A proposed strategy for automating Intermeshed Steel Connection assembly using robotics

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Abstract – The assembly of steel structures is a complex and labour-intensive process that poses significant safety risks to workers. The Intermeshed Steel Connection (ISC) is an emerging type of structural steel connection that requires fewer bolts and can benefit from the use of robotics. The assembly process for traditional structural steel connections requires humans to work-at-height, which is unsafe and unergonomic, and the few robotic and automatic steel building assembly systems are not readily adoptable. In response, this paper proposes a novel strategy for automating the ISC assembly using off-the-shelf robotic manipulators. The proposed method aims to enhance safety and efficiency by incorporating a collaborative human-robot approach in the assembly process, which leverages computer vision and robotic manipulation technologies. A detailed workflow for the robotic assembly of the ISC is conceptualized by dividing the assembly process into multiple stages. A small-scale experimental setup has been created for future demonstration. The experimental setup includes a scaled-down ISC column-to-column connection, utilizing a KUKA LBR iiwa14 manipulator equipped with multiple cameras and computer vision algorithms for precise alignment and assembly.

Keywords – Intermeshed Steel Connection, robotic assembly, structural steel connections

Introduction

The process of assembling a steel building is a thoroughly organized sequence of steps that ensure the structure's integrity, functionality, and adherence to safety standards [1], [2]. Recent coupling of robotic arms and advanced manufacturing cutting enables a simpler connection that uses fewer pieces, and, thus, may be better suited for robotic assembly in the field. To demonstrate this concept, this paper uses the recently developed Intermeshed Steel Connection (ISC) to illustrate this concept [1], [3]. This section is divided into multiple sub-sections beginning with the steel structure assembly process in section 1.1. Next, section 1.2 describes the state-of-the-art robotic steel structure assembly process. Then, a brief introduction on ISC is provided in section 1.3. Finally, the limitations of the current SOTA and contribution of this research are described in section 1.4.

1.1 Steel structure assembly process

Steel buildings are comprised of individual beams and columns, which are prefabricated in a manufacturing shop floor. These beams and columns are then transported for on-site assembly. After site preparation and foundation installation, columns and then beams are assembled sequentially according to the construction program. Erection and assembly of structural steel buildings are a critical process comprising many uncertain activities [4] and heavily rely on manual labour [5]. The labour cost for assembly accounts for almost 25% of the total steel building cost [6]. Onsite assembly can be divided into four main steps: 1) lifting the structural steel members from storage area, 2) transporting them to the installation area, 3) aligning each member according to the design and with consideration of what is already assembles, and 4) connecting with bolts and/or welding [7]. There are several risks and safety concerns associated with the current assembly process. Human workers must work-at-height for significant periods of time during the alignment and connection steps. Another safety risk is the size and weight of the beams and columns. As per British Standard, the depth in the cross-sectional size of a beam can vary from 127.2mm to 1036.3mm, while for column it can vary from 152.4mm to 474.2mm. Moreover, the length of the beams and columns can be any length up to 12m depending on the design. The weight of beams and columns range from 1 tonne to 10 tonnes based on the cross-section and length. Manipulating these large, heavy objects during the alignment step of the assembly pose safety risks to human workers. In many cases, the human worker must conduct the assembly process by standing on a beam, which is unergonomic and has inherent safety risks, as shown in Figure 1 [8]. The greatest risk of overall structural collapse is during the assembly process prior to the building achieving full stability and strength once all connections are made.

Figure 1 Safety risks of a human working at height during steel building construction [5]

1.2 State-of-the-art (SOTA) robotic technologies used in steel structure assembly

The use of robotics to automate assembly operations has grown in prominence in different industries including warehouse, automotive, and electronics [9]. Robotics have the potential to increase assembly processes' efficiency, precision, and safety by substituting intelligent machine systems that can quickly and accurately complete repetitive tasks, as compared to human labour. In an effort to make steel assembly safer and more profitable, researchers on robotics in the construction industry is a growing field.

