Senior Design Capstone Project: Design and Development of Mount Structure and End-Effector for Automated Robotic Stacker

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Abstract

In this paper, the results of a control project sponsored by Nucor Steel Corporation, Marion, Ohio, are presented. This student project is conducted at University where in which a team of graduate and three undergraduate students are involved. This project is credited as the Senior Design (SD) project for the undergraduate students and hence enhanced their control education through a real industrial application. The student involvement includes visiting the production line at Nucor Steel Corporation, conducting the project at University, and delivering the completed project and installing it on the production line at Nucor Steel Corporation. The objective is to design a robotic system for precise stacking of highway sign posts, while complying with the required stacking pattern as well as time constraints. The Nucor Steel Corporation bar mill relies heavily on manual work force in its highway products division. A highly manual process introduces many safety hazards as well as inefficiencies and inconsistencies. One hazardous position is the bundling of heavy sign posts, which are manually raked into bundles before being manually banded, and workers are at risk for overuse injuries. Moreover, the sign posts are randomly positioned within a bundle, and hence the disorganized bundle is much larger than an organized stack of the same count. Disorganized bundles also hinder further automation processes downstream the production line, such as banding and powder coating the sign posts. This paper offers a robotic stacker solution utilizing Fanuc robot manipulators, custom-built end-effectors, and programmable logic controller (PLC) that will result in smaller and organized stacks as compared with the current disorganized bundles, and the removal of a worker from the hazardous position in the process. Organized stacks will also allow for further downstream automation processes. This paper gives an overview of the developed robotic solution and specifically focuses on the design and development of the robot's mounting structure, along with the custom end-of-arm tool. In addition, authors describe an effective approach of working on industry sponsored SD project, the SD team requirements, significance of the project, specific project outcomes, and assessment tools used.

Introduction

The capstone project course is an intrinsic part of the undergraduate education. The capstone projects are widely regarded as an excellent mechanism for assessing the outcomes of engineering and engineering technology programs and can serve as a direct measure of the quality of graduates. Capstone projects provide an opportunity for students to demonstrate their critical thinking skills, communication skills, as well as time and project management skills. The capstone course prepares students to better understand the professional roles in the engineering and technology community[1]. In many universities, senior-level capstone courses have been incorporated as an integral part of engineering and engineering technology education in an effort to correlate the practical side of engineering design and the engineering curriculum. Such courses provide an experiential learning activity in which the analytical knowledge gained from previous courses is joined with the practice of engineering in a final, hands-on project.[2-4] The development of capstone design courses and corresponding requirements have been influenced by various sources, including the Accreditation Board for Engineering and Technology (ABET), industrial advisory boards (IAB), faculty leading capstone projects, numerous industrial companies, and engineering research.

Earlier research[4-15] showed the importance of industrial involvement in the capstone environment, which became more than just the financial support described above. However, support in the form of equipment, materials, and technical consulting is common and in most cases necessary.[6, 8, 11] Most industrial sponsors have a liaison engineer who assists the students and who follows the progress of the project.[7, 10] Other forms of industrial support include providing awards for meritorious designs and assisting in the evaluation of teams and projects.[4]

More recent studies provide further in depth analysis on the importance of the various benefits of capstone projects for the students' preparation for real world jobs. These include but not limited to the importance of industry involvement,[16-18]familiarizing students with product development process and system engineering,[16,19-23] improvement in the professional skills of students,[16,21] providing multidisciplinary training,[16,22,24,25]cultivating creative problem solving skills,[16,26] and preparing students for globalization.[16,27,28]

Recently, a new trend in conducting capstone projects became noticeable. Some capstone projects are sponsored by faculty members instead of industrial partners that play an important role of supporting some larger scale externally funded faculty research projects[16]. For example, at Texas A&M University, the undergraduate students involved in these projects as a capstone team had to work with the graduate students, faculty members, and potential customers. Software, hardware, interface, system integration, and testing all involved other researchers instead of just the capstone team.[16] These types of projects may resemble projects conducted in industrial settings, where multiple divisions have to collaborate on a single, large scale project.

The technology revolution is introducing robotics and automation in many of the industrial applications. Most of the difficult and repetitive tasks can easily be performed by robots with high accuracy and efficiency. Many industrial sectors are embracing new robotic and automation technologies to attain high level of accuracy and quality in their processes, reduce the costs and stay ahead in the field.

Nucor Steel Corporation is the top steel producer having a wide range of products with a production capacity of nearly 29 million tons[29]. Nucor Corp. have always been one of the first to implement new technology in their production line. This project of an automated robotic stacker for Nucor Steel Corporation aims at increasing efficiency in the production line of highway signposts, by creating highly organized stacks of signposts and also providing high safety by removing the presence of a worker from hazardous operating conditions. The organized stacks can later be used for further downstream processes involving automation of banding and coating of the signposts.

The Nucor Steel Corporation located at Marion, Ohio relies highly on manual labor in its highway products division. The signposts varying in size and weight, come out of a pressing machine through transfer chains to a platform. A worker collects the signposts at this platform and manually racks them into a bundle and then manually bands them. This operation is hazardous and tedious for the worker since the signposts are bulky and heavy. Also, since the signposts are manually bundled in random position, the stack is disorganized, which creates complications for further processing and transportation.

The design challenge was to automate this process and thereby remove the worker from the hazardous position. Automation results in the bundles being highly organized and more efficient for any further processes of banding or coating.

Capstone Course Description

In the past several years EET program in the School of Technology at UNIVERSITY was very successful in establishing collaboration with the industry. This, in turn, triggered nearly all the capstone projects conducted in the EET program to be industry sponsored. Only during the last few years, EET program has successfully completed 15 capstone projects with 13 of them being industry sponsored. The benefits of having SD projects industry sponsored are very significant for both the students and faculties.

A capstone course in the EET program requires the application of knowledge gained in lower and upper division courses. Students participating in a capstone project demonstrate the ability to perform independent and creative work by successfully completing a major design project. Projects are normally team oriented, where the team consists of two to four members, with one member chosen as team leader. Team oriented capstone projects provide a better simulation of industrial environment, to better train today's engineers. [2] Weekly progress reports are required, and the work culminates with a final report and oral presentations, including a poster of the project. Six credits of Senior Project are required for graduation, normally satisfied in two three-credit semesters.

