Advances in the Development of a Custom End Effector for Construction Automation

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Abstract –

Beyond increasing productivity, improving quality, performing hazardous tasks and reducing costs, robotics also offers sustainable solutions by optimizing the use of materials and improving energy efficiency. In addition, modern robots are highly adaptable platforms that result in more intelligent systems capable of performing complex tasks. The following article presents the advances in the development of an end effector that promises to be a more economical and efficient option, which is used together with a single robotic arm to allow for the gripping, positioning and fixing of construction panels. The focus of this research effort has been the programming of a digital twin in the Robot Operating System (ROS) framework which allows to analyze the kinematics of the robot and the end effector working together; in addition, the redesign of the physical connectors between the robot and the end effector is also discussed. It is known that nowadays digitization, simulation and the use of digital twins in robotic systems are essential to maximize efficiency and accuracy in the modern construction industry; besides, they have become competitive factors that give added value to construction processes.

Keywords –

End Effector; Robotic Arm; Digital Twin; Construction Robotics; Automation in Construction

1 Introduction

Population growth and urbanization have increased the demand for housing and buildings. However, construction faces a shortage of qualified personnel due to the risks and efforts involved, discouraging young people as the current workforce emigrate, age, or can no longer continue their work due to accidents or other complications. The construction industry is a sector of the global economy exposed to significant risks of workers' health and safety. In general terms, this is a sector with high ergonomic risks in its execution due to lifting heavy weights, handling tools that can be dangerous in their use, and in general, because most of the activities are carried out in environments where there are constantly changing and dangerous situations. Consequently, falls and injuries related to the use of tools and construction materials are relatively frequent.

The high physical demands of construction work, coupled with the prevalence of injuries, underscore the urgent need for innovative solutions to improve safety and efficiency. For instance, the repetitive task of handling plywood sheets, often weighing fifty pounds or more, exemplifies the ergonomic and safety challenges faced by workers. Manual handling exposes workers to risks of back injuries and fatigue, which could also contribute to workflow inefficiencies. Additionally, according to the International Labor Organization (ILO), construction workers experience some of the highest rates of occupational accidents and injuries, the leading causes being falls, being struck by objects, and repetitive strain injuries [1]. Furthermore, just in 2022, the United States Occupational Safety and Health Administration (OSHA) reported over 5,000 fatalities in the construction industry, accounting for nearly 20% of all workplace deaths [2]. Furthermore, non-fatal injuries, which include musculoskeletal disorders and cuts, contribute to billions of dollars in compensation claims, lost productivity, and medical expenses annually, according to the Workplace Safety Index, in 2024, $58.07 billion dollars were invested in compensation for worker injuries, the main cause being excessive physical effort involving external sources, which represents 21.5% of the total [3].

The use of robots and automation technologies in construction is increasingly heard, such is the example of the work conducted by T. Hachijo. and S. Igarashi [4] where they describe the development of an autonomous mobile system of two robots for construction called “Robo-BC”. In addition, incredible advances are seen in the way these types of robotic systems are trained, such as in the case of the work of L. Ci-Jyun and collaborators [5] where they teach a robotic arm to place panels on the ceiling through videos, along with which they call "Learning from Demonstration".

The creation of digital twins continues to revolutionize all industries, A. Ali created a digital twin that identifies dangerous areas and tracks worker movements to ensure safety [6]. Another interesting way to take advantage of the digitalization of cyber-physical systems is the remote control and monitoring of applications where robotic elements are employed [7]. In this context, robotics has proven to be a fundamental ally in addressing the challenges of a society that demands more and more infrastructure solutions that are faster to build, affordable, and with fewer risks for those who build them.

To address these challenges, this research effort focuses on the improvement and continuation of an end effector conceived from the patent of Zhang J. et al [8], which gave rise to the work by Borgo et al. [9], where details of the design and construction of the end effector are provided. This first approach was designed for a commercial robotic arm available on the market, capable of grasping and placing plywood sheets, as shown in Figure 1, as well as manipulating them and nailing them in the context of residential construction projects. By leveraging robotics, the system aims to improve safety, precision and efficiency, thereby transforming conventional construction methods. The overall goal of this work is to create more economically accessible automation tools that improve the safety and efficiency of building construction.