The Shimizu Manufacturing system by Advanced Robotics Technology (SMART), is a fully automated construction system for high-rise buildings [10]. The system weighed 1,200 tonnes and required over two months to install. It faced issues with low productivity and financial viability. To address the challenges of transporting large and heavy objects and placing it precisely, a rail-boom robotic system and wire-suspended positioning system were proposed but not implemented [8]. In Korea, a robotic beam assembly system, including a robotic transport control system and a robotic bolting device were developed and tested [11], [12]. However, both proposed systems depended upon the creation of a large Construction Factory (CF) and a guide rail mechanism. To date, while industrial manipulators have been used extensively for automating many repetitive tasks, there are very few attempts to use them for the steel structure assembly process. Work by Liang et. al experimented with a scaled-down Robotic Assembly System (RAS) to automate the alignment and bolting process with an industrial manipulator and specially designed rotational device [7]. The manipulator transported both the beam and rotational device prior to correct alignment with the help of a marker and camera. However, how the system would transport a large and heavy beam was not considered.

1.3 Intermeshed Steel Connection

Although bolting requires assembling a large number of pieces, it is favoured over field welding due to easier installation, quicker connection times, better quality control, reusability, and lower inspection demands. However, the typically high number of bolts necessary for structural connections adds complexity to the use of field robotics. Advances in manufacturing techniques have enabled the development of new steel connections that could significantly reduce the number of bolts required, particularly in column-to-column connections. The Intermeshed Steel Connection (ISC) [1], [2], [3] is one such innovation, designed to speed up assembly and offer the possibility of direct reuse. Figure 2 displays an ISC connection in 3D CAD design software and from previous experimental project. The connection leverages advanced manufacturing capabilities to create precision cuts at the ends of the structural members, which allow a quickly assembled, load transferring connection with fewer bolts and auxiliary members to transfer the various load modalities (e.g. compression, shear, bending).

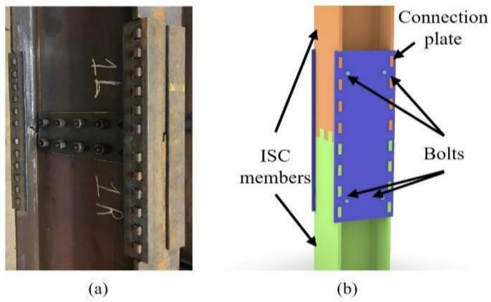


Figure 2 Proposed ISC; a) fabricated ISC with initial design [3] and b) CAD design of ISC with

alternative design with only two connection plates and fewer bolts [1],[2].

1.4 Limitations of SOTA and contribution of this research

Most of the proposed robotic steel structure assembly systems to date require customized robotic devices and structural systems before starting the actual construction. Use of these robotic or automatic assembly systems would require significant changes in the conventional construction method and mindset of the construction company and worker. A new type of structural steel connection, ISC, has been introduced that follows a similar assembly process as the conventional structural steel, but with many fewer bolts, thus lending itself more favorably to robotic assembly. The following research describes the design and experimentation of a robotic assembly process for the ISC using an off-the-shelf manipulator avoiding the need for significant customization. The main contribution of this research will be:

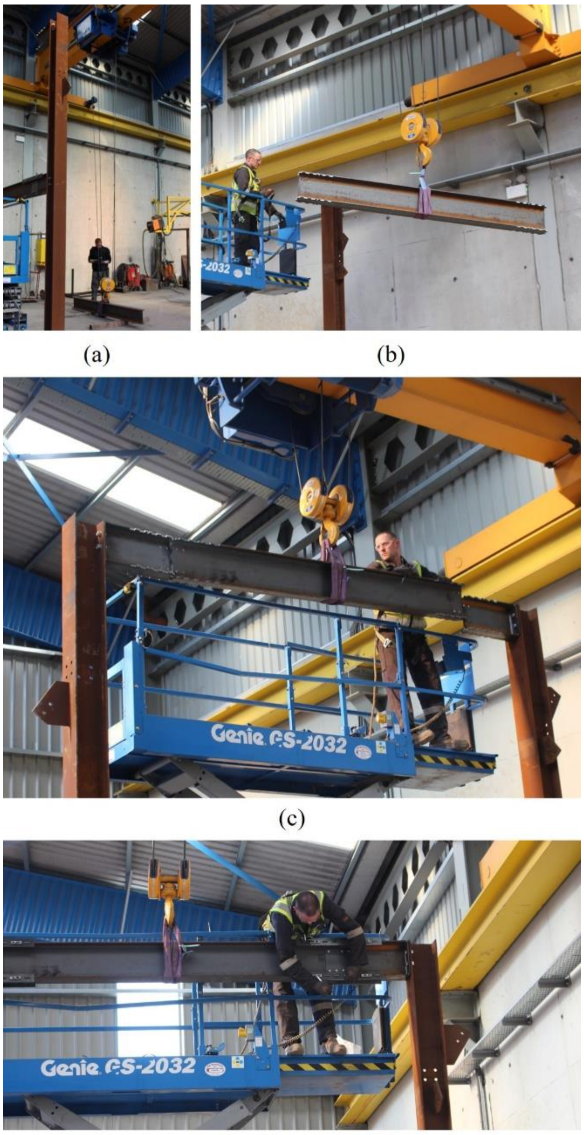
1. Conceptualizing a feasible assembly workflow for ISC using an off-the-shelf manipulator
2. Developing a dummy construction site with small-scale column-to-column ISC for future demonstrations

To place these contributions in context, section 2 of this paper describes more of the ISC assembly process. Section 3 discusses the theoretical framework for robotic assembly of the ISC. Section 4 introduces the proposed workflow of the assembly process, and the final section concludes with the results, the shortcomings, and future recommendations.

2 ISC assembly process

Before conceptualizing and developing the theoretical framework of ISC assembly with robots, it is required to understand the elements of ISC and the manual assembly process. A total of 3 types of elements are required for a complete ISC connection: (1) the ISC member, (2) connection plates, and (3) bolts. Each ISC require 2 structural members and 2 connection plates.

Assembling the members in an ISC requires matching the corresponding grooved sections of the steel members and then locating corresponding cuts that match those on the connection plates' edges. Similar to traditional structural steel members, assembly of ISC require 4 steps (lifting, transporting, aligning, and bolting) [7]. Figure 3 illustrate the steps of manual beam-to-beam ISC assembly inside a lab environment. The assembly process starts with attaching the member with the crane and then transporting it to the designated area as shown in Figure 3(a) and Figure 3(b) respectively. After that, a human worker aligns the member and connection plates (Figure 3(c)) and inserts the bolts (Figure 3(d)). The current ISC assembly process reduces but does not eliminate risks related to human safety and ergonomics. Using robotic technologies to assemble the elements of ISC could further reduce the time and requirement of human working at height and in awkward postures, which will improve safety and ergonomics.



(a) (b) (c) (d)

Figure 3 Steps of ISC assembly; a) lifting, b) transporting, c) aligning, d) bolting

3 Theoretical framework for robotic assembly process of ISC

ISC provides advantages over the conventional connection as it requires fewer bolts and improves the possibility of automation [1]. ISC members contain grooved sections, while conventional structural steel members contain flat ends. With the advancement of sensors, computer vision techniques, and accurate manipulation capabilities of industrial robots, robots have been proven to be efficient in repetitive tasks. With the help of computer vision technology and robotic manipulation, humans can potentially be removed from the dangerous task of assembling ISC. This section discusses the theoretical framework for using robotic technologies in the ISC assembly process.

3.1 Robotic assembly process of ISC

Though the manual assembly process of traditional steel connection and ISC, described in Figure 3, has 4 steps, robotic assembly of ISC will have 5 steps. Third step of the assembly process, aligning, will be divided into 2 steps, alignment and connection plate attachment. The whole assembly process can be divided into three main stages: pre-assembly, assembly, and post-assembly stage as shown in Figure 4.