Upon successful completion of the capstone project course, students should fulfill the following course objectives:

- Prepare background research on applied electrical engineering technology.
- Research and organize data for synthesis.
- Prepare written reports.
- Prepare and present oral reports.
- Work in teams.
- Coordinate and work to meet scheduled deadlines and facilities, manage resources, etc.
- Consider non-engineering considerations in your work (e.g., Economic issues, marketing issues, esthetics).

At the beginning of the first semester team is required to prepare a typed project proposal in a formal memo format, including a proposed timeline. During the course of the project student's team meet with their faculty advisor weekly to discuss the progress report. The weekly formal memo is required the day prior to each weekly meeting and addresses the following three areas: current progress, problems encountered and their resolution, and plan for the following week.

To stay on the top of industry requirements sponsoring the project and to receive valuable engineering feedback students conduct by-weekly web conference calls with industry liaison. The oral and written reports due near the end of each semester are to concern themselves with the progress made in each semester. The one at the end of the first semester will be a progress report, with a full final report due at the end of the second semester. To further improve the quality of capstone projects conducted in the EET program in the SOT at the UNIVERSITY and make students experience as participating in undergraduate research, in the middle of the second semester the team led by the faculty prepares the paper to be further submitted in one of the engineering journals or conference proceedings. In the author's opinion, this experience should become an integral part of any capstone project since it derives an additional benefits previously not included in the capstone environment. First, this requirement makes the students to fill them proud to be engaged in undergraduate research, which in-turn derives more responsibility and teamwork. Second, it provides the students with the opportunity to learn different styles of technical writing following required formats associated with various journals and conference proceedings. The last but not the least, it significantly improves graduates portfolio that while looking for the job can "bring to the table" more than their competitors - applicants.

System Overview

The developed solution is an automated robotic stacker with two wall-mounted Fanuc M710iC robots[30] being used in dual-arm configuration providing coordinated motion during operation. A mount structure for robots was built to be strong enough to bear the load from the robots and the payload being lifted. The robots are equipped with a custom built end-of-arm tooling retrofitted with total of 8 magswitches. These magswitches are permanent magnets that are used to pick the signposts, when engaged, and to drop the signposts, when disengaged. There are also sensors attached to the end-of-arm tooling to detect the presence of the signposts being lifted, and sensors to detect the status of the magswitches (engaged/disengaged). Both robots are configured for safety, and also connected to a PLC in order to track the status of the production line, and terminate the operation in case of any faults in the production cycle. The robots are then programmed to operate in a single-arm (for smaller signposts) or in a dual-arm (for larger and heavier signposts) configuration. Next we provide detailed information on the system's components.

Signposts:

The signposts in production at Nucor's facility varies in size and weight. Size variations are from 3.5ft to 12ft in increments of 0.5ft, and each of the signposts have 9 weight options with 5lb/ft being the heaviest one. So, the largest signpost that will handled by the developed robotic stacker is 12 feet in length and made of 5 lb/ft steel, resulting in a 60lb (27.22kg) maximum.

Fanuc M710iC Robots:

The developed automation solution incorporates dual arm synchronized Fanuc robots to build organized stacks of the signposts. While one robot can physically lift and maneuver the 12ft long signpost, the two synchronized robots operating in the dual-arm configuration, offer stability in the system by not allowing the signpost to bend from the sheer weight of itself when being

moved, as well as it provides a greater safety factor in carrying out the overall process. The robots shown in Figure 1, are wall mounted 6ft apart on a rigid steel structure, positioned above an incoming conveyer, which carries the signposts. Each robot, individually, picks and stacks signposts of all lengths equal to and below 5ft and with the weight variations. Any signpost length equal to or greater than 6ft is picked and stacked by 2 robots simultaneously.
The robots in use are two Fanuc M-710iC/70 robots[31], operating in dual-arm configuration. Dual-arm configuration refers to the fact that the two robotic arms work as a team to accomplish the same task. The Fanuc M-710iC/70 robot provides a payload capacity[32] of 154.32 lbs (70 kg). With the weight of the largest signpost picked being approximately 60 lbs (27.2 kg), and the system is designed to pick 2 signposts at a time, the total payload is well within the load bearing limit of the robots[32].

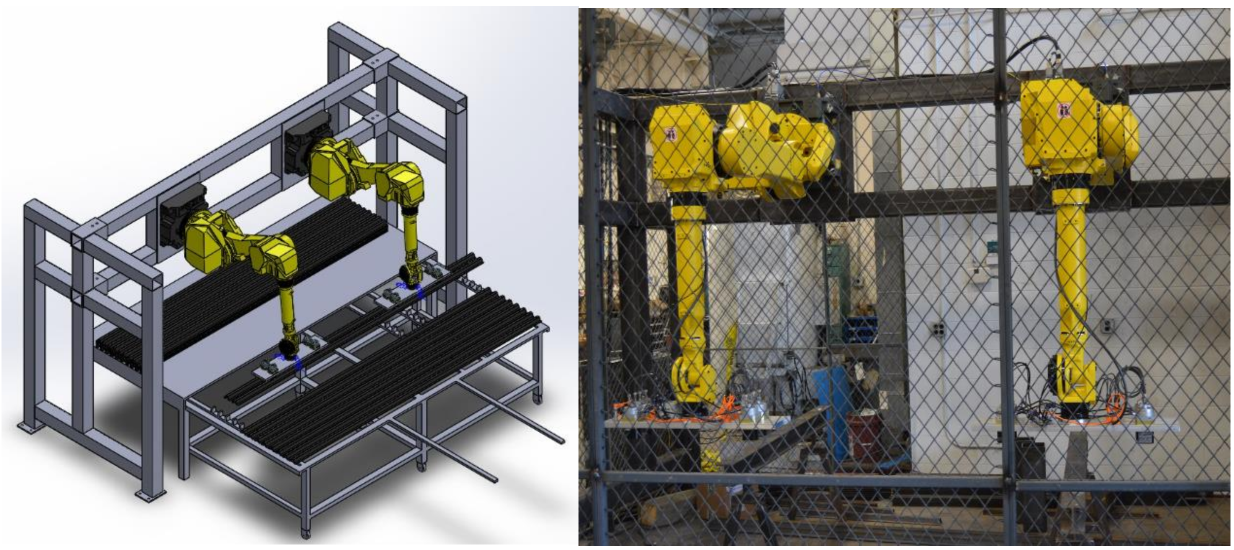


Figure 1 System Overview | Model (Left) and Actual (Right)

The Fanuc 710iC robots have R30iB controllers[33], preloaded with software required for the programming and functioning of the robots. The software has options to enable the robots to work in the single-arm or dual-arm configuration, depending on the task being executed. The teach pendant (TP) acts as a human machine interface (HMI) via the Software Panel Wizard. The TP is used to create programs, input the size of the signposts being stacked and the stack count, thereby offering multiple program solutions.

