Adjustments and Assembly of a Novel Robotic End-effector for Construction Automation

Megan Rudo[1], Jiansong Zhang, Ph.D.[2]

[1] Elmore Family School of Electrical and Computer Engineering, Purdue University, United States
[2] School of Construction Management Technology, Purdue University, United States
mrudo@purdue.edu, zhan3062@purdue.edu

Abstract -

The construction industry is currently behind other non-farming industries on the trends of updating technologies, especially in implementing robotic automation in its processes. Because of this, there are numerous opportunities for development of new technologies in the construction domain for automating tasks, lowering risks, and decreasing costs. The focus of this paper was to take a newly patented design for a robotic end effector to build wooden frames and start to build a physical prototype. More specifically, unfinished or nonfunctional parts are updated, and portions of the end effector were assembled.

Keywords

Robotic Automation, End Effector, Timber Construction, Construction Robotics

1 Introduction

It is widely known that construction industry has lagged behind other non-farming industries in its productivity improvement, yet not enough has been done with advancements in technology to improve that in recent years. This research investigates one of the possible solutions through robotic automation, specifically the development of a prototype to demonstrate how a new end effector can help automate the construction of timber frames.

Robotic automation is set out to address different challenges within the construction community such as in improving safety. According to Pinto et al [1], some of the causes of construction safety hazards include large company sizes and therefore a large number of workers to train, constantly changing worksites, worker specialization to one machine or area, insufficient protective equipment, use of drugs on the job, and long-term health problems from the stress of lacking job security [1]. Robotic automation provides a promising solution for mitigating such risks. However, for the last 50 years, limited advancement in robotic automation has come to the construction industry [2], which is notably delayed compared to other industries [2].

In addition to safety risk exposure, the construction industry is also costly, partially due to the number of employees, materials, equipment, and accidents related. It is estimated in a study by Everett and Frank Jr that the cost of accidents in the construction industry has risen from 6.5% in 1979 of total cost of nonresidential construction to between 7.9% to 15.0% in 1996 [3]. That increase, which is at least 1.4%, is millions of dollars that could have been spent on updated technologies. In 2002, it’s estimated that $11.5 billion was spent on injuries in construction [4]. According to the federal reserve bank of St Luis, the average annual cost of construction in the US in 1994 was 530,980 million dollars. In 2023, that average was raised to 2,021,695 million dollars, a 280.8% increase [5]. As projects become more complicated and more costly, the need to mitigate these costs increases. Robotic automation is considered a promising solution. One way to pursue this is to use robots to construct elements that are used multiple times within a project, such as timber frames. Zhang et al. [6] patented a technology in that regard and this paper focuses on implementing the patented technology to an existing robotic arm.

2 Methodology

The goal is to build a working prototype of the patented end effector design [6] (Figure 1) as a proof of concept for companies to adopt this technology in future construction operations. This integrates: (1) a mount for a robotic arm, (2) two rotating shafts enabling it to encircle timber pieces, (3) suction plates for secure wood handling, and (4) a nail gun for efficient timber assembly. This configuration ensures precise and robust manipulation of timber, enhancing the overall automation process in construction tasks.

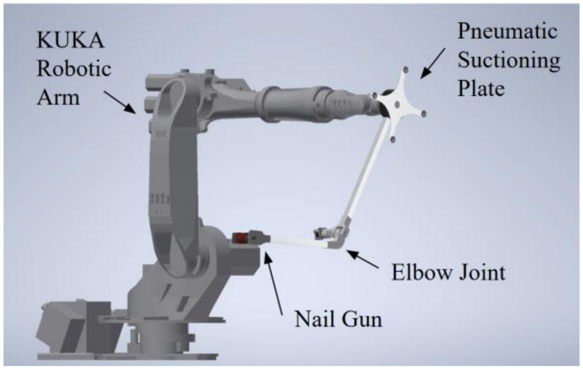


Figure 1: Patented End-effector Design [6]

Figure 2 shows the work breakdown structure of this research, representing all tasks to be completed. These tasks are categorized into design, manufacturing, assembly, electrical, programming, and documentation. The prioritization of tasks was based on assemble sequence (onto the arm), with documentation being produced and used throughout the design iterations. CAD designs and sample prints were used for validation of design.