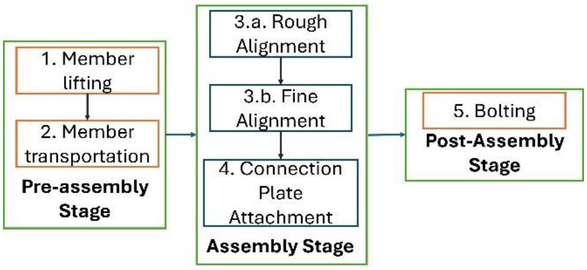


Figure 4 Stages and steps of robotic ISC assembly

Pre-assembly stage consists of lifting and transporting the member to the assembly site with the help of a human operator and crane. With the help of multiple cameras and computer vision algorithms, a robotic manipulator will assemble the member and connection plate during the assembly stage. After the rough alignment, the lateral distance between 2 members of ISC will be around 10-20 cm. but the orientation of the members might be incorrect, as shown in Figure 5(a). However, the rotation, translation correction, and fine placement will be conducted in the fine alignment step, shown in Figure 5(b). Subsequently, the connection plate is attached to the structural members. Finally, a human will put the nuts and bolts in place, which will be considered a post-assemble stage.

3.2 Detail workflow of assembly process

As the steps of assembly and usage of robotic technologies have been determined in Figure 4, this yields a detailed workflow of the whole assembly, as shown in Figure 6. The workflow starts with getting information regarding the member pickup location, assembly location, member size and shape from Building Information Modelling (BIM) through the communication module into the Human Machine Interface (HMI).

This assembly process requires lifting and transporting heavy metals by robot in different stages. Any small error in the robot program or incorrect path planning may lead to catastrophic disaster and cause human deaths. Hence, a strict separation of workspace and task must be maintained for safety reason. The HMI is used to maintain communication between robot and human, initiate tasks, and provide feedback for completion of tasks.

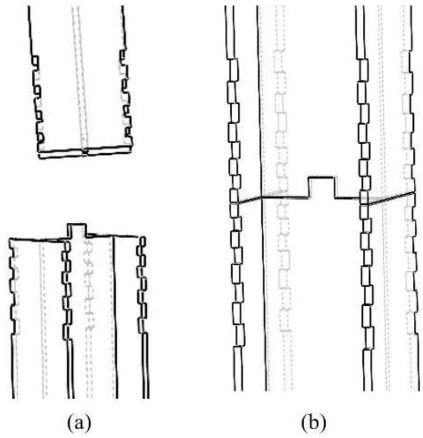


Figure 5 Alignment of members in assembly stage; (a) rough alignment, (b) fine alignment

With the introduction of Industry Foundation Class (IFC), BIM became a popular tool in managing construction projects by representing the information digitally [12]. A human will attach the rope and lifting attachment on the member. Once this is done, the member will be transported to the assembly area from the pickup location with the help of a crane operated by a human. During the whole assembly process, the crane will carry the member's full weight.

In the beginning of rough alignment, a perception module detects the object and determines the pose, with the help of multi-view cameras and trained computer vision algorithms. After receiving pose estimation through the communication module, the robot will move the member to desired location. Control and safety module of the robot will determine the presence of any obstacle in the planned path. If it is unavoidable, feedback will be sent to the operator for manual intervention. Otherwise, the robot will try to finish rough alignment by trying new paths.

To assisting this step, an identity tag will be attached in the grooved section of the ISC members, which will provide better pose information for the robot perception. The perception module will detect and determine the pose of the identity tag to find the exact placement location. The robot will then correct the rotation and translation of the member, while it hangs from the crane. Once both members are aligned properly, the suspended member will be slowly lowered into the exact connection spot as guided by the robot with the help from the crane operator.