End Effector:

For the robots to be able to move the signposts, a custom end-effector was built, as shown in Figure 3. The requirements for the end-effector (EE) are:

- satisfy the payload schedule
- detect the presence/absence of a signpost at the picking position,
- pick two parallel signposts at a time, and drop them at the destination position.

For the detection of the signposts, a photoelectric sensor mounted on the EE is used. Since the signposts are made of steel, the permanent magnets Magswitch M50 HDC[34] were found to be an ideal option for pick-drop operation. The designed end-effector is capable of lifting two signposts at a time using 4 Magswitches, operated by pneumatics. A pneumatic manifold is housed on the end-effector that provides for the activation and deactivation of the magswitches.

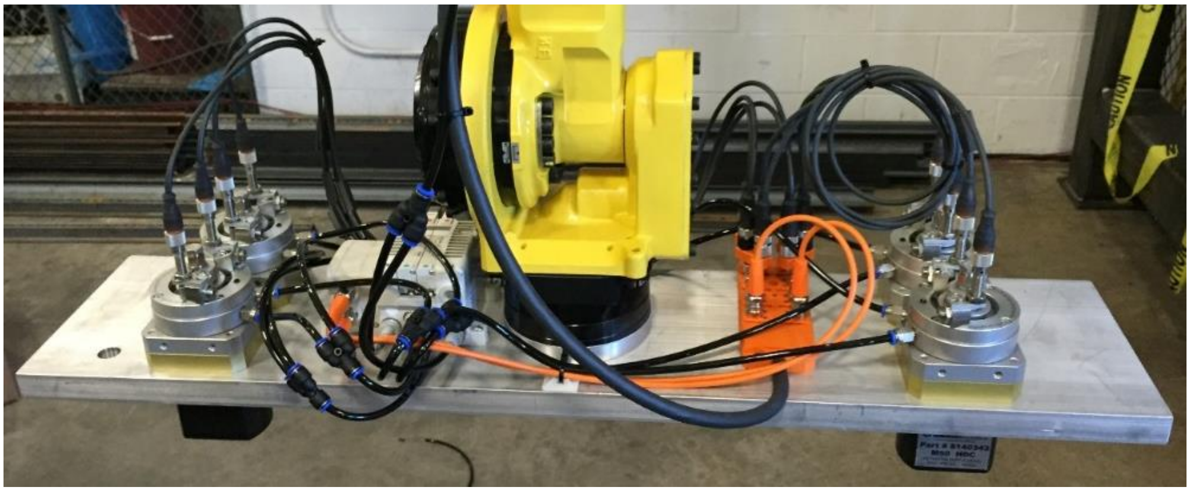


Figure 2 Mounted Robot End-Effector

The system's end-effector required a custom structural design that would provide adequate strength and remain as lightweight as possible in order to not take away from the payload of the system. The material choice for these specifications was therefore aluminum, which is both lightweight and strong. The end-effector structure incorporating aluminum 36in x 8in x 1in plate was designed to withstand the weight of the four Magswitches and a payload.

The main interface between the signposts and the robotic arms is the Magswitch, which allows the system to physically handle the signposts in an efficient and timely manner. Conducted research had proven that electromagnets would not be sufficient for this system as they introduce a delay in charging/discharging, and leakage magnetic flux as they charge the material they are connected to, and therefore providing for a safety concern in-case the power loss in the system. The Magswitch M50 HDC provides a safe working load[34] of 150 lbs (68.2 kg). Figure 4 shows how the total load is distributed among four Magswitches on the two end effectors. The total load on each Magswitch is therefore a maximum of 15 lbs (given that heaviest payload being 60lbs) which is well below the safe working load of the chosen M50 HDC Magswitch. The M50 HDC also has a shallow field depth (hence the 50 series) [34], which allows for maximum magnetic saturation without oversaturating and interfering with other materials near the signpost to be picked. Another great advantage of the Magswitch is that when power is lost, the Magswitch will retain its current state, minimizing the risk of dropping the work piece. The Magswitch consists of two permanent magnets, magnetic poles of which either cancel or amplify each other depending on the orientation of the two magnets, which is controlled using pneumatics. Compressed air is readily available at Nucor's facility and allows for a quick and seamless integration into their current resources. In order to determine whether the Magswitch is on or off, a sensor is utilized for each state. With two sensors being configured as a complementary pair, one sensor will determine if the magnet is off while the other will determine if the magnet is on. This provides a redundancy that can help eliminate any error in operation.

The front two Magswitches work together and are responsible for lifting one signpost while the back two lift another signpost. This requires each pair to be both activated and deactivated simultaneously. To accomplish this, a pneumatic manifold is used to control the air to the magnets. The manifold, custom designed by H.H. Barnum[35], consists of two VQC 2200N-51 solenoids and receives a digital signal from the robot's digital output, for activation or deactivation of solenoids. The manifold is fitted with M12 connectors, allowing for easy integration with the sensors, equipped with M12 connector. A custom field wired cable, coming from the robot's EE port, attaches to the M12 junction box which provides two digital signals necessary for control. Figure 5 shows the pneumatic manifold integrated with the magswitches.

