Implementation of a Robotic Manipulator End Effector for Construction Automation

Aarón Borgo[1,2*], **Arturo Ruiz**[1,2*], **Jiansong Zhang, Ph.D.**[1] **and Luis C. Félix-Herrán**[2**]

[1] Polytechnic Institute, Purdue University, United States
[2] Tecnologico de Monterrey, School of Engineering and Sciences, Mexico.
[*] These authors contributed equally to this research work
[**] Corresponding author

A01251945@tec.mx, A01750408@tec.mx, zhan3062@purdue.edu, lcfelix@tec.mx

Abstract -

The construction industry presents very strong challenges such as being an industry where many fatalities occur, and delivery times have a great impact on the cost of the final product. In this context, an area of opportunity was found, which consist of automating the process of grabbing and nailing plywood sheets in construction site. To achieve this, our previous research proposed an end-effector for a robotic arm capable of performing these tasks. Built upon that end-effector design, a fundamental advancement was made in this paper. Specifically, our focus is placed on the selected robotic arm, and proposing new ways to integrate the electronic and pneumatic systems by making modifications to the initial design, as well as proposing a new manufacturing plan. The midterm goal is to manufacture a complete prototype that meets the requirements about grabbing and nailing the plywood sheets to potentially incorporate it into construction tasks. The use of robotic arms in grabbing and nailing plywood sheets could contribute to reducing construction times and accidents in this industrial sector.

Keywords -

End Effector, Robotic Arm, Plywood Grabbing and Nailing, Construction

1 Introduction

It is well known that the construction industry is one of the most dangerous economic sectors in the world. Based on the Occupational Safety and Health Administration (OSHA) statistics, of the 4,764 workers who died on the job in the United Stated of America during 2020, 976 were from the construction and extraction occupations, i.e., 28.48% of the total fatalities [1]. Moreover, according to reports from the Health and Safety Executive (HSE), the construction industry continues to hold the record for the highest number of fatalities among all economic sectors in the United Kingdom [2]. Actually, fatalities related to construction activities increased by 55% from April 2022 to March 2023.

Construction is one of the few industries that has not been able to evolve with technology since most of the construction techniques used today have been used for many years, and most of the work still need to be performed manually. However, a study by Carra et al. [3] states that robots can vastly help in the installation, construction, maintenance, and inspection for the construction of a new building. This finding means that automation could potentially reduce the number of fatalities and could decrease the time and costs needed for a building to be finished; nevertheless this consideration relies on the capabilities of the end effector since it needs to be able to handle different types, sizes and weights of materials.

Nowadays, there is an increasing search for ways to implement robots in construction to support human activities and reduce accidents. This intervention includes from the design of the structure and support for the planning of the project to the visualization of the construction itself. For example, Son and Han reported image acquisition planning for image-based 3D reconstruction using a robotic arm [4]. In addition; Wang, Fukuda, and Shi did a preliminary comparison between manual and robotic construction of wooden structure architecture, verifying the much higher efficiency and accuracy of construction processes supported by robots compared with manual ones [5].

Examples of robots have been reported in the construction of wooden structures [6], but also in steel structures, where different technologies for the automation of steel beams assembly have been studied [7],[8],[9]. One inquiry includes a review of the state of the art with possible future opportunities for the application of robotic technologies in the construction industry, and highlights the applications of robots in support of construction [3]. Another approach has focused on the use of complex robotic systems [10] whereas others have been on mobile robots for construction applications, ranging from grasping small parts [11], to building reduced structures of heterogeneous brick patterns [12]. In all these cases, it has been observed that the end effector is a key element for the successful use of robots in the different construction tasks, so it is a topic of great interest for academia and industry.

There are many different designs of end effectors, but they are still prototypes since it is really difficult to test designs in real life. One example is an anthropomorphic end effector developed by Firth et al. [13], which simulates a human hand that can hold heavy and dangerous items. Another instance is the design of Bae et al. [14], which is an end effector that can support an H-Beam alignment in high rise buildings, as well as the design of Liu et al. [15], which can handle glass substrate at high speeds. All of these innovative designs could potentially lead to safer and more efficient ways of construction.