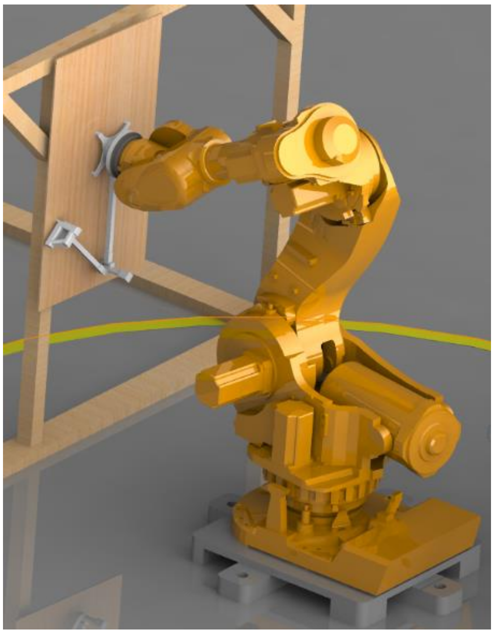

Figure 1. Render in SolidWorks of a robotic arm and end-effector placing a plywood panel on a wooden frame.

2 Methodology

Two significant advances were made in this work, the first advance was to analyze and make updates to the original design of the end effector to improve the robustness of the physical connection to the robot flange. [9]; the second was to use the ROS framework to simulate the motion of the end effector together with a robotic arm to test algorithms safely and inexpensively.

2.1 Observation

A comprehensive review of the lineage project documentation was undertaken to gain a thorough understanding of the target end effector's functionality and goals [9]. In addition, a detailed inventory of the materials, components, and resources available for the project was compiled. With this knowledge, a comprehensive literature review was conducted using SCOPUS as the primary database.

2.2 Proposal

Based on the gathered information regarding the project's current state and available resources, some proposals were formulated to enhance the development of the end effector, culminating in the objectives outlined at the beginning of this article. Besides, a workflow diagram was designed as shown in Figure 2, for the period of August to December 2024 as the proposed allocated timeframe.

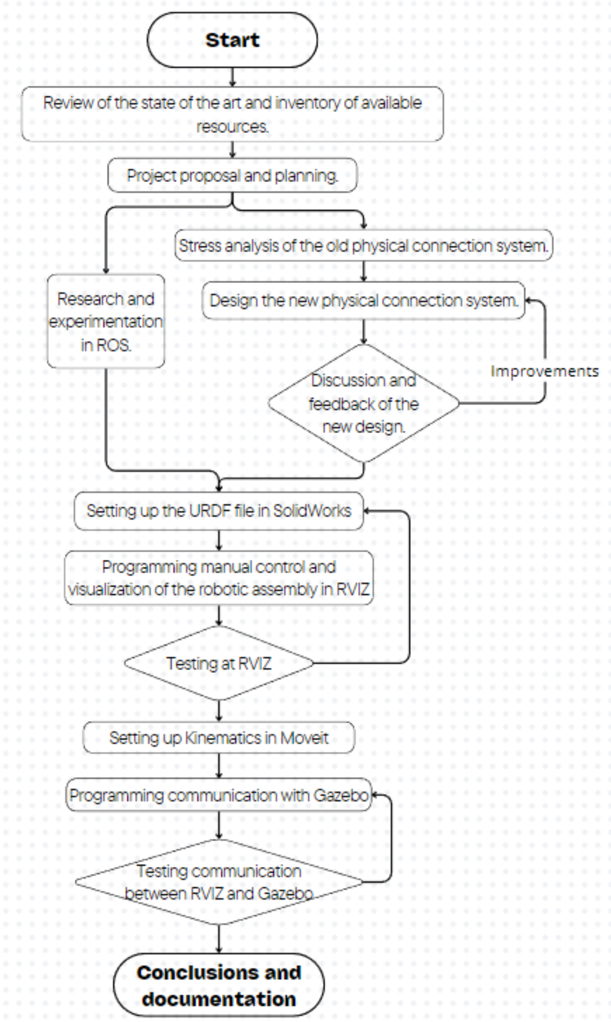

Figure 2. Workflow diagram showing the flow of work performed.