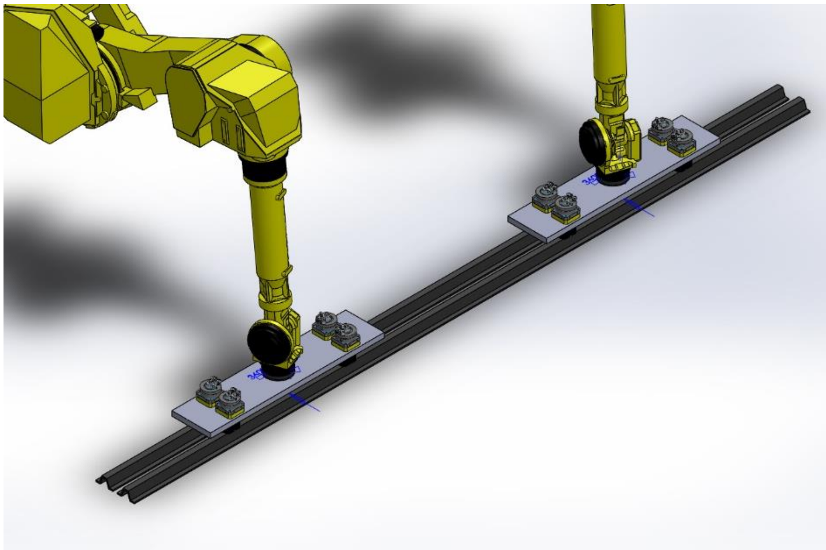


Figure 4 End-effector with Magswitches

Figure 5 Pneumatic Manifold Mounted on End-Effector with Magswitches

Mount Structure

The rigid structure built at University, shown in Figure 6, was designed to have the strength to accommodate the load of both robots, custom built EE with the maximum payload.

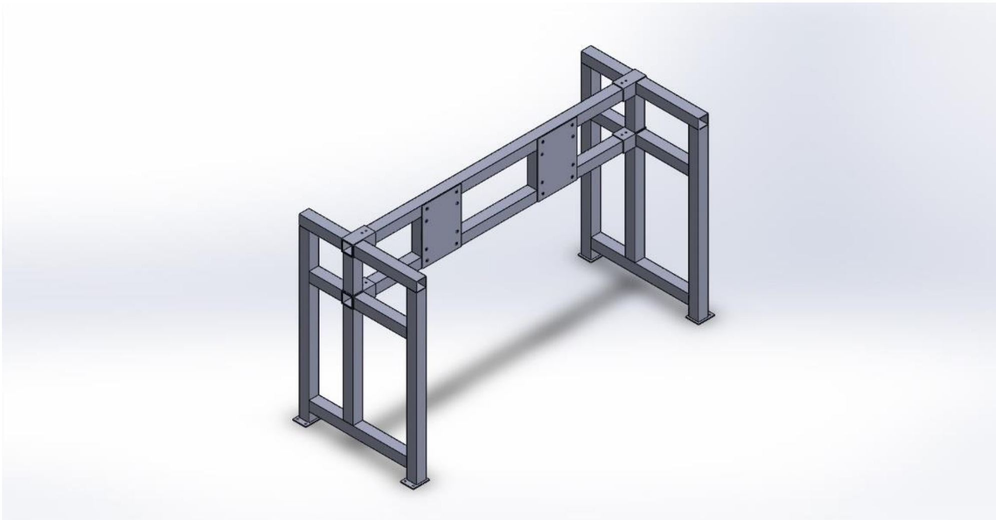


Figure 6 Structure built at University

The following were the weight/load considerations for the structural design of the mount structure:

- Weight of the robot: 1250 lbs per robot [32]. With two robots in place, the structure should be able to withstand 2500 lbs.
- Weight of the end-effector: 15 lbs for aluminum plate plus 78.4 lbs from end-effector. With two end effectors, the total weight is 186.8 lbs, which also accounts for the heaviest lifted signpost.

Based on these considerations, the total weight that the structure must withstand is 2690 lbs, which is around 12,000 N of force. All the beams and columns are 6in x 6in x 0.25in with ASTM A36 steel being the material. With all the design considerations made, an FE model was created in HyperMesh and LSA was simulated with Optistruct as the solver to check for maximum static deflection and von mises stress.

Signpost Feeder

The signposts at Nucor facility arrive from the press on transfer chains, with a walking beam mechanism. A similar signpost feeding mechanism was designed to feed the signposts to the robots, for the prototype system built at University. The walking beam at Nucor's facility has teeth that are 4 inches apart center to center. The same measurements were replicated in the signpost feeder.

The signpost feeder had to fulfill the following requirements:

- The center to center distance of the teeth carrying the signposts has to be exactly 4 inches.
- The feeder should be able to deliver the signposts to robot's picking position continuously throughout the operation cycle, until the signpost stack is fully assembled according to Nucor's specifications.
- The feeder should have 2 signposts ready to be picked by the robots, every 6 seconds.

Apart from the above requirements, a platform below the mounted robots, is required for stacking the signposts once they are picked from the feeder.

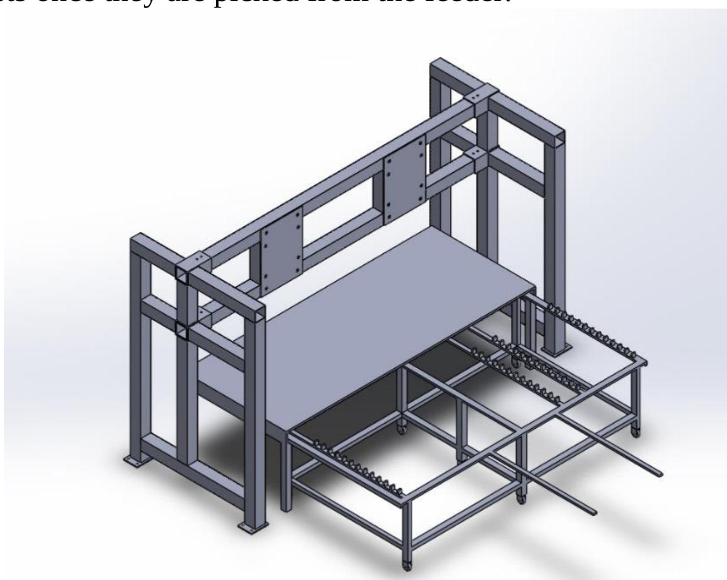


Figure 7 Signpost Feeder

Figure 7 shows the developed signpost feeder considering all the above requirements. The feeder is a frame structure made of long steel strips with the teeth on the feeder to be 4 inches apart center to center. The wheels attached to the legs of the feeder, move on a steel guideway with graduations which enables the feeder to move exact distances making sure that 2 signposts are fed to the robot picking position. Considering temporary nature of the signpost feeder, it was decided not to retrofit it with motor but engage manual operation only with the help of 2 rods located on the front side of the feeder.

