Towards Safer and More Efficient Construction – The Development of a Multi-Robotic System for Heavy Block Assembly

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***Abstract*— Construction processes involving placement of heavy construction elements are high-risk activities. Typically, these activities are carried out by a team of masons using a lifting device (such as a crane). Following the technological development of other industries, there have been several attempts in construction to use robots for risky activities. This research work presents a multi-robotic system that consists of robots with complementary capabilities able to perform construction activities with heavy construction elements. The proposed solution consists of a "non-rigid" robot, such as a crane, and a mobile manipulator. The robotic system is able to perform heavy block assembly, while improving safety and productivity.**

Keywords - Robotics; Cooperative control; Bricklaying; Robots for construction; Constrained control.

I. Introduction

In contrast to other sectors [1], construction industry has also slowly begun a development process that involves the gradual use of new methodologies and robotic technologies. Bricklaying is a conventional building technique used in construction for centuries, that requires placing thousands of almost identical blocks together to build walls. Despite continuous evolution of construction processes, bricklaying remained substantially unchanged. Even today, this process is mostly done manually and it requires careful attention as the process itself is quite dangerous and repetitive. Therefore, the predominant motivation to use robots and automation in construction is to increase safety and productivity. Several robotic devices have been developed with the aim of introducing robots in construction. Among them, SAM100 is currently the only commercially available robot for this construction process [2]. This robot is designed to operate in a well-structured environment, as it requires tracks to move around the construction site to perform the construction operations. SAM100 is an industrial rigid manipulator mounted on a mobile base with a gripper that can handle small blocks (in the range of 3-5 kg). Similar to SAM100, ABLR [3] is a mechanical system that works with small blocks (same range of SAM100). A novel parallel-kinematic manipulator (PKM) operating as a CNC machine and equipped with a vacuum gripper and a tool for mortar application is developed in [4]. In [5], a mobile manipulator is being used to build outdoor structures consisting of heterogeneous lightweight brick patterns. All the previous cited solutions are able to work only with small and lightweight blocks, however, the global trend (particularly for large civil projects) is to use big and heavy blocks, which can speed up the construction process. Following this trend, a mobile manipulator is proposed that is capable to handle medium-weight blocks [6]. This robot is equipped with a hydraulic gripper and has a payload capacity of 40 kg [6]. There have been other proposed solutions that were, however, excessively bulky and heavy. Such examples are ROCCO [7] and BRONCO [8]. One of the most advanced robotic prototypes made for construction with heavy blocks is Hadrian X [9]. This machine consists of a big truck with a telescopic arm and a conveyor belt that brings the blocks [9]. It is only used for low-rise buildings and detached houses, and operates in empty and structured environments. Moreover, its adaptability to high-rise buildings and dense urban environments is questionable at its current stage [10]. Recently, a robotic excavator has been employed in constructing free-form stone walls [11]. This robot comes equipped with a shovel and a gripper, suggesting potential applicability for handling heavy blocks. Overall, all the existing solutions can be categorized into two main groups: robots designed for constructing walls with small bricks in either structured or unstructured environments, and big and bulky robots capable of handling heavy brick placements in low-rise buildings within structured environments. *The current solutions for placement of heavy bricks are failing to reach the market as they are not practical due to their enormous size and cost.* This paper proposes an alternative way for a robotic system solution to overcome several limitations of the existing designs used in construction. The proposed solution is based on multi-robotic system, where robots combine their capabilities to perform the task of constructing walls with heavy blocks.

II. Potential Advantages of Robotics in Construction Industry

To explore the potential benefits of integrating robotics into the construction industry, it is crucial to acknowledge their positive impact observed in manufacturing. One notable advantage is the ability to boost production speed and lower the costs [1]. Robots operate continuously, and perform repetitive tasks with consistent accuracy. In addition, robots can operate effectively in hazardous environments such as construction sites.

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A. Robotics challenges in construction

Even if the use of robots can bring some benefits to the construction sector, at the same time, there are several challenges that have to be faced.

The unstructured environment. Construction sites differ significantly from the controlled environments of manufacturing, presenting challenges for existing robotic systems. Adaptation to constantly changing conditions, often in confined and clustered spaces, is necessary [12]. As a result, solutions developed for manufacturing cannot be directly applied to construction without the necessary adaptations to navigate these dynamic and complex environments.