As an evolution of using robots in the construction environment, where there is a significant amount of human interaction, collaborative robots emerge as a potential choice. The role of industrial robots includes: inspection, welding, spray painting, assembly, among others. In all these cases, human-robot interaction is vital and key challenges for human-robot collaboration (HRC) are task sharing, intent recognition and optimal trade of space and cost [16]. As it is important to understand these challenges, a critical review of HRC in on-site construction has been performed [17], and a new generation of collaborative robots for material handling for the automotive industry is shown in [18], and [19]. In addition, it is important to consider that collaborative mobile robots seek to combine the precision of a machine with the innate cognitive human skills to build structures that are not possible through conventional manual methods [20], [21], [22]. In other words, there are several benefits of HRC, which enables generalized robots to swiftly adjust to the complex and dynamic construction environments.

Furthermore there has been a lot of progress in evaluating the viability of having robotic arms perform simple tasks that occasionally cause accidents. These assignments, like nailing or bolting consume a lot of time, since the same movement need to be repeated many times. Chai et al. [23] created an end effector design which reinforces the beam network by nailing wood slabs. This realization was done with a mobile robotic arm equipped with a camera and a nail gun. First the camera detected where the wood slab needs to be placed, then the robotic arm placed the slab with a nail gun. Wang et al. [24] reported a similar design of end effector, but this design includes a glue dispenser and focuses more on a building method than on the capability of the end effector, so the results are much time saving achieved than if it was made by hand. Jung et al. [25], designed and created a similar end effector, but this time it's not made for wood and nails, but with bolts in steel beams. Their experimental results showed that the force emitted from the end effector was enough for the bolting task, but its time performance was not evaluated. There is also a different approach taken by Cheng et al. [26], who designed an end effector which could dispose nails on a wasted board. They focused more on all the waste that is created when working in construction and how this waste can be reduced to avoid any unwanted accidents or injuries on the job. Each design in each robot focuses on some different objectives, and they have very promising results in their respective areas.

Even though plywood has gained widespread popularity as a construction material due to its capacity to endure moisture and provide strong support, it has little mention in research papers involving robots for construction. Because of its sturdiness and adaptability, plywood continues to be a cost-effective and long-lasting choice for small buildings [27]. Therefore, the herein research seeks to implement a new construction method involving plywood.

The contributions of this research effort are: the design adjustments, manufacture and assembly of the design reported by Zhang et al. [28], which consists of an end effector attached to a robotic arm, capable of grabbing and nailing plywood sheets in place, to take a first glance on how this process could be automated. This manuscript presents a Work-In-Progress regarding the methodology, robot setup, design and implementation of this innovative end effector. It should be noted that the patented design reported by Zhang et al. [28] focused on the design of the end-effector only. In contrast, this research effort focuses on how to adapt the design to a real robotic arm. This task thus requires further design (in more detail) and actual manufacturing of the components/parts to connect the end-effector and the robotic arm, and the final assembly of all components/parts to achieve a robotic system capable of grabbing and nailing plywood sheets.

2 Methodology

The main goal of the proposed method is to obtain a first working prototype for the autonomous construction robotic system newly invented [28]. A series of steps were proposed to reach a functional prototype, based on a need, a motivation and a reported patent. Figure 1 shows the stages of the applied methodology.

As shown in Figure 1, the red arrows represent the path followed for the implementation of the first prototype, leaving aside the vision system, to focus on the structure, electronic components and pneumatic system of the end effector. Besides, the first prototype of the robotic arm was performed, in order to make the necessary connections for its correct operation. As of now, design implementation and robotic arm debugging are being worked on (contoured in red in the flow diagram).