2.3 Experimentation and Results

Research was conducted to learn about the use and functionality of ROS, Gazebo and RVIZ for implementing project digitalization. Also, adjustments were made to the original design to attach the end effector to a new IRB7600 robotic arm, with heavier load capacity and simulating the real-world application better than the previous arm used, as well as certain improvements to strengthen the new component that connects these two elements. Furthermore, several programs were developed within the ROS framework to simulate the joint movement of an IRB7600 robot and the end effector, and some opportunity areas were found to carry out updates on the original design of the end effector. The modifications are aimed at improving performance, expanding the operation and improving the robustness of the end effector.

3 End effector Design

This robotic tool, as shown in Figure 3, possesses two degrees of freedom. The primary degree of freedom involves a rotary vacuum system equipped with suction valves to rotate a cross-shaped piece. The secondary degree of freedom allows the elbow of the end effector arm to rotate, enabling the nail gun to move in two dimensions within a circular area of approximately 4.15 square meters.

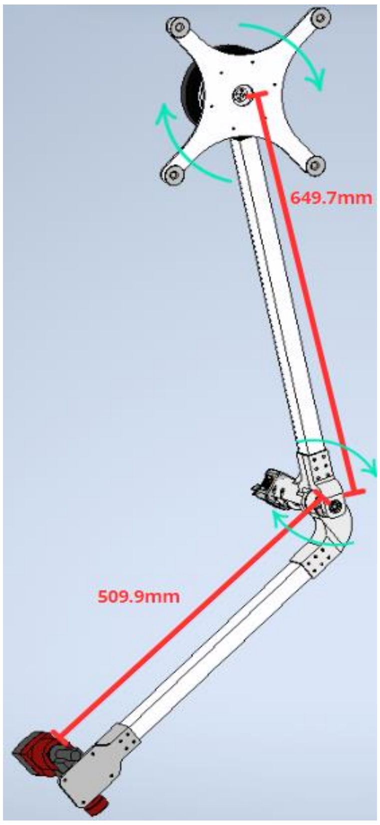

Figure 3. End effector assembly in Inventor.

3.1 Connector Design

The two components that physically connect the robot and the end effector have been redesigned [9]. The initial designs were intended for a KUKA KR16 L6, as shown in Figure 4. This component is attached to the robot's end and features small teeth that engage with the end effector. This initial design highlighted the importance of a simple coupling system that allows for easy separation and attachment of the end effector to the robot. In addition, it offers a cost-effective solution for attachment to other robots, as only this component needs to be redesigned and manufactured to suit the specific dimensions of the robot flange. However, a stress analysis, as shown in Figure 5, where a distributed load of 14 kg was applied, approximately equivalent to the weight of the end effector and an attached wooden panel, shows a critical concentration of stresses in regions susceptible to shear failure. Furthermore, this component is made of an ABS plastic material, which is not flexible, and the two protruding teeth are too thin.

For practical and prototyping purposes, all components were analyzed using ABS plastic, as it is suitable for 3D printing and, unlike conventional PLA, offers greater strength and better temperature resistance. Additionally, ABS is more accessible, and less abrasive compared to materials like carbon fiber. With this approach, the aim is to create a low-cost prototype to validate the design and functionality before manufacturing it in a more robust and expensive material like aluminium.