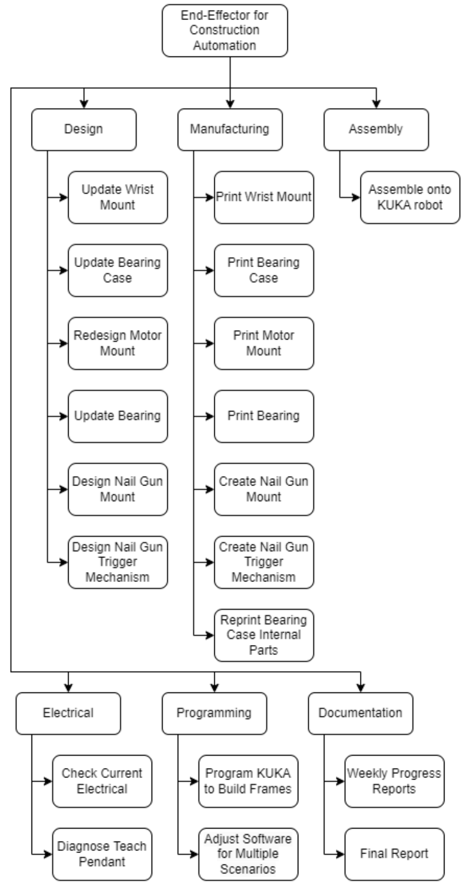


Figure 2: Work Breakdown Structure

3 Previous Research

The researchers chose to use the KUKA KR 16 L6 robotic arm with a KR C2 controller for implementation, following a lineage research [7]. Before powering the robotic arm, an inspection was done to ensure all connections were secure and accurately placed. Although a design for the end effector was almost fully implemented in CAD, the nail gun mount and trigger were not yet designed. All parts of the CAD design had been ordered, printed, or manufactured [2].

4 End Effector Updates

4.1 Design

The first piece updated was the wrist mount, which is a 3D printed attachment that directly connects the end effector to the KUKA's mounting plate. When initially attempting assembly, the screws rested about ¾" above the surface of the wrist mount, making the connection to another bracket impossible. As a solution, the wrist mount was extended, and countersinks were placed (Figure 3). This edit ensures the screws are underneath the top surface of the bracket, so the connecting bracket lies flush on the surface and connecting screws can be placed through the holes between the two.

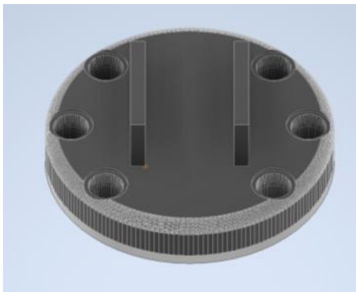


Figure 3: Countersunk Wrist Mount

Since the thin slots in the wrist mount form a weak point, which could potentially snap and cause problems later, they will be connected instead by a solid block. As shown in Figure 4 below, the cutout is now one rectangle in the counterpart to the mount, and on the mount it is a rectangular prism extrusion with holes for the connection screws. For the bearing case, the existing CAD was duplicated and split into two halves, as shown in Figure 5. There are already built-in holes for screws to attach the two pieces.

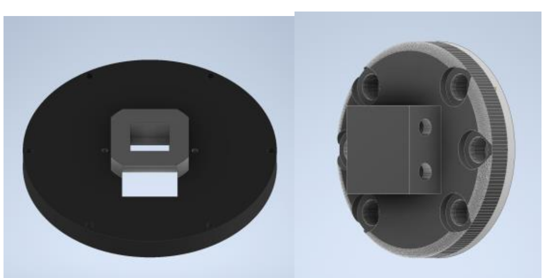


Figure 4: Wrist Mount Updated CAD

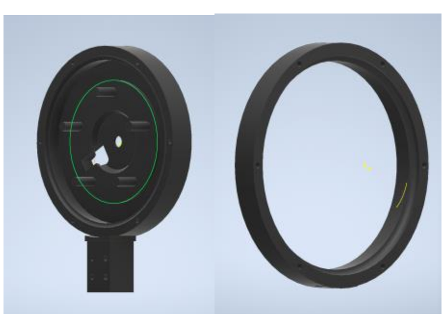
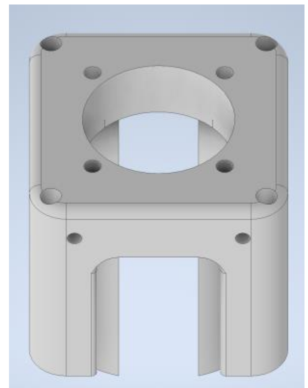
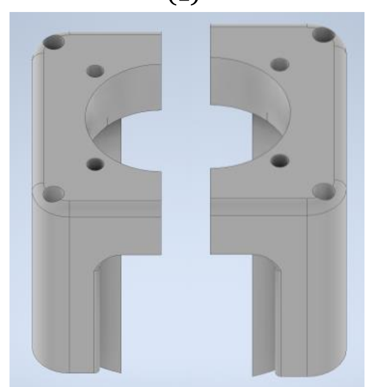