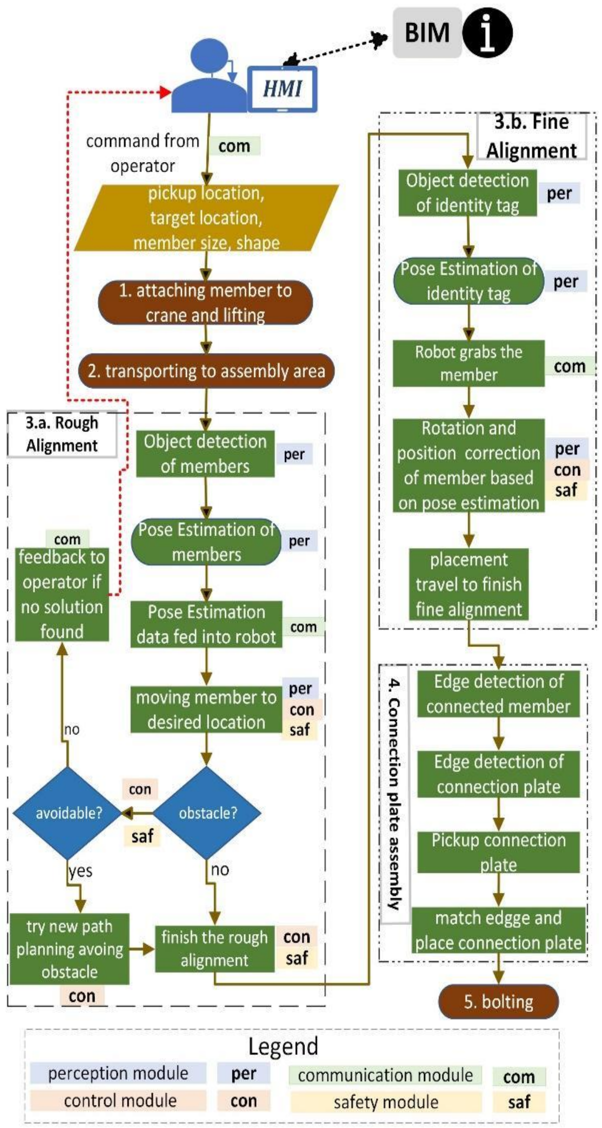


Figure 6 Detail workflow of ISC assembly using robot

The next assembly process step is placing the connection plate. An edge detection algorithm of the perception module will calculate both the edge of the grooved section in the connected members and connection plate. By matching the edges, the robot will align the connection plates on the members. After that, a human will attach the nut and bolts to finish the assembly process.

3.3 Schematic of small-scale demonstration

A scaled construction site along with ISC column members will be developed as a part of the second contribution, which will be used to test the previously described theoretical framework. Figure 7 shows the schematic diagrams of dummy construction site for small-scale ISC assembly with the help of robot. A total of 3 cameras (referred as C1, C2, and C3 in the diagram), will be fitted to create a multi-view perception. One camera will look at the site from top, while the other two will look at the scene from front and back, respectively. Specific areas will be designed for material input and assembly location.

4 Discussion

ISC assembly was divided into multiple stages and a detailed workflow combining manual and robotic steps was proposed.

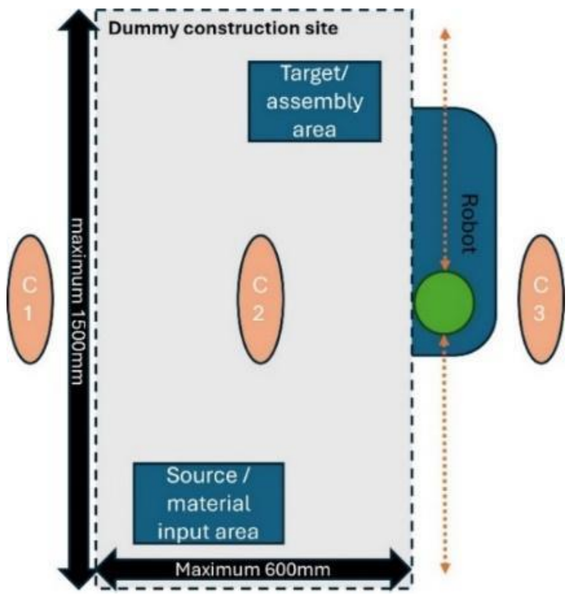


Figure 7 Schematic diagram of small-scale construction site for assembly of ISC using robot