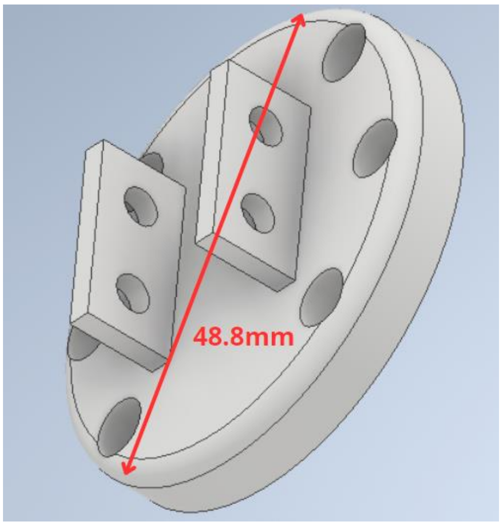

Figure 4. Old connector for the flange of a KUKA KR16 robot.

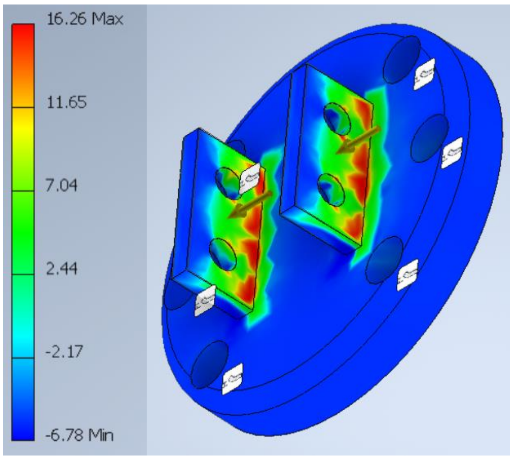

Figure 5. Stress analysis of the old connector. A total distributed load of 14 kg was applied. The color bar indicates the stress levels in MPa.

Due to the above, a new connection system, as shown in Figure 6, was designed to attach the end effector to an IRB7600 robot and incorporate physical features that improve its structural integrity by better distributing the stress caused by the loads, thus reducing the risk of shear failure in this component.

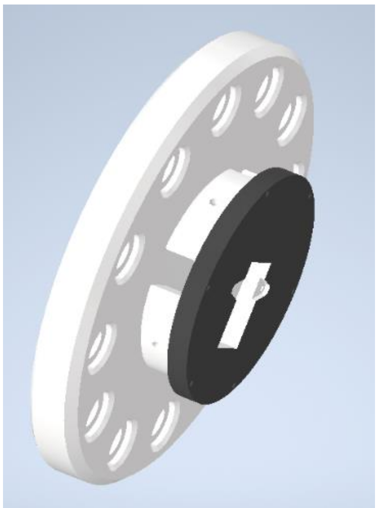

Figure 6. The assembly of the new connection system between the robot and the end effector. The white piece corresponds to the connection with the robot's flange, while the black piece is the base of the end effector.

In this new design, as shown in Figure 7, two additional teeth were added, and the design was smoothed with chamfers and fillets, resulting in a larger contact area and fewer stress concentrators. The original design had stress concentrations of up to 16.26 MPa in critical areas, as shown in Figure 5, while the new connector has only small stress concentrations in non-critical points, reaching a maximum of only 0.705 MPa, as shown in Figure 8. The new design also improves stress redirection during rotation thanks to the circular symmetry of the four teeth. Another notable aspect is that assembly only requires four screws.

Additionally, in this same stress analysis, it was found that the old connector exhibited a displacement of 0.2318 mm in the two connector teeth, compared to the new design, which showed a maximum displacement of only 0.0089 mm. This provides a clearer indication of the improved resistance to deformation and stress accumulation in the new connector. By reducing these factors, the new design enhances durability, especially considering that ABS material has very low flexibility, and the layer-by-layer nature of 3D printing makes it more susceptible to breaking even under slight deformations.

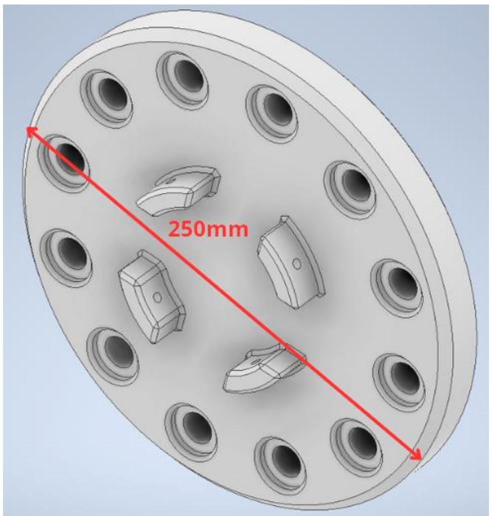

Figure 7. The new connector for the flange of an IRB7600 robot.