3 Robotic Arm

To know what characteristics the end effector needed to have, an inspection of the robot's characteristics was performed. For this purpose, as shown in Figure 2, the chosen

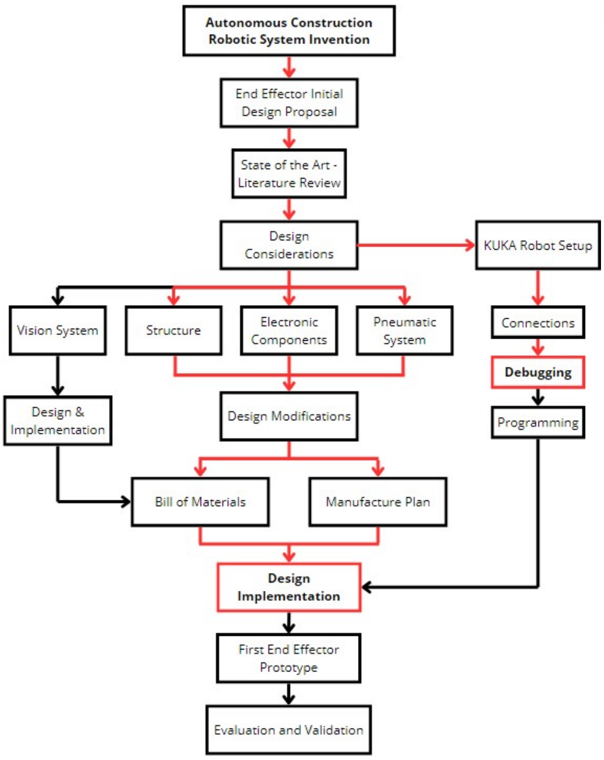

Figure 1. Applied Research Methodology

robotic arm was a KUKA KR 16 L6 with six degrees of freedom with a KR C2 controller. The mechanized system is capable of handling a maximum payload of sixteen kilograms when the center of mass of the payload is less than thirteen centimeters away from the robot's flange.

Figure 2. Robotic Arm KUKA KR 16 L6

Part of the work to be done was to fine-tune the robotic arm, since it has been used for other purposes, and subsequently, it was not used for a couple of years. There were many loose cables and missing connections which indicate the robot had a lot of extra components, so an in-depth examination of this connections was made to ensure the robot could be used as intended, and could potentially add more extra components if needed. Some of the changes that have been made until now are: addition of an equipotential bonding cable, CMOS battery replacement and changing of controller batteries as well as removal of some unnecessary cables. The debugging phase is still in progress, as shown in Figure 3.

Figure 3. Debugging Process

4 The End effector

The design adjustments were performed on the patented design [28]. To achieve the job of grabbing and nailing plywood, the end effector needs to have two degrees-of-freedom (DOF), as shown in Figure 4. It is worth noting that one DOF rotates the plywood and the second DOF moves the nail gun. Moreover, the herein reported prototype focuses on the mechanical, electrical and pneumatic subsystems to ensure the correct movement of the whole system. Once this is done, the robot programming and the vision features of the end effector will be added.

4.1 Design

As mentioned before, the only strict conditions for the design of the end effector are the weight and the distance between the end effector's center of mass and the robot's flange. Under this constraint, the materials that were decided mainly concern toughness, weight and in the case of some special parts, the need to have very low friction. For this first prototype the properties that are expected to have are: the weight for the end effector is six kilograms without the plywood sheet, and with the plywood sheet is twelve kilograms, however this still doesn't take into account all of the electronic, and pneumatic components. These items should not add more than two kilograms to

Figure 4. End Effector Design in CAD

the total weight because many of them are very light and can be arranged in a way that does not add any weight to the payload. The center of mass of the end effector is located 6.6 centimeters away from the robot's flange. This design stage was done with a CAD modeling software.

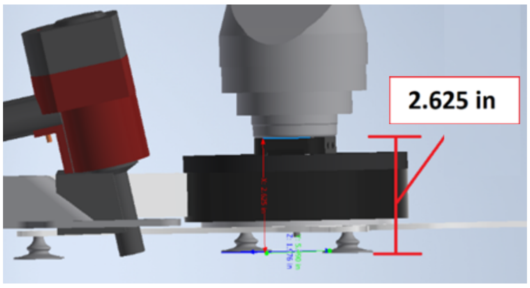

Figure 5. CAD Design of the End Effector. Enlarged View that Allows the Reader to Better Perceive the Elements of the Final Actuator in Figure 4.