Sensors

It is important to know the current state of the magswitches (activated/ON and deactivated/OFF). Utilizing the EE port on the robot limits the system to eight digital inputs and eight digital outputs. To account for this, the sensors are combined through a M12 T-Connector with AND circuit [36], giving the ability to retain the two status indicators without sacrificing any I/O points on the robots EE port.

In order to wire the pneumatic manifold, the Magswitch on/off sensors, and the proximity sensors into the EE port of the FANUC robots and ultimately into the I/O modules of the controller, the M12 connectors of these components need to be wired into the EE pin module provided by Fanuc. To keep the end-effector organized, allow for future modification, and/or replacement of components the ASBV8/LED5-242/5M M12 [37] is used. By corresponding appropriate wires with the correct EE port pins, a fluent interface is created between the end-effector and the digital I/O's of the R30ib controller.

Determining if signposts are present to be picked is critical to the operation of this system. Two photoelectric sensors were placed on the master robot's end-effector for this purpose. The FFI7-BP-1E photoelectric sensor [38] was chosen for its 400mm sensing range, normally open and normally closed logic capability, as well as the ability to teach the sensor its sensitivity.
The 400mm sensing range provides the clearance needed for the end-effector to correctly be situated above the moving signposts while maintaining accurate reading on the presence of the posts. With the extra range, the sensor can also be imbedded into the end-effector, protecting it from debris and physical contact. When determining whether a sing post is present or not, only a true or false signal is required and, as a result, the normally open and normally closed logic capability is ideal for this application. Being able to configure or set the sensitivity is also an important feature of the photoelectric sensor. This allows the sensitivity to be determined by the programmer to account for any minor variations between the system and design built at University and the actual installation of the product at Nucor Steep Corporation.

Structural Analysis

The main purpose of the structure being built is to take the load of both robots and EE along with the maximum payload hence it needs to be designed for strength. When designing for strength, stress is the key factor to be considered. So a Linear Static Analysis (LSA) is performed to determine the stress values generated due to the load on the structure (both rigid support and the EE structure) and results obtained, are well within the safe limits for developing a safe design. There shall also be consideration for safety factor, which is defined [39] as "the ratio of the maximum stress that a structural part or other piece of material can withstand to the maximum stress estimated for it in the use for which it is designed." Consideration of this factor will ensure guaranteed performance, safety and prolonged life of the structure being designed. Geometric models of the structures are created and analyzed in HyperMesh [40], the software used for modeling the geometry, creating stimulations and results based on given parameters. A Finite Element (FE) Model of the structure is created in HyperMesh to do the LSA. FE model is a computer model created in which the system/structure to be analyzed is discretized into finite number of points, and all calculations needed (Ex: stress generated, deflection) are made at these points and interpolated to obtain the results for the entire system. The LSA is done on the structures (Mount structure and End-effector structure) in this project to study the static deflection and von mises stress.

End Effector Structural Analysis
The system's end-effector required a custom structural design that would provide adequate strength and remain as lightweight as possible in order to reduce its contribution to the payload of the system. The material choice for these specifications was therefore aluminum, which is both lightweight and strong. The EE structure incorporating aluminum 36in x 8in x 1in plate was designed to withstand the weight of the four Magswitches and a payload.

The following are the weight considerations for the structural design of the end-effector:

- Weight of the Magswitch: with each Magswitch being 4.6 lbs, four magswitches per end-effector, the total load due to the Magswitches is 18.4 lbs.
- Weight of the Signposts: If single-arm configuration is used, the maximum weight of the signpost is 22.5 lbs per signpost. Since we are lifting two signposts, the payload is 45lbs. If dual arm configuration is used, the largest post lifted would be 12 ft constructed of 5 lb/ft steel, resulting in 60 lbs of weight. Since there are two posts and two end effectors per post, the payload is 60 lbs. The design is based on this 60 lbs requirement because it is larger than the 45 lbs requirement.

Combining the two weights used for analysis, the end-effector structure must withstand 60 lbs of weight in addition to the 18.4 lbs from the four Magswitches for a total of 78.4 lbs.

Finite Element (FE) Model for End-Effector

The material and its properties are defined for the components of the model in HyperMesh with the next step is to decide the element type and size for meshing the model. The plate being solid, the mesh used was 3D Solid Elements. Since the magswitches are housed on the plate from the top, as shown in Figure 26, the force is distributed over the area housing the magswitches in the FE model. The holes pattern in the center of the plate is used to attach the end-effector to the robot's faceplate. So, this area was given single point constraints in all the 3 translational and 3 rotational degrees of freedom. Figure 8 shows the completed FE model.