Large scale of devices and construction elements. While the manufacturing industry utilizes rigid manipulators to handle components, construction materials are often much heavier. Simply replicating manufacturing approaches could result in large and heavy robots, as observed in [13].

Strict rules and regulations. Stringent regulations in the construction sector pose challenges for the seamless integration of robotic solutions.

Skepticism. Construction stakeholders, like companies, clients, and regulators, often show skepticism, favoring traditional practices over new technologies.

B. Case study: Bricklaying activity

Despite the challenges outlined, significant efforts have been made to implement robotics in construction tasks, with bricklaying being one such area of research focus. While bricklaying has historically relied on manual labor, recent advancements in robotics have paved the way for automated solutions. Among the different bricklaying activities, this research focuses on sand-lime laying activity. The use of these blocks is very common in many civil construction projects thanks to their mechanical and insulation characteristics [10]. The automation of such construction process has been selected for the following reasons: *i)* economic impact, with an expected boost of company profits by 5% [10]; *ii)* the potential for safety improvement; and *iii)* important contribution to the field of construction robotics.

III. Mechanical design and challenges

Based on the limitations of the current designs highlighted in the introduction, our aim is to find an alternative concept to address the challenges while making use of already existing devices. Specifically, in our research work we developed a solution based on a lifting mechanisms (such as cranes) and robotic arms. Cranes are commonly employed in construction tasks, and their size and design are well-suited for construction settings [14]. Mobile manipulators of an appropriate size that allows to navigate various spots within a construction site are considered. Thus, the main guidelines at the basis of our design were: ***i)* design a robotic solution capable of handling heavy blocks**; and ***ii)* have a lightweight design and be maneuverable**.

Therefore, we propose a multi-robotic system with complementary capabilities. This multi-robotic system consists of a "non-rigid" robot, such as a crane, and a mobile manipulator. While the crane manages macro-movements and sustains the primary weight of the block, the robot arm, mounted on an aerial work platform, facilitates precise block positioning on the wall. A visual representation of the proposed solution is provided in Fig.1 [10].

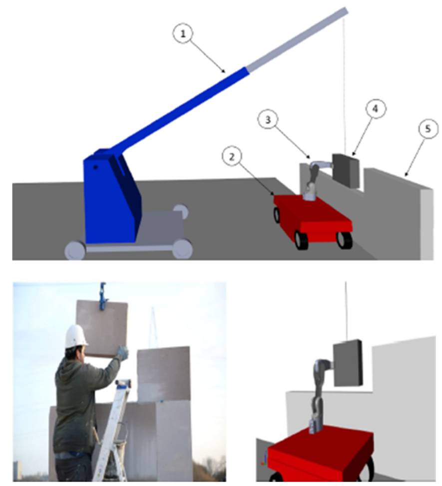

Fig. 1. Layout of the robotic solution. (1) is the crane, (2) the aerial work platform, (3) is the robotic arm, (4) is the heavy construction element, and (5) is the existing wall.

A. Advantages of this solution

By combining the features of the two used devices, the proposed solution not only maintains a compact design (regardless of the heavy loads to handle) but also offers several distinct advantages.

- **Reduced R&D:** The primary focus of innovation and research is on enhancing control solutions within existing matured systems to improve their capabilities in handling heavy loads through cooperative control, rather than pursuing the development of entirely new robotic systems. The use of mature technologies enables faster and less costly implementation and reduces the need for extensive research and development.
- **Flexibility:** The components of the proposed solution, including the crane, aerial work platform, and manipulator, can be deployed independently for a variety of construction tasks.
- **Simplicity over complexity:** Rigid manipulator simplifies block positioning as it dictates the pose of the block, thereby reducing the necessity for complex sensors.
- **Extensibility:** The proposed solution can be used for other tasks requiring precise placement of heavy materials, potentially applicable to other industries. For example, in the assembly of heavy machinery, as well as in naval and aviation construction projects. Moreover, this concept can be deployed to use very large prefabricated elements, by combining a crane and multiple robots.