The CAD shown in Figure 5 is flexible in terms of payload and the center of mass distance, which is helpful in case there are some major changes in the design. There were some key elements which the whole model was designed from, one of them are the DC motors. They are high RPM motors because these motors have a gearbox capable of delivering the necessary torque to move the components attached to it. This decision was made because these brushless motors are for long-endurance multirotor aircraft, but are designed to be lightweight with high efficiency and consistency, and are much cheaper than servo motors that can provide the desired torque. This way a cycloidal gear was designed for the first motor to be able to rotate the part where the plywood sheet will be attached with a pneumatic system as shown in Figure 5. In addition, the cycloidal gear helps with the location for the center of mass to make sure it is in the required range of the robotic arm's payload diagram.

An aluminum arm is attached to the case that holds the cycloidal gear together. This arm connects to an elbow joint that is also powered with the same motor as the cycloidal gear, but in this case there is no cycloidal gear, instead a planetary gearbox is used. This is done to have less weight on this area, so the center of mass stays closer to the robot's flange. Also this planetary gearbox has a different gear ratio because it needs to have a different amount of torque. On the other end of the elbow joint, there is going to be a twenty three gauge pneumatic nail gun. This part of the design will let the nail gun move around the edge of the plywood sheet where the nails are supposed to be.

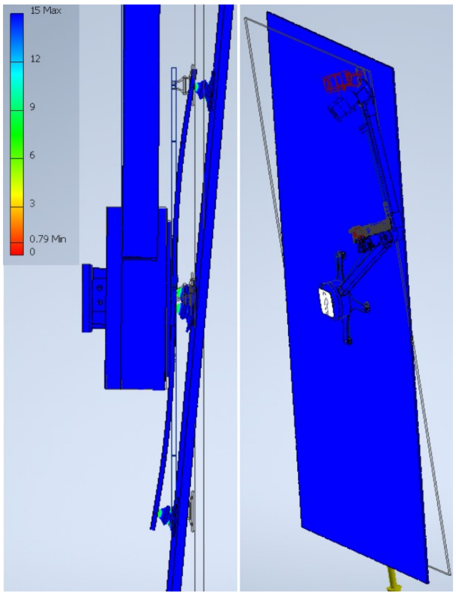

Figure 6. Stress Analysis. Safety Factor Results with Color Scale of End Effector with Plywood (Right) and a Closed-up Image of the Suction Cups (Left).

Furthermore, a stress analysis was conducted to ensure that the materials chosen for this design can handle the plywood's weight, therefore the only force interacting with the design is gravity. The focus in this analysis is the safety factor, and as shown in the scale in Figure 6, there are no elements of concern except for the suction cups. Nonetheless, this study does not incorporate the pressure exerted by the pneumatic system on the suction cups, as this additional pressure often contributes to their sturdiness. Moreover, the data sheet for the suction cups intended for use in the physical model confirms their capability to support the weight of the plywood. In Figure 6, it can also be seen that the design will slightly suffer deformation caused by gravity, but it is greatly exaggerated in the figure since the deformity is less than 0.2 inches when the plywood is in vertical position.

Figure 7. CAD Pneumatic System Implementation

As shown in Figure 7, the pneumatic system involves four suction cups that are going to be connected to four vacuum generators connected to an air supply. The whole system will be connected with a series of adapters and tubes. These selected components are easy to obtain since those are commonly used in the industry. However, this system was designed to be as close as possible to the cycloidal gear because there must be enough space to fit all of the air tubes and adapters, so that the center of mass of the end effector will not be affected by this system, as well as not interfering with the cycloidal gear and the moving arms. This part of the end effector is designed to grab and let go of the plywood sheet.