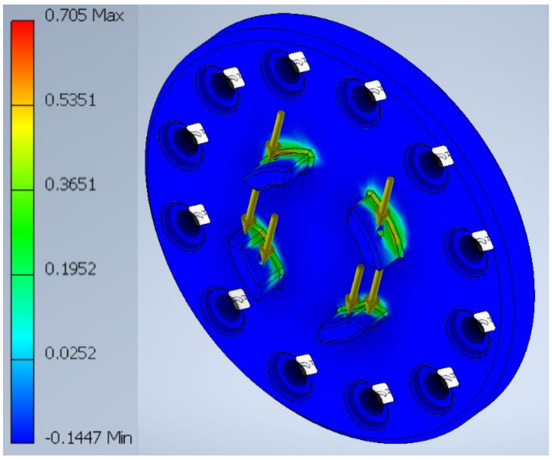

Figure 8. Stress analysis of the new connector for the flange of an IRB7600 robot. A total distributed load of 14 kg was applied. The color bar indicates the stress levels in MPa.

Due to the new robot connector, the end effector connector had to be adjusted, as shown in Figure 9. As with the previous parts, a stress analysis was performed, which shows that there are no stress concentrations at cut points, as shown in Figure 10.

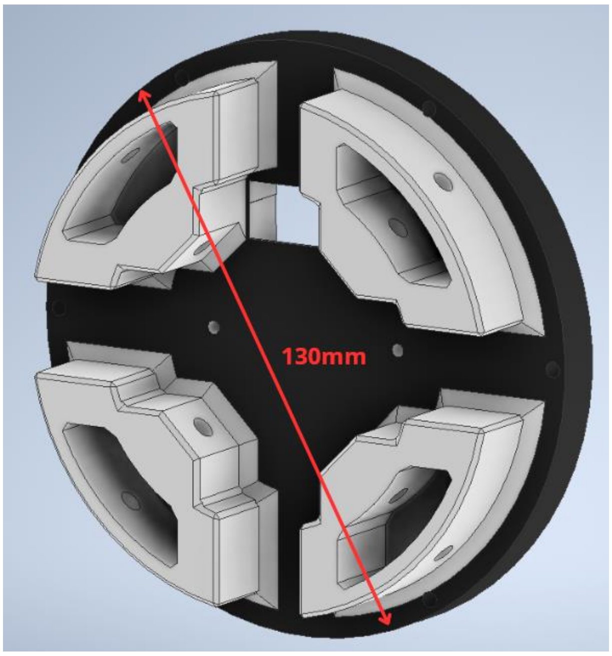

Figure 9. The new connector for the end effector.

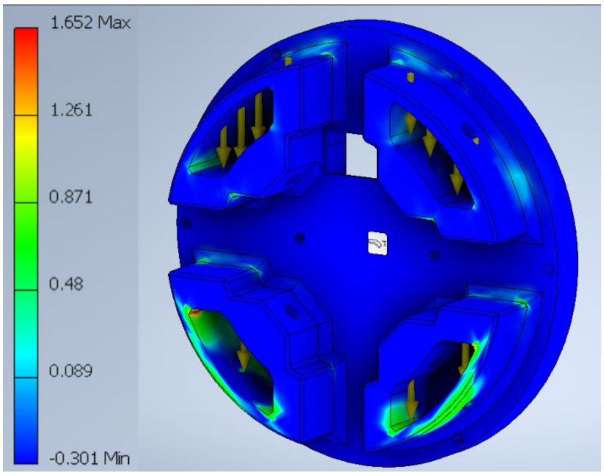

Figure 10. Stress analysis of the new connector for the end effector. A total distributed load of 14 kg was applied. The color bar indicates the stress levels in MPa.