Figure 5: Bearing Case Updated CAD

Redesign of the motor mount was also conducted which is challenging due to small tolerances, yet it still needs to be able to provide ample support for this motor and the attaching encoder. Figure 6 shows the redesign results which extended the previous mount design on both ends by ¼”, and then split in half.



(1)



(2)

Figure 6: (1) Motor Mount CAD and (2) Halved Versions

In addition, two larger holes were added on the opposite sides of the motor mount for the shaft collar adjustment to be possible once the motor is mounted (Figure 7).

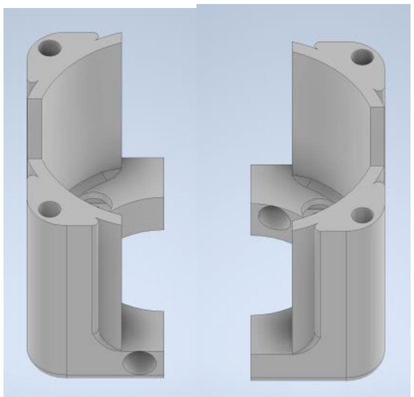
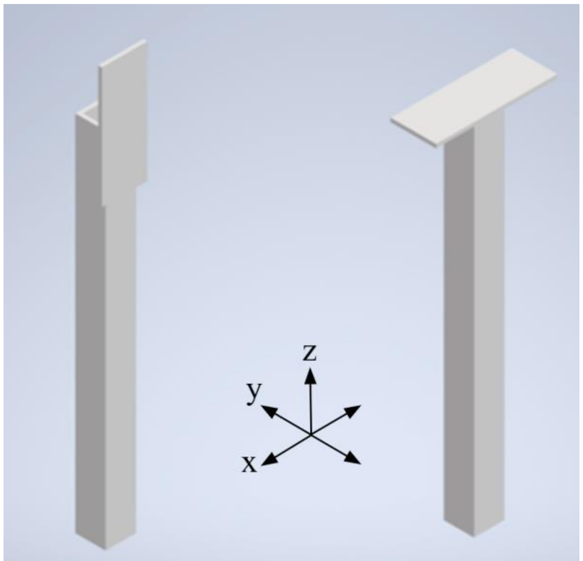


Figure 7: New Motor Mount CAD

The top innermost portion of the bearing case, known as eccentric bearing 2 in previous design [7], was too far off center to fit properly flush with the case due to the off-centered nature of the dovetail joint portion. The outer ring is cut down significantly to ensure its fit (Figure 8).

Figure 8: Updated Bearing

For the nail gun mount, the main concern was the amount of torque applied on the connected arm due to the kickback force when the nail gun is fired. We therefore designed the nail gun to be attached to a metal bar. This needs to be secure, because the kickback force when a nail gun is fired will apply a lot of torque on the rest of the system. Figure 9 below shows how the different mounting positions will affect the direction the kickback force is applied. For the option on the left, the force is dispersed throughout the metal bar, applying torque on the joint the bar is attached to. For the option on the right, the torque is applied directly on the mount for the nail gun and the bar itself. With a sturdy bar and mount, this would be the best option. Our prototype is currently being built with a hollow aluminum bar, which would most likely twist over time with continued use. For long-term solutions, a solid aluminum bar or a hollow steel bar would be good alternatives.