4.1 Manual and robotic process

In this theoretical framework, 2 stages – pre-assemble and post-assemble stage – were considered as manual processes, while the assembly stage was considered as a robotic process. Based on the size of the beam and column, members can weigh up to 10 tonnes and be up to 10m in length. Manipulating such a long and heavy object with an industrial robot is likely to be unsafe. Hence, the lifting and transporting steps in the pre-assemble (Figure 4) stage will be conducted by a human operating a heavy-duty crane. A special end-effector or gripper will be required to perform the bolting operation as bolting operation requires continuous rotational movement with high torque. In the current theoretical workflow, once all the elements are assembled, a human can quickly tighten the bolts which will significantly reduce the amount of time for working-at-height. In the future bolting will also become a robotic operation.

Aligning the ISC members is dangerous as the workspace is tight and at-height, and the object is heavy. During the assembly stage, machine learning based object detection and pose estimation algorithms can provide accurate results. Moreover, while the members are supported from a crane, a robot can guide the members and connection plate in place.

4.2 Robotic module and their functions

As shown in Figure 6, there are four main robotic modules: perception, control, safety, and communication, in the assembly workflow. These modules and their functionality are required in different steps to ensure the successful assembly of ISC.

Perception of a robot is the ability to sense and interpret the surroundings. For the proposed ISC assembly process, multiple cameras will be used to give the robot to ability to see the environment. Moreover, a trained computer vision algorithm will be used for detection and pose estimation of the assembly components. However, classical edge detection algorithm will be used in the connection plate assembly steps.

As ISC is novel type of connection, there are very few real images of ISC which are inadequate for training any CV algorithm. Hence, a hybrid dataset containing real and synthetic images is currently being generated. Performance of the CV algorithm will be tested in the simulated environment, small-scale experimental setup, and full-scale construction environment and the result will be shared with the research community.

The control module works as the brain of the whole system. It will be responsible for path planning of the manipulator to pick and place the ISC elements while avoiding obstacles with the help of perception and safety module.

The safety module is the part of the software architecture that ensures the safety of the robot and human during the assembly process. By analysing the data from the camera, the safety module will be able to determine any static or dynamic obstacles in the planned path. Finally, the communication module will be responsible for transferring necessary information among different modules and HMI.

4.3 Robot transportation

This proposed workflow herein avoids the current strategy of building another structure to support the robotics. However, the currently proposed workflow assembly of the ISC is divided into stages between manual and robotic process and uses human-robot collaboration to complete the assembly process. As part of this, a crane will be used to transport the robot between places to perform the rough alignment and fine alignment during the assembly stage. Ultimately, these tasks are repetitive in nature and can be replicated with robot and computer vision technology.

4.4 Small-scale assembly scene

To demonstrate the proposed workflow of ISC assembly and find affiliated challenges and shortcomings, a small scale ISC column to column connection was fabricated, and an experimental setup was created with a manipulator and multiple scene cameras.

To fabricate the small-scale column connection, universal column dimensions from the BS EN10056:1999 standards were used. One universal column, 305x305x97, was selected, and the sectional depth and width was scaled down to 103mm and 100mm respectively, with a ratio of 1:0.33 compared to the original dimensions. In this installation, the ISC column connection comprises three elements; bottom part (fixed with base), top part, and connection plates.