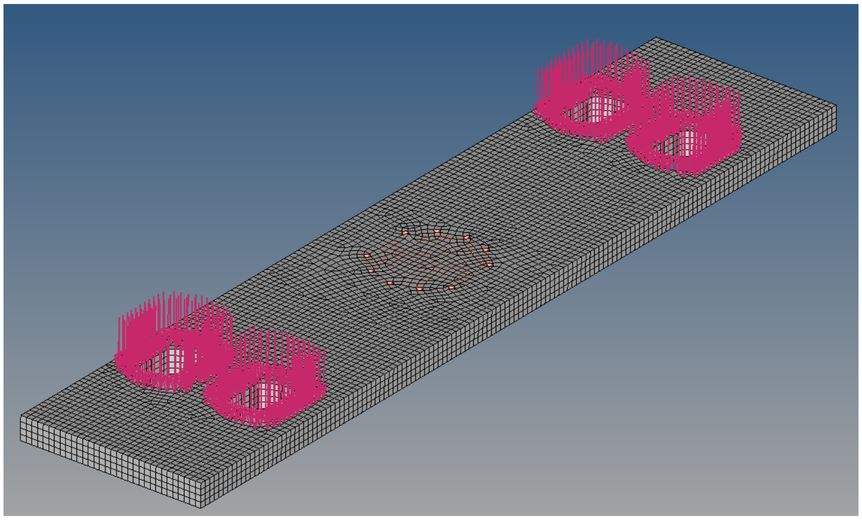


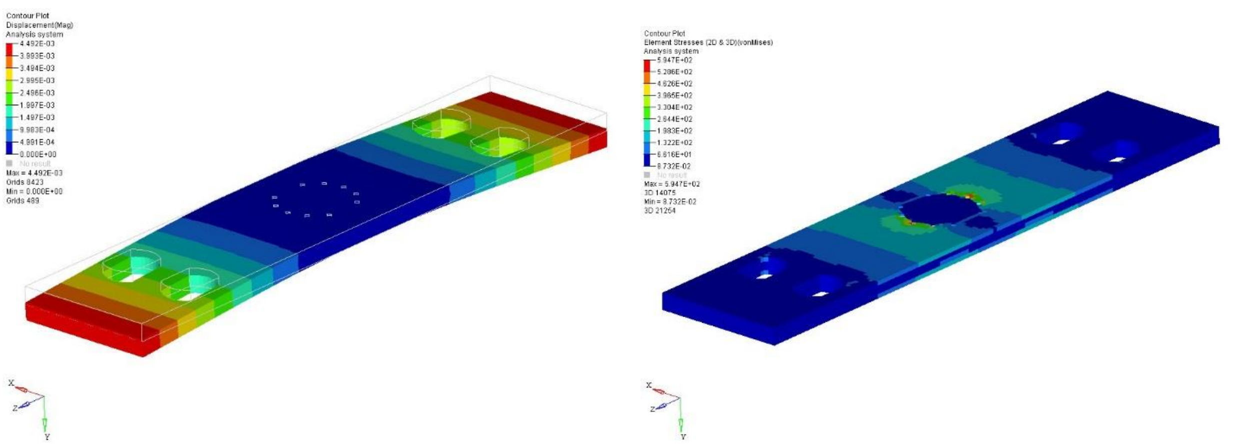
Figure 8 End-Effector Boundary conditions

With all the properties and boundary conditions discussed, the FE model was simulated in HyperMesh with OptiStruct solver and results shown in Figure 9 (a) demonstrates that the structure will endure a maximum static deflection of 0.0045in (0.1mm). Figure 9 (b) shows the von mises stresses generated in the structure due to the load. The structure generates 594.7 psi von mises stress while the permissible limit is nearly 8000 psi for aluminum providing 13.5 safety factor (SF). With the static deflection being very small, and the stresses generated well below the permissible limit for aluminum, thereby providing for a large SF, the design is considered to be safe for development.

Mount Structure Analysis

The rigid structure being built at University should have the strength to take the load of both robots and EE with the maximum payload. The following were the weight/load considerations for the structural design of the mount structure:

- Weight of the robot: 1250 lbs per robot. With two robots in place, the structure should be able to withstand 2500 lbs.
- Weight of the end-effector: 15 lbs for aluminum plate plus 78.4 lbs from end-effector. With two end effectors, the total weight is 186.8 lbs, which also accounts for the heaviest lifted signpost.



(a) (b)

Figure 9 (a) End-Effector Static Deflection Plot; (b) End-Effector Von Mises Stress Plot

Based on these considerations, the total weight that the structure must withstand is 2690 lbs, which is around 12,000 N of force. All the beams and columns used for construction at University, are 6in x 6in x 0.25in with ASTM A36 steel being the material. With all the design considerations made, an FE model was created in HyperMesh and LSA was simulated with Optistruct as the solver to check for maximum static deflection and von mises stress generated.

FE Model for Mount Structure

The material and its properties are defined for the components of the model in HyperMesh with the next step is to decide the element type and size for meshing the model. Since the structure is constructed using hollow steel tubes, 2D shell elements were used with thickness assigned over the mid-plane to be equal to that of the hollow steel tube (0.25in). Considering solid nature of the base plate it was meshed with 3D solid elements. The weight due to the mounted robots on the base plate and their payload on the mount structure was simulated by using RBE3 elements to transfer the effect of load on to the structure. RBE3 elements are common type of rigid body elements that are used to transfer point loads onto several dependent nodes on the structure being analyzed. The load is distributed based on the distance of the dependent nodes on the independent RBE3 element. A point load, equal to the total weight from the robot and the signposts being lifted, was applied on the RBE3 element, which was distributed on the mount structure where the robots were attached. Since the structure is rigidly secured to the ground, all the four base corners were given single point constraints in all 3 rotational and 3 translational degrees of freedom. Figure 10 shows the completed FE model with all the boundary conditions in place for the analysis of the structure.