For this first prototype, the robot, DC motors and pneumatic system, are controlled independently and cannot communicate with each other. Work is underway for making all of the systems controllable by a single laptop (or equivalent) to support the whole automated operation. Some additional adjustments to the design are not rejected either.

4.2 Manufacture

Once the design of the first prototype was finished, and the raw materials were acquired, a manufacture and assembly plan was developed. It was decided for this first prototype to make all of the pieces easy to assemble and dismount in case further modifications need to be done.

For this prototype most of the pieces were 3D printed because most of the parts are new designs, adjustments can be made in an easier and faster way. Polyoxymethylene (POM) or acetal resin was the first option for 3D filament to be used because of its key properties to offer better toughness and lower friction than Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS). However, having successful prints with this filament is not easy nor cheap because of the employed printer properties, and its difficulty for its layers to stick together. Work is underway to pursue successful printings with POM material.

In order to have a better understanding on how the end effector will be assembled, the 3D prints were done with PLA as shown in Figure 8. With a reliable 3D printer filament, using Ender v3 3D printers with the help of Ultimate Cura software high quality prints were obtained. Parts 3D printed in this manner include the cycloidal gear components, robotic arm mount, nail gun mount, motors plus drives cases, elbow joint and rotation segment. All of the pins, bearings and electronics that go with them were left out from the 3D printing.

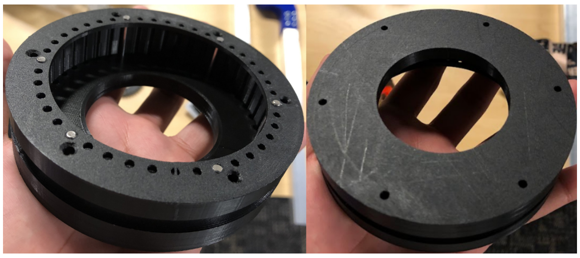

Figure 8. 3D Printed Component

Some pieces have very special material requirements. The elbow joint is planned to have a shaft that will be manufactured with stainless steel disks and rod, since it has to hold the weight of the pneumatic nail gun and an aluminum arm. For the end effector's arms, and suction cups mount, the chosen material was aluminum since there is no need for those pieces to be tougher than steel and they need to be as light as possible. First, the aluminum arms were cut to the desired size using a bandsaw machine. Then, for the manufacture of the elbow joint disks and suction cups mount, a laser cutter was used to make the complex figures needed, with high precision cutting on the stainless steel and aluminum sheets.

For the electronics and pneumatic systems, the selected components are easy to obtain since those are commonly used in the industry. For most of these components there were no modifications needed; however, the length of the cables and air tubes need to be modified to fit the design.

4.3 Assembly

To further discuss the missing details about unforeseen issues, the first prototype was built with the parts that were already manufactured and printed. In this case only the cycloidal gear, elbow joint, aluminum arms and part of the pneumatic system were assembled.

Figure 9. Cycloidal Gear Assembly

The cycloidal gear was the first section that was assembled together as shown in Figure 9. This is because it is the system's portion that may had more constraints once all of the parts were put together. The gear has to run smoothly, and with as less friction as possible to avoid wearing out once it is used with the DC motor. The initial testing with the assembling progress shows that everything is working as expected, but there will be some changes to the design to make the assembling process easier.

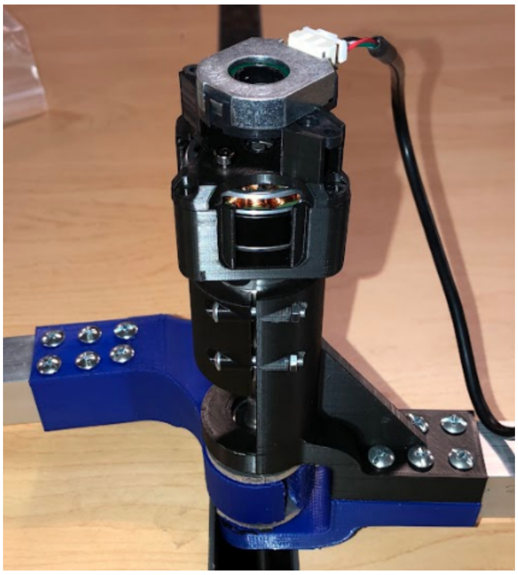

Figure 10. Elbow Joint Assembly. An In-depth Observation of the Elbow and Its Constituent Parts, for an Enhanced Understanding of Components that are Represented in Figure 4.