B. Considerations for the proposed solution

While the multi-robotic solution offers advantages, it comes with considerations. Coordinating multiple agents increases control complexity compared to single industrial manipulators. Scaling for larger objects requires more robotic agents, and ensuring a rigid connection demands a custom gripper solution.

C. Research challenges

Despite the advantages described above, the robotic solution poses some challenges that need to be addressed. Ensuring the safe and correct cooperation between the "non-rigid" crane and the rigid manipulator is crucial. This necessitates careful consideration of how these robots interact with each other. Specifically, through cooperative control strategies, it is imperative to ensure that the robot arm is never overloaded by the weight of the block, with the crane bearing the majority of the load. Additionally, it is essential to explore the precision capabilities of the robot arm to accurately place the block on the wall. Addressing this challenge is of high importance, therefore it will be the focus of this research work, and it will be elaborated on the subsequent sections. Secondly, achieving precise placement and adjustment, particularly for tall and narrow blocks, requires a controller capable of mimicking the skills of a mason. This includes understanding and modeling the interaction between the block and the wall, as well as the application of the glue itself. Note that, the application of the glue can be done using a dispenser integrated with the gripper, similarly to [4]. In our implementations, when positioning the block on the wall we do not take into account the presence of the glue. However, some preliminary analyses carried out show that when laying with sand-lime blocks, the mortar layer is very thin and almost uniform [10]. This will therefore not prevent the control strategy to be effectively implemented. The last challenge is environmental awareness. For such application, the robot must be aware of the surrounding and able to localize itself within the construction site. A promising solution involves the usage of SLAM algorithms based on stereoscopic vision and lidar sensor, as in [15].

IV. Laying activity: From Theory to Practice

As outlined before, the goal is to correctly position a suspended payload that exceeds the maximum payload capacity of the robotic arm alone. In particular, this control strategy must ensure: *i)* correct cooperation between the robot and the crane, to move the block to the desired position; and *ii)* safe cooperation between the two robotic systems while not overloading the robot. To be able to address this challenge, we must first develop a mathematical model, based on which we propose a control solution. We will develop the dynamic model of the multi-robotic system during the phase of cooperation, where the robot arm has grabbed the suspended block and they work together to place the block on the wall.

To do so, we first must express the mechanical configuration of the entire robotic system [16]. By treating the block as part of the crane and assuming secure grasping by the robot arm that prevents sliding or rotational motion, we can consider the combined system as a single entity [16]. This integrated system (i.e., the multi-robotic system), is defined by a state vector $q = [q_r,\ q_c]^T \in \mathbb{R}^n$, where q_r and q_c represent the joint configurations of the robot arm and the crane, respectively, and $n = n_r + n_c$ represents the total number of joints, where n_r and n_c denote the number of joints of the robot and the crane, respectively. Additionally, this system is subject to a set of holonomic constraints $h(q)$, originating from the interconnection between the robotic manipulator and the crane [10], [16]. The dynamic model of the multi-robotic system can be concisely expressed as follows:

$$\begin{cases} M(q)\ddot{q} + C(q,\dot{q})\dot{q} + F_r\dot{q} + g(q) = Su + J_c^T(q)\lambda \\ h(q) = 0 \end{cases}, \qquad (1)$$

where $J_c(q) = \frac{\partial h(q)}{\partial q} \in \mathbb{R}^{6\times n}$ is the Jacobian of the constraints, $u \in \mathbb{R}^{n_a}$ is the control input vector, $\lambda \in \mathbb{R}^6$ is the vector of Lagrange multipliers, and the matrices $M(q) \in \mathbb{R}^{n\times n}$, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$, $F_r \in \mathbb{R}^{n\times n}$, $g(q) \in \mathbb{R}^n$, and $S \in \mathbb{R}^{n\times n_a}$ represent the joint-space inertia matrix, centripetal-Coriolis matrix, friction matrix, gravitational vector, and the matrix mapping the inputs, respectively. Here, n_a denotes the number of actuated joints of the crane system and the robot arm.