Orientation 1 Orientation 2

Figure 9: Mounting Positions

To address this kickback force issue, the forces were analyzed to determine which direction the torque should be applied to minimize the impact of the kickback force. In orientation 1, the rotational kickback force is applied along the xz plane, possibly bending the metal bar in that plane. In orientation 2, that force is applied along the xy plane, potentially twisting the metal bar in that xy plane. Because the metal bar is hollow, it needs additional support (not shown in figure) in both orientations to prevent damage with use. In orientation 1, this bracket would need to extend along a significant portion of the bar. However, with orientation 2, the bracket only needs to span the top portion (either covering a small portion of the sides or within the hollow bar) to prevent any twisting. Correspondingly, a design was created to mount in orientation 2, but it should be noted that the kickback force could shatter the bearing and might need to be addressed in another design update. This is currently partially addressed by the choices in manufacturing. Since the latest print is made in PLA+ filament instead of regular PLA, it can handle a relatively stronger torque being applied onto it, and with 60% infill and gyroid pattern infill, this has the potential to be able to handle the forces applied in orientation 2.

For mounting the nail gun, the initial conceptual design is to put the nail gun in a fitted 3D printed box, and zip tie it tight.

The very first nail gun mount design is shown in Figure 10. It is a box slightly larger than the nail gun itself, (⅛” walls, inner box 2” x 9.5”) for the gun to slide into with minimal wiggle room. In addition, there is a slot at the bottom of the box for the tip of the nail gun to sit in, and for nails to shoot out from.

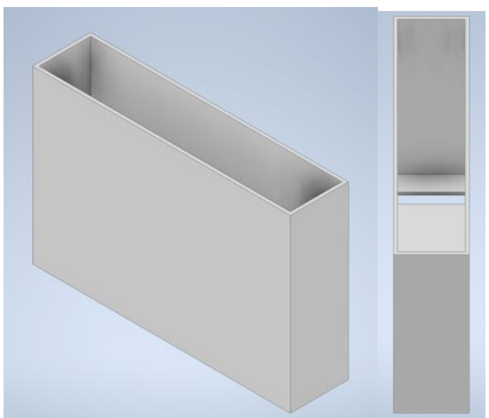


Figure 10: Nail Gun Initial CAD

The updates to the nail gun CAD are shown in Figure 11. For the update to the nail gun mount, 4 ¼” holes were added around the main handlebar for the nail gun. In addition, the slot previously in the design was changed to be a smaller centered hole, in the hope of minimizing any jitter by the gun affecting the aim of the nails, by having that extension of the nail gun more tightly slotted into place. Also, the back corner of the box was cut out just enough to be able to access the nail refill easily, without taking away much structural integrity from the mount.

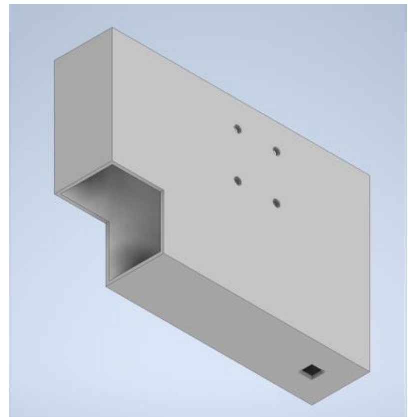


Figure 11: Nail Gun Updated CAD

By making the mount a flat sheet instead of a full box, it will be significantly easier, faster, and cheaper to build. After a few iterations, Figure 12 shows our final design. The updated nail gun CAD from Figure 11 was copied, and then cut to be the back plate only. More holes were then added for security of the nail gun.

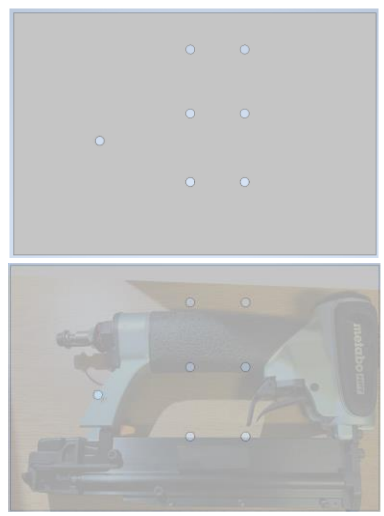


Figure 12: Buildable Nail Gun Mount, Overlay

The nail gun selected has two triggers, as shown in Figure 13. The bottom trigger is a safety, and the trigger on top is for shooting the nail.