4 ROS Simulation

The ROS structure allows decomposing a robotic system into nodes that communicate with each other through messages. This facilitates the creation of complex simulations and the integration of different sensors and actuators. With this approach, more functions and components are added to the representation towards improving the capabilities of the herein end-effector, all integrated into a single robust and efficient operating system.

After several tests to program and configure the simulation of a robotic arm and the end effector in ROS, three significant advances were reached for this digitization. The first breakthrough was to visualize the robotic assembly in RVIZ, the second was to generate the inverse and direct kinematics of the robot with Moveit, finally, communication to a digital twin in Gazebo was achieved.

4.1 Configuration of the URDF file in SolidWorks 2021

Specialized Software for computer aided design was employed to model and assemble an IRB7600 robot and the proposed end effector. SolidWorks has an extension that allows the use of URDF (Unified Robot Description Format) file where the details of the robot are described, such as 3D models, joints, hierarchies, type of movements, masses of components, inertial properties, collision meshes, among other factors. The IRB7600 robotic arm, as shown in Figure 11, has six degrees of freedom and with the end effector they total eight degrees of freedom.

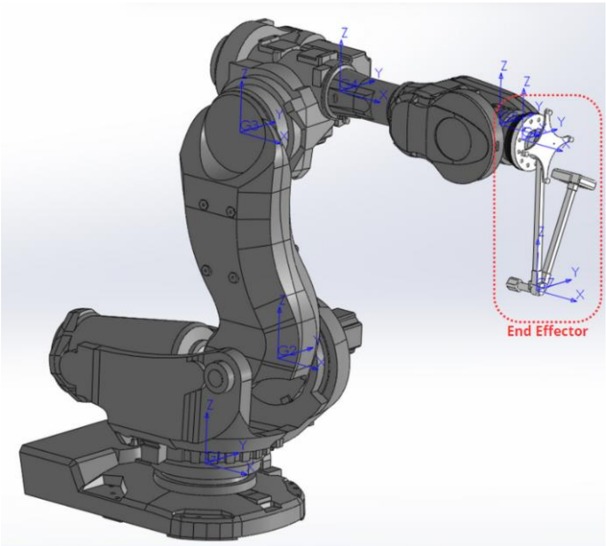

Figure 11. SolidWorks assembly of the IRB7600 robot with the end effector and in blue the coordinates of the joints of both systems.

4.2 Visualization of the URDF file in RVIZ

RVIZ is a tool that allows 3D visualization, as shown in Figure 12, within the ROS ecosystem. Thanks to this, a program, as shown in Figure 13, was designed and coded. In his algorithm, the IRB7600 robot and the end effector are displayed together in the RVIZ environment. In this program it is possible to manually control each of the degrees of freedom of the system independently. To obtain this result it was necessary to generate the URDF file.

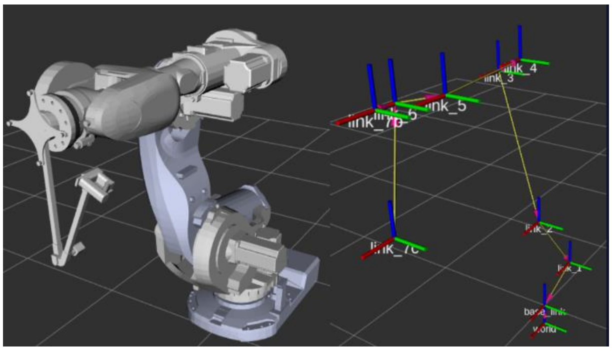

Figure 12. Visualization of the robotic assembly and its kinematic chain in RVIZ.