To ensure that the robot is never overloaded by the block during the cooperative motion, the torque limits of the robot arm must never be violated. To ensure that constraints are always satisfied, a constrained control scheme is needed. Additionally, considering that the dynamic model (1) is highly nonlinear, we must ensure that the control scheme meets the real-time requirements. A constrained control scheme with real-time capabilities that does not require online optimization is the theory of Explicit Reference Governor (ERG) [17]. This control strategy requires a pre-stabilized system with a low-level controller [17]. In this research work, we propose to use the trajectory-based Explicit Reference Governor [18].

A. Practical implementation

To showcase the capabilities of the proposed robotic and control solution, we conducted a cooperative task in which we considered an overhead crane and a robot arm, see Fig.2 [19]. The overhead crane has two actuators that allow for motion in the x-direction and z-direction, while the robot used is a KUKA IIWA14 with 7 degrees-of-freedom (DoFs). This experiment involves handling a block weighing 65 kg, while the maximal payload of the robot arm is only 14 kg. The control architecture was developed in two external computers: a Windows based machine and an Ubuntu-machine [19], Fig.3[1]. A CAN bus communication was established between these two machines to ensure exchange of information. For pose estimation we use an ArUco board that we have attached to the block. A D456 IntelRealSense RGB-D camera is used, where detection and pose estimation is done using the computer vision library OpenCV. The software aspects were developed in ROS framework using C++, Python, and Matlab. The low level controller (a PD with gravity compensation) runs at 1KHz, while the governing unit at 20 Hz. The low-level controller consists of two

[1]The developed code is available upon request.

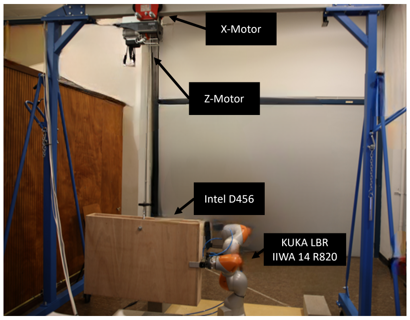

Fig. 2. Robotic prototype consisting of an overhead crane and a robotic arm. Overhead crane has two motors allowing motion in the x and z directions. The robotic arm is a 7 DoFs KUKA LBR IIWA 14 R820. A D456 IntelRealsense camera is used for pose estimation of the block.

nodes: crane_publisher.cpp and kuka_iiwa.cpp, responsible for controlling the crane and the robot arm, respectively. The ERG is implemented in the governing_unit.cpp node. This node ensures constraint satisfaction and at each step time reads the robot and crane configurations and computes the applied reference to be sent to the crane and robot arm low-level controllers. The nodes of the ERG and low-level controllers are run in parallel to ensure that the entire system remains stable while the new reference is being computed[2]. This experiment demonstrates that the multi-robotic system is able to automatically place the block to the desired location, while ensuring that the robot arm is never overloaded, thereby showing the feasibility of this approach.

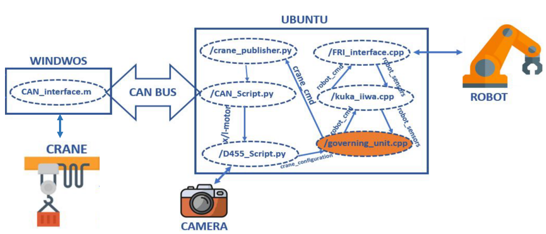

Fig. 3. Robot control architecture. In an Ubuntu machine are implemented the governing unit (/governing_unit.cpp) and the low-level controllers (kuka_iiwa.cpp and crane_publisher.py). The commands are sent to the Windows machine through a Control Area Network (CAN) interface, and then are sent to the crane via CAN_interface.m.

V. Conclusion and Future Lines of Work

The proposed multi-robotic system offers several advantages. Firstly, it allows to use multi-purpose devices. Secondly, the collaborative approach between the crane and manipulator maintains the necessary maneuverability and adaptability required for construction sites. Finally, the cooperative control strategy ensures safety by preventing the overloading of the manipulator while enabling precise placement of heavy blocks. Future work includes integrating an aerial work platform for site navigation, and the construction of an entire wall with the multi-robot. In addition, improvements in vision and sensing aspects for environmental awareness.

[2]A video of the experiment is made available at https://youtu.be/wJWgmQT9NoM.

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