In the future demonstrations of the small-scale ISC assembly, a KUKA LBR iiwa14 will be used as a manipulator. It has 7 degree-of-freedoms and can lift a maximum payload of 14kg with a maximum reach of 820mm. That manipulator is also equipped with an Intel RealSense D-435i depth camera for perception and a 2-finger parallel gripper from Robotiq. Furthermore, 2 RGB cameras (one in the front and one in the back and one depth camera for aerial view) are attached in the scene. Figure 8 shows the scene setup for a small-scale column-to-column connection for future demonstrations of the assembly process.

4.5 Performance analysis

Few research had been conducted previously [7], [8], [10], [11], [12] to automate the steel building assembly using conventional steel connections. However, ISC is a novel connection type which has emerged from recent research. There was no research found in the literature which use robots or completely manual processes for steel building assembly using the ISC connection. This proposed framework reduces the amount of time for work at height as the lifting, transportation and alignment will be carried out by the robot, as shown in Figure 4 and 6. Hence, using robot will improve the safety of the human worker and reduce the number of accidents.

Accuracy of our proposed assembly process depends on the accuracy of CV algorithm in the detection and localisation of ISC member and ISC connection plate and by extension the robot manipulation in fine alignment and connection plate attachment. Moreover, the overall time required for the assembly will depend on the completion time of each step. As this research is currently ongoing, details on the accuracy and time can be calculated only after conducting small-scale and full-scale assembly.

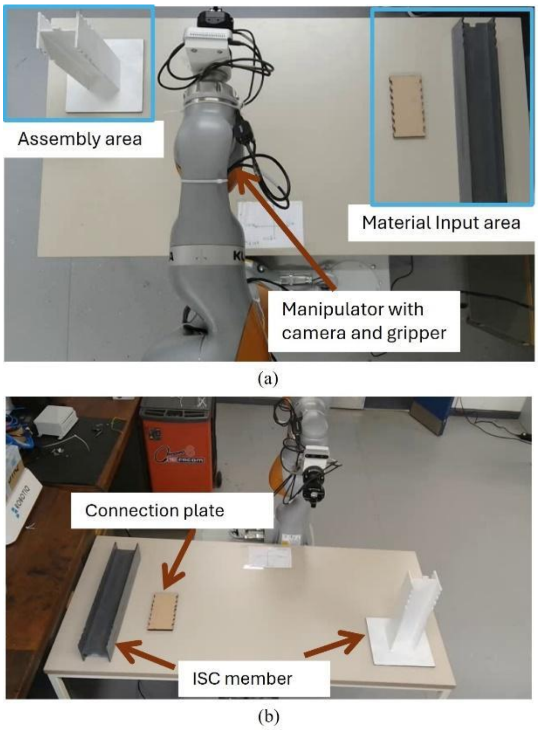


Figure 8 Demonstration scene setup with small scale ISC column to column connection; (a) aerial view, (b) front view

5 Conclusions

This research presents a novel strategy for automating the assembly of Intermeshed Steel Connections (ISC) using off-the-shelf robotic manipulators. The proposed method aims to enhance safety, efficiency, and precision in the assembly process by leveraging computer vision and robotic manipulation technologies. By conceptualizing a detailed workflow and creating a small-scale experimental setup, this study demonstrates the feasibility of integrating robotic technologies into conventional construction workflows without extensive modifications.

The experimental setup, which includes a scaled-down ISC column-to-column connection, highlights the potential of the proposed method to reduce manual labour and improve overall safety and ergonomics. The results indicate that the robotic assembly of an ISC can significantly mitigate the risks associated with human workers handling heavy components at height.

However, the study also identifies several limitations and areas for future research. The current setup is limited to small-scale demonstrations, and further work is needed to optimize the system for large-scale applications. Additionally, the integration of advanced computer vision algorithms and the development of specialized end-effectors for bolting operations are crucial for enhancing the system's performance. Another limitation is the need for a process to synchronise the motion between robot and crane. Future research will focus on refining the robotic algorithms and modification of end-effector for automating the bolting step, improving system integration for robot and crane synchronized motion, design of an HMI for the assembly process command and control centre, and conducting extensive field trials to validate the system's performance in real-world scenarios.

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