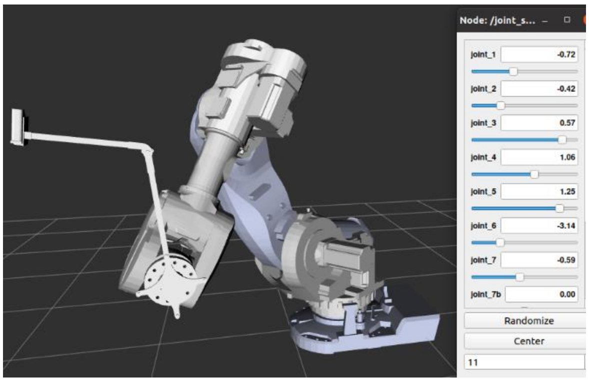

Figure 13. Program visualized in RVIZ that allows to manipulate each degree of freedom of the robotic system.

4.3 Robot Kinematics with Moveit software

The “Moveit” application was used as a framework to create the kinematics and control of the robot and to define some poses to test the movements of the assembly. As can be seen in Figure 14, with this tool the movements and groups of the robotic assembly are planned. In addition, it allows generating YAML (YAML Ain't Markup Language) files that were used to configure the controllers and startup parameters for the nodes.

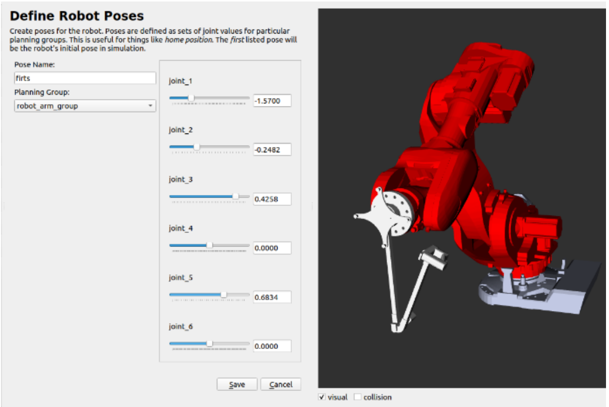

Figure 14. Moveit assistant to define positions.

4.4 Twin communication in Gazebo

This program displays two windows, the first one shown in Figure 15, depicts the robotic system in RVIZ with the displacement and rotation axes of the robot flank. The program calculates the inverse kinematics of the robot, performs several iterations from the original point to the target point, generating a linear displacement between both points.

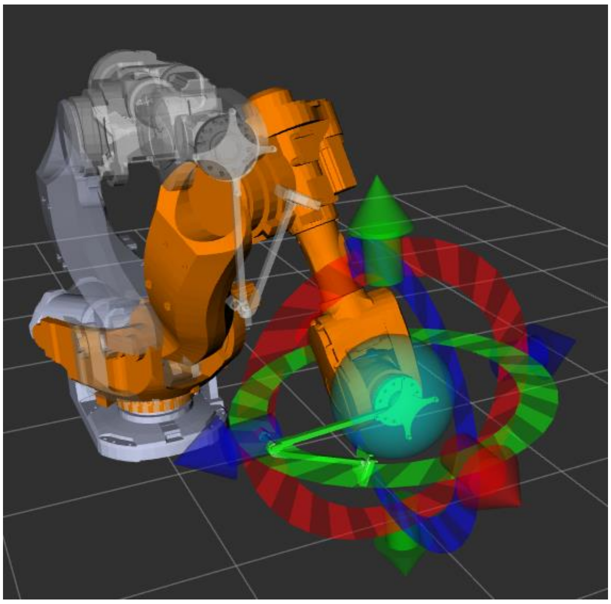

Figure 15. Inverse kinematics of the robotic system in RVIZ.

After the program calculates the robot's displacement path, it performs the movement and communicates it to the twin in Gazebo. This is included in the second window, as shown in Figure 16, and replicates the previous movements.