The elbow joint is the second section that was put together as it appears in Figure 10. This process consisted of joining every part with screws. As of this date the assembly process is almost done since the elbow shaft is the only missing piece to be manufactured.

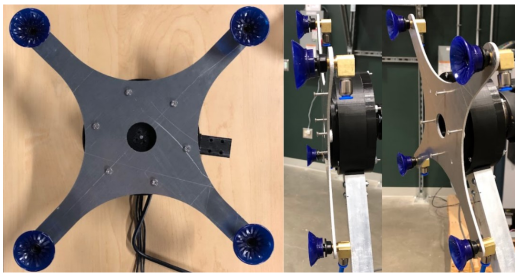

Figure 11. Pneumatic Components Assembly. A Physical Representation of the Implementation of the Pneumatic System as Depicted in Figure 7.

The pneumatic part of the end effector has been the least complex part to assemble since it was outsourced. This component does not need any sort of manufacture process except for the length of the air tubes. This section status is as shown in Figure 11 and there are no unforeseen issues.

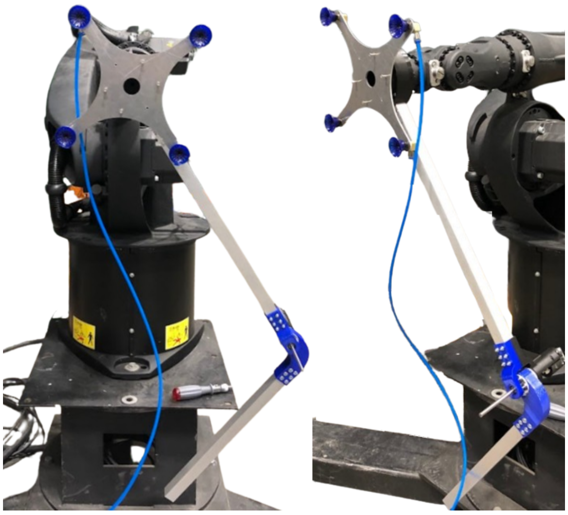

Figure 12. First End Effector Prototype. A Portrayal of the Implementation of the End Effector Illustrated in Figure 4.

Once these components were put together, a first glimpse of the physical end effector can be seen in Figure 12. As of now the majority of parts are within the expected characteristics and properties, and have not suffered major changes.

5 Conclusions and Future Work

Adaptations to a reported end-effector design are presented, as well as progress in the manufacturing and assembly of a robotic arm for grabbing and nailing of plywood sheets with a focus on construction tasks. The outcomes in this research allow to have a better physical visualization, integrated understanding and evaluation of all the components together to finish the implementation of the pneumatic and electronic system. Moreover, the expected specifications for the first prototype involve a weight of less than fourteen kilograms, accounting for the absence of cables and the pneumatic system tubes. Additionally, an evaluation will be conducted whether any material adjustments are deemed necessary once the assembly process is finished. This also allows to have the components ready to be elaborated with a more resistant material to withstand continuous tasks. Moreover, further considerations that need to be taken into account are the need of a cooling system for the motors in addition to having a micro-controller that can connect all of the electric, pneumatic and robotic arm components in order to automate this process once the testing phase is concluded; as well as validations with the complete prototype.

6 Acknowledgements

This work was supported by the School of Construction Management Technology at Purdue University. The authors would like to acknowledge: Dr. Jose Garcia Bravo for granting access to Banton Fluid Power Lab and supporting with the 3D printing process; Dave Kotterman, Built-It-At-Scale Lab Director, for having provided the required manufacturing equipment; As well as Rosita Lopez, Construction Lab Technician, for her help on the procurement process of materials.

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