemplify a manufacturing process that needs to be analyzed from quality control point of view. Other courses may be impacted, such as Fluid Power, Programmable Logic Controls and Programming courses. The hands-on activities that can be developed using this industrial grade device put students within an industrial environment, showing them when and where and how all the theoretical concepts do apply. The lesson learned from this project are (1) the necessity of developing industrial grade but lab-scaled devices is a reality and (2) with the help of these equipments we can endow our students with the skills and knowledge they need to thrive in an industrial career as engineers. The multi-disciplinary character of these types of equipments and the activities that may be developed do motivate students to study and learn those topics that they might not seem beneficial for their immediate goals.

Although this project may be difficult to replicate at another institution, **the main idea of this paper is focused more to the scope, efforts and educational benefits of developing a lab-scaled industrial set-up.** The educational benefits are can be regarded from both short and long term perspective, for the team of students developing systems of such broad scope and for future students that may benefit of the laboratory activities stemming from such projects.

The project presented above, together with other projects proposed by the authors in the areas of manufacturing, industrial systems and renewable energy have been used to draw student’s interest in the field of advanced and intelligent monitoring systems.

References

1. R.S. Friedman, F.P. Deek, *Innovation and education in the digital age: reconciling the roles of pedagogy, technology, and the business of learning*,, IEEE Transactions on Engineering Management, Vol. 50, No. 4, Nov. 2003, pp. 403-412.
2. Wormley, D.N., “Challenges in Curriculum Renewal,” International Journal Engineering Education, Vo. 20, No. 3, 2004, pp. 329-332.
3. Splitt, F., *Environmentally Smart Engineering Education: A Brief on a Paradigm in Progress*, Journal of Engineering Education, Vol. 91, 2002, pp. 447-450.
4. Blumenfeld, P.C., E. Soloway, R.W. Marx, J.S. Krajcik, M. Guzdial, and A. Palinscar, Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning, Educ. Psychologist, Vol. 26, 1991, pp. 369-398.
5. Engineering Accreditation Commission, *Criteria for Accrediting Engineering Programs*, http://www.abet.org/criteria.html. (2002).
6. Felder, R.M., and R. Brent, “Designing and Teaching Courses to Satisfy the ABET Engineering Criteria,” Journal of Engineering Education, Vol. 92, No. 1, 2003, pp. 7-25.
7. Lakes, R., 2012, “Meaning of Poisson’s ratio”, from http://silver.neep.wisc.edu/~lakes/PoissonIntro.html.
8. Adam C. Bell, ScD, 1999, “The origin and cure of wrinkles in a running web”, http://www.convertingresource.com/news/yorkshire.html.

9. Lynch, R. ME, Procter & Gamble, Web Handling Seminar, October 2010, Applications seminar at Web Handling Research Center - Oklahoma State University, College of Architecture, Engineering and Technology, Chap. 7. *http://webhandling.okstate.edu*
10. Cognex http://www.cognex.com/ProductsServices/SurfaceInspection/default.aspx?id=1990&langtype=1033
11. Dover Flexo Electronics www.dfe.com
12. RKB Opto-electroniks http://www.rkbopto.com/Products.html
13. Applied Roller Technology http://www.appliedroller.com/Products/tabid/55/Default.aspx