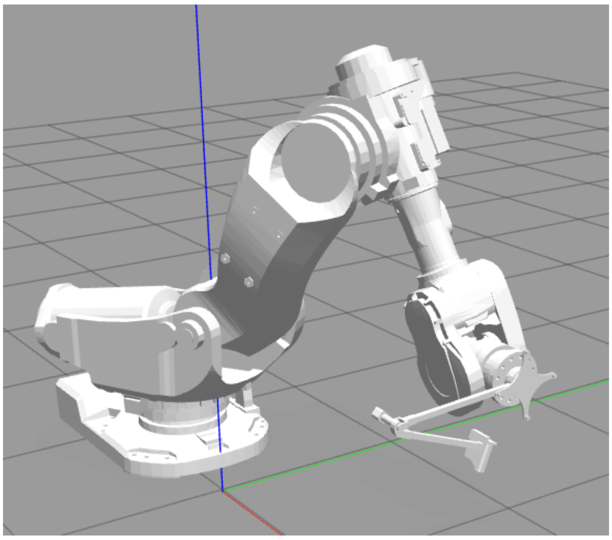

Figure 16. Visualization of the twin robotic system in Gazebo.

Unlike traditional ROS-based simulations, the herein work develops and implements the fundaments of a new frame that integrates ROS for Digital Twin. This integration provides enhanced real-time simulation and visualization capabilities that are not typically available in standard ROS-based digital twin frameworks. In another hand, the proposed approach aims to provide technical capabilities to the ARM and End Effector System for prediction. By leveraging ROS simulation environment, the ability to model and anticipate robotic interactions is improved by enhancing decision-making processes and reducing errors in real-world deployment. Furthermore, although digital twins are broadly used, this work intends to apply this technology to the construction engineering field. To create a training environment for construction workers, allowing them to interact with robotic systems learning process before real-world implementation. This addresses a critical gap in robotics education and deployment in construction.

5 Results and Conclusions

Progress in the design of an end-effector for a robotic arm, oriented to automated construction tasks has been presented. This manuscript introduces the development, analysis, and refinement of a patented robotic end effector for timber construction. Improvements in the design of the connection between the robot and the end effector provide greater robustness due to a larger contact area and better distribution of stress. Furthermore, the connector's teeth allow for easier coupling and decoupling and offer the advantage of physical compatibility with other robots, as it is easier to design a single piece that does not modify the function or structure of the end effector.

During the programming of the end effector and robotic arm in ROS, an inconvenience was found with the current design of the end effector, which prevented it from acting independently of the robotic arm. This represents a problem as it complicates the algorithm necessary to synchronize the robotic arm and the end effector and prevents the same programming from working for a different robot, meaning that the robot's kinematics would have to be recalculated and reprogrammed each time it is attempted to use on a different robotic arm. The implementation in ROS of the proposed solution digitalization brings a new perspective on the project's scope, as it allows for a faster development pace by eliminating the need for a physical robot. This enables safe testing of algorithms, making changes, and adding more features to the simulation.

The time required to recalculate the robot's kinematics may vary depending on its design and degrees of freedom. However, this can be avoided by implementing a design in which the robotic arm's end-effector can be isolated to function independently of the robot. This would also provide the advantage of using the end-effector for testing or other tasks without the need for a physical connection to the robot.

This improved end-effector design will increase the lifespan of the robotic system. Stress concentrations in the critical areas where the end-effector connector and the robotic arm met, were reduced, as well as the deformations caused by the load from the actuator and the plywood. This enhancement will improve task safety and the precision with which the plywood is placed. Furthermore, the automated system will reduce construction times for handling, placing, and securing the plywood, thereby reducing construction costs.

6 Future Work

Thanks to the use of cutting-edge, the kinematic behavior of the robotic assembly has been understood in greater detail, allowing the identification of areas for improvement in the end effector design. As a result, it is planned to make improvements to the original design, leading to a more robust and functional version. It is also planned to continue programming and simulation in ROS, aiming to create a digital twin that integrates other functions such as fault anticipation, maintenance support, and other aspects and characteristics of a digital twin.

As part of the future work, an effort to mitigate the effects of latency and noise in the proposed system could be implemented. Techniques such as Extended Kalman filtering (EKF) and fusion sensor techniques could be applied to eliminate or minimize these issues and enhance system accuracy. Additionally, it is planned to implement robust communication protocols, including I2C, UART, and Serial, to minimize latency and noise in data transmission between the robotic arm and the end effector. These improvements will contribute to a more realistic and reliable digital twin representation.

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