Figure 13: Nail Gun

4.2 Manufacturing

3D printing was used for manufacturing. When selecting the filament type, the goal was min/maxing cost/strength. PLA+ presented a good balance, so eSUN PLA+ 1.75mm in a 2.2lb spool was selected, because of its high tensile strength, comparable to that of POM filament but with a fraction of the cost. It is necessary to have high tensile strength on these prints given the amount of weight they will be carrying and the resultant gravitational force being placed, so regular PLA or ABS was passed.

With the PLA+ filament and 60% gyroid infill and supports where needed, the parts were printed (Figure 14).

Figure 14: Finished 3D Prints

In addition, during the 3D printing process, the distance between supports and the print was decreased. This does make the supports more difficult to remove and uses more filament, but it made the printing results significantly better than before so is worth the added effort. The difference between the two prints (white vs red, as shown in Figure 15) is the direction the lines were drawn (linear vs concentric, respectively). The white one came out with smoother finish and less cracking/holes, so it will be the one attached to the build.

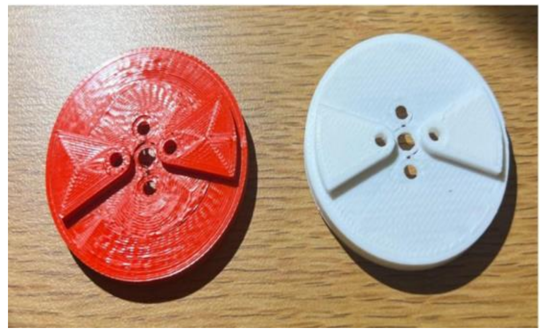


Figure 15: Eccentric Bearing Reprints

4.3 Assembly

Once the prints were completed, an assembly of the end effector was attempted.

Figure 16: Elbow Arm Assembly

Figure 17: Motor Mount Assembly

Parts were sanded down in order to fit in their respected places due to a bit of filament scraps stuck on. For example, both wrist mount pieces have some sharp spots on the corners that were sanded down before sliding into place. The bearing case assembled is shown in Figure 18.

Figure 18: Partially Assembled Bearing Case

Figure 19: Motor Mount Too Thick

Currently attached to the KUKA, as shown in Figure 20, is the wrist mount, bearing, and the encoder and motor.

Figure 20: Current Assembly

5 Conclusions and Future Work

A partially functional prototype of a patented end effector for robotic automation in timber construction is assembled, new and updated parts are added onto the previous design, and a possible solution to the previously reported issue on the robotic arm is identified. For the future, the nail gun mount needs to be built and attached, and aluminum sheet can be used as its material. The electronic parts of the end effector then need to be connected. Once the end effector is fully assembled and connected, the KUKA arm is ready to be programmed with the teach pendant and tested for full functionality. For evaluation at that stage performance metrics include for example a 95% success rate of assembly of the wooden frames and no damage to the end effector after 20 heavy uses.

6 Acknowledgements

The authors would like to thank the National Science Foundation (NSF). This material is based on work supported by the NSF under Grant No. 1827733. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

[1] A. Pinto, I. Nunes, and R. Ribeiro, Occupational risk assessment in construction industry – Overview and reflection. *Safety Science*, 49(5):616-624, 2011.

[2] W. Alaloul, M. Liew, N. Zawawi, and B. Mohammed. Industry Revolution IR 4.0: Future opportunities and challenges in construction Industry. In *MATEC Web Conference*, 2018.

[3] J. Everett and P. Frank. Costs of Accidents and Injuries to the construction industry. *Journal of Construction Engineering and Management*, 122(2):158, 1996.

[4] G. Waehrer, X. Dong, T. Miller, E. Haile, and Y. Men. Costs of occupational injuries in construction in the United States. *Accident; analysis and prevention*, 39(6):1258-1266, 2007.

[5] Total Construction Spending. *Federal Reserve Bank of St. Louis*, U.S. Federal Reserve Economic Data, On-line: https://fred.stlouisfed.org/series/TTLCONS?form=MG0AV3#0. Accessed: 12/30/2024

[6] J. Zhang, M Lacny C., and Reardon N. Autonomous robotic system for placing and fastening paneling material for building construction operations, U.S. Patent Number: 12090628, September 17, 2024.

[7] A. Borgo, A. Ruiz, J. Zhang, and L. Felix-Herran. Implementation of a robotic manipulator end effector for construction automation, In *Proceedings of the 2024 International Symposium on Automation and Robotics in Construction (ISARC 2024)*, Pages 177-184, Lille, France, 2024.