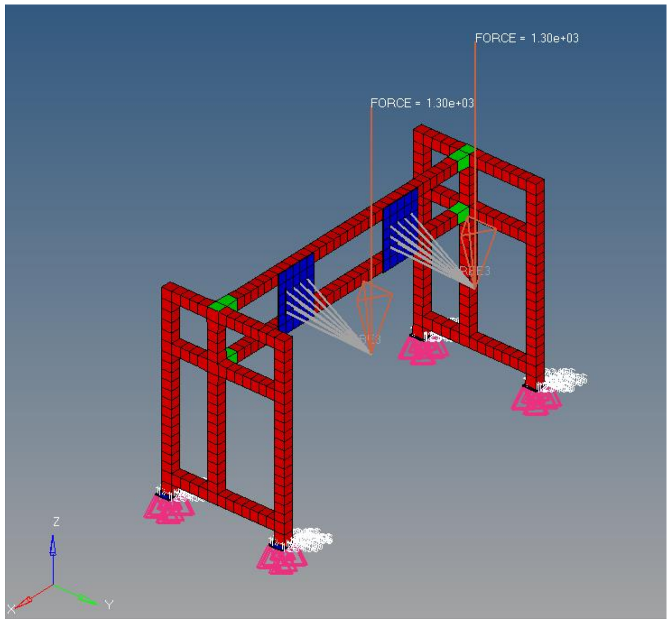
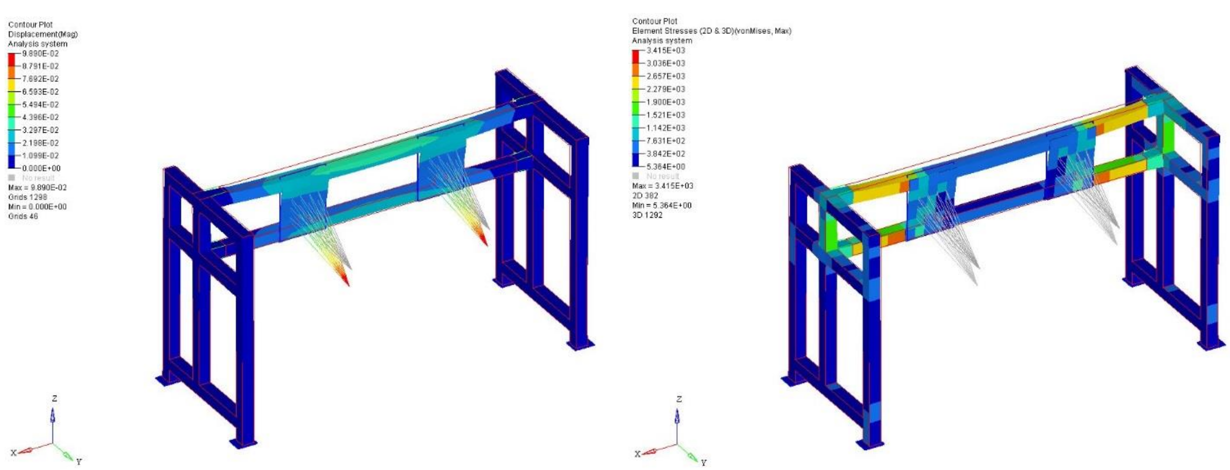


Figure 10 Mount Structure Boundary Conditions

Figure 11 (a) shows the simulated result obtained from HyperMesh indicating the static deflection generated in the structure, the maximum value being at the beam and is equal to 1.397 mm (0.055 in). The deflection observed is very small and well within the safe limits, and so the design is safe to be developed.



(a) (b)

Figure 11 (a) Mount Structure Static Deflection Plot; (b) Mount Structure Von Mises Stress plot

The von mises stress generated in the structure due to the loading conditions mentioned before is shown in Figure 33. The structure generates 3415 psi von mises stress while the permissible limit is approximately 36000psi for A36 steel. The induced stresses ensures that the structure is meeting all the requirements with SF approximately equal to 10.5.

Capstone Project Assessment

To effectively assess the capstone project course outcomes the direct and indirect assessment tools have been implemented. In general, direct assessment involves looking at actual samples of student work produced in the course. These may include initial project proposal and a time line, team weekly memos, written report & project brief, team poster, and oral presentation. Indirect assessment is gathering information through means other than looking at actual samples of student work. These include student's self-evaluation, faculty and IAB members' evaluations, and exit interviews. Each serves a particular purpose. Indirect measures can provide an evaluator with the information quickly, but may not provide real evidence of student learning. Students may think that they performed well or say that they did, but that does not mean that their perceptions are correct. As an indirect assessment tool the authors developed and implemented senior project peer feedback form and oral presentation scoring rubric with the last one being distributed to the faculty and IAB members during the final presentation conducted by the team at the end of the second semester.

The final grade is derived using both direct and indirect assessment tools and based on the satisfactory completion of the capstone project and the presentation of the final results in an appropriate engineering report. The final grade is based on individual and team performance throughout the semester. The points are awarded as follows:

- Initial Project Proposal and Time Line 10% Team
- Weekly Memos 20% Team
- Written Report & Project Brief 30% Team
- Poster 10% Team
- Oral Report 20% Individual
- Peer and Self Evaluation 10% Individual

To conduct peer and self-evaluation, students of the team were asked to complete and submit to the faculty advisor a senior project peer feedback form. To collect the faculty and IAB members' feedback, oral presentation scoring rubric was distributed during the final presentation conducted by the team at the end of the second semester. Students participated in the capstone senior design project described in this paper provided highly positive feedback to the team peers. Moreover, the students gained a very satisfactory score on the oral presentation evaluated by the faculty and IAB members.

Conclusion

Academic programs in the School of Technology at University are designed to prepare technical and/or management-oriented professionals for employment in industry, education, government, and business. This industry sponsored Senior Design (SD) student project was conducted by a team of one graduate and three undergraduate students at University. In this project, the students designed and developed a robotic system for precise stacking of highway sign posts, while complying with the required stacking pattern as well as time constraints. The students conducted the project at University and programmed the robots to meet the automation specifications. This research and development project was successfully completed at University, and the complete automated robotic stacker system was delivered to Nucor Steel plant to be installed at Press #2 of the production line in highway products division.

References:

1. Bai, T., Zhu, J., Varma, V., "Characteristics of capstone design projects at universities in US and China: An Analysis", ASEE *Annual Conference & Exposition (ASEE 2007),* AC 2007-1755
2. Dutson, A., Todd, R., Magleby, S., Sorensen, C., "A review of literature on teaching engineering design through project-oriented capstone courses," *J. of Engineering Education*, Jan. 1997, pp. 17.
3. Pomberger, G., "Software Engineering Education — Adjusting our Sails," *Education and Computing,* vol. 8, no. 4, 1993, pp. 287-294.
4. Thorpe, J. F., "Design of Mechanical Systems: A Capstone Course in Mechanical Engineering Design," *ASEE Annual Conference & Exposition (ASEE 1984)*, pp. 803-807.
5. Todd, R. H., S. P. Magleby, C. D. Sorensen, B. R. Swan and D. K Anthony, "A Survey of Capstone Engineering Courses in North America," *Journal of Engineering Education,* vol. 84, no. 2, 1995, pp. 165-174.
6. Banios, E. W., "Teaching Engineering Practices," *Proceedings, 1992 Frontiers in Education Conference,* IEEE, 1992, pp. 161-168.
7. Todd, R. H., C. D. Sorensen, and S. P. Magleby, "Designing a Senior capstone Course to Satisfy Industrial Customers," *Journal of Engineering Education,* vol. 82, no. 2, 1993, pp. 92-100.
8. Rochefort, S., "An Innovative ChE Process Laboratory," *Chemical Engineering Education,* vol. 19, no. 3, 1985, pp. 150-155, 161.
9. Frechleton, J. E., and W. W. Walter, "Constructing Prototypes in a College-Wide Capstone Design Course," *Proceedings, Advances in Capstone Education Conference, Brigham Young University,* 1994, pp. 177-180.
10. Durfee, W. K., "Engineering Education Gets Real," *Technology Review,* vol. 97, no. 2, 1994, pp. 42-52.
11. Born, R. C., "A Capstone Design Experience for Electrical Engineers," *IEEE Transactions in Education,* vol. 35, 1992, pp. 240-242.
12. Magleby, S. P., C. D. Sorensen, and R. H. Todd, "Integrated Product and Process Design: A Capstone Course in Mechanical and Manufacturing Engineering," *Proceedings, 1992 Frontiers in Education Conference,* ASEE, 1992, pp. 469-474.
13. Sloan, D. E., "An Experiential Design Course in Groups," *Chemical Engineering Education,* vol. 16, no. 1, 1982, pp. 38-41.
14. Hamelink, J. H., "Industrial Oriented Senior Design Projects. A Key for Industrial Experience," *Proceedings, Advances in Capstone Education Conference, Brigham Young University,* 1994, pp. 87-89.
15. Walter, W. W., "Using a Large-Displacement General Purpose Dynamics Code in a Capstone Design Course," *Twenty Third International SAMPE Conference*, 1991, pp. 288-296.
16. Zhan, W., Goulart, E., Morgan, J., Bird, M., "Integration of Capstone Experience and Externally Funded Faculty Research," *ASEE Annual Conference & Exposition (ASEE 2012),* AC 2012-3139
17. Brackin, M. P. and Gibson, J. D., "Capstone Design Projects with Industry: Emphasizing Teaming and Management Tools," *ASEE Annual Conference & Exposition (ASEE 2005)*
18. Karimi, A., Eftekhar, J., Manteufel, R., and Singh, Y., "Industrially Supported Projects in a Capstone Design Sequence," *ASEE Annual Conference & Exposition (ASEE 2003)*
19. Corns, S., Dagli, C. H., and Guardiola, I. G., "SE Capstone: Integrating Systems Engineering Fundamentals to Engineering Capstone Projects: Experiential and Active," *ASEE Annual Conference &*

Exposition (ASEE 2011),
20. Crain, G. E. and Tull, M. P., "A Capstone Course Targeting Industry Transition," *ASEE Annual Conference & Exposition (ASEE 2004),*
21. Gerbus, D., Cordon, D., Walker, M., Drew, R., Odom, E., Beyerlein, S., and Rink, K., "Improving the Professional Skills of Engineering Graduate Students through a Capstone Project Mentoring in IEWorks," *ASEE Annual Conference & Exposition (ASEE 2002),*
22. King, L., El-Sayed, M., Sanders, M. S., and El-Sayed, J., "Job Readiness through Multidisciplinary Integrated Systems Capstone Courses," *ASEE Annual Conference & Exposition (ASEE 2005),*
23. Sheppard, K. G., Nastasi, J., Hole, E., and Russell, P. L., "SE Capstone: Implementing a Systems Engineering Framework for Multidisciplinary Capstone Design," *ASEE Annual Conference & Exposition (ASEE 2011),*
24. Redekopp, M., Raghavendra, C., Weber, A., Ragusa, G., and Wilbur, T., "A Fully Interdisciplinary Approach to Capstone Design Courses," *ASEE Annual Conference & Exposition (ASEE 2009),*
25. Seaward, G. H., "Converting Single Disciplinary Capstone Projects to Interdisciplinary Experiences," *ASEE Annual Conference & Exposition (ASEE 2001),*.
26. Lumsdaine, E., "Creative Problem Solving in Capstone Design," *ASEE Annual Conference & Exposition (ASEE 2007),*
27. Lin, Y. and Harby, D., "Teaching Capstone Design in Globalization Environment," *ASEE Annual Conference & Exposition (ASEE 2004),*
28. Lin, Y., Harby, D., Jang, D., and Ye, Z., "Problems and Solutions in Internationalizing Capstone Design," *ASEE Annual Conference & Exposition (ASEE 2005),*
29. Nucor Steel Corporation. (2015) Nucor. [Online]. http://www.nucor.com/products/products/matrix/
30. Fanuc Robotics. (2015) Fanuc America. [Online] http://robot.fanucamerica.com/products/robots/productbyseries.aspx?seriesId=12&robotseries=M-710iC
31. Fanuc Robotics. (2007) FANUC Robotics America. [Online]. http://www.fanucrobotics.com/cmsmedia/datasheets/M-710iC%20Series_20.pdf
32. Fanuc Robotics. (2015, Feb.) Fanuc America. [Online]. http://www.fanucamerica.com/cmsmedia/datasheets/M-710iC%20Series_178.pdf
33. Fanuc Robotics. (2015) Fanuc America. [Online]. http://robot.fanucamerica.com/products/controls/Images/R-30iB%20Controller%20Product%20Information_179.pdf
34. Magswitch. [Online]. http://magswitch.com.au/product/m50-hdc/
35. H.H.Barnhum [Online] http://www.hhbarnum.com/
36. Lumberg Automation. (2015) Lumberg Automation USA. [Online]. http://lumberg-automationusa.com/con/pdf/ASBS2M125.pdf
37. Lumberg Automation. (2015) Lumberg Automation USA. [Online]. http://www.lumberg-automationusa.com/con/pdf/ASBV8LED5242.pdf
38. Automation Direct (2013). [Online]. http://www.automationdirect.com/adc/Shopping/Catalog/Sensors_-z-_Encoders/Photoelectric_Sensors/18mm_Round_-_IP69K_%28Harsh_Duty_-z-_Food_-a-_Bev.%29_%28FF_Series%29/Diffuse_%28FFR3_-z-_FFI7_-z-_FFI8_Series%29/FFI7-BP-1E
39. http://www.cas.phys.unm.edu/rsmith/homepage.html
40. Altair Hyperworks [Online] http://www.altairhyperworks.com/Product,7,HyperMesh.aspx