In-situ Robotic Construction: A Technological Approach to Housing Affordability

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Housing supply challenges are looming large, with estimates suggesting a need for 2 billion new homes over the next 80 years to accommodate a growing global population. Governments, including Canada, are striving to address this issue through ambitious housing development initiatives, but the complexity of the problem calls for more than just policy strategies. To meet such targets, radical and fundamental shifts are required across all stages of design and construction. This paper introduces a technological approach to housing through the development of a cable-driven parallel robot (CDPR) as an innovative and alternative method for in-situ construction. CDPRs have the potential to transform current methods of construction, by eliminating the requirement for highly skilled labor, minimizing waste, and significantly reducing costs and construction timelines. Through a cross-disciplinary collaboration between engineering science and architecture, this paper presents the research conducted towards the development of a functional prototype, one that is highly flexible, portable and modular ensuring the provision of a physical platform for construction. As architecture continues to be bound by outdated methods and high costs of construction, bold technological explorations are required to unlock new territories in delivering affordable and accessible housing, representing a significant step toward a future where housing supply can keep pace with the ever-growing population.

INTRODUCTION

Housing supply is one of the greatest challenges we are facing today. The World Economic Forum has estimated that 2 billion homes will be needed in the next 80 years in order to keep up with the world's rising population [1]. Housing shortages have a detrimental effect on communities, leading to overcrowding, the rapid deterioration of housing stock, unaffordable market rents and potentially homelessness. Accordingly, governments are prioritizing housing development in order to meet current needs of its citizens, however, it is important to recognize that solutions for this complex issue won't be achieved through policy strategies alone. To meet such targets, radical and fundamental shifts are required across all stages of design and construction.

Within Canada, the Federal Government has proposed measures in the Budget 2022 to double housing construction over the next decade. This includes a $4 billion investment for the launch of a new Housing Accelerator Fund that will help create 100,000 new housing units over the next five years [2]. In the province of Ontario, the government introduced a new legislation: Bill 23; also referred to as the "More Homes Built Faster Act". This legislation outlines a plan to build 1.5 million homes over a 10 year period as an immediate response to the current housing crisis. Despite these ambitious targets, current output is far below expectation after a year of deployment, and current projections indicate that only 25% of the targeted output will be achieved after a 5-year period. Furthermore, recent studies have indicated that in order to achieve such targets, an additional 70,000 to 100,000 skilled trade workers would be needed in Ontario, at a time when employment in the construction industry is declining steeply [3]. In North America, The Architecture, Engineering and Construction (AEC) industry, continues to be bound by traditional methods and materials of construction, that will only continue to drive the cost of housing to unreachable heights. Intensified by labor shortages in the skilled trades, rising labor costs and short construction seasons (in northern regions), this paper presents an alternative method of construction, inspired by a technological framework for manufacturing and assembly. It focuses on the development of a cable-driven parallel robot (CDPR) as an innovative semi-automated construction system, aiming to accelerate construction and reduce costs, in hope of radically rethinking how we design and construct buildings.

Through a cross-disciplinary collaboration between engineering science and architectural units, the research was conducted over a two-year period focusing on cable robotics and more specifically on the design and development of a CDPR as an innovative and alternative method for in-situ construction. A working CDPR prototype was developed, based on kinematic sensitivity and payload requirements, that is highly flexible incorporating strength, portability and modularity to ensure the provision of a physical platform for construction. Its target application is for small structures such as the construction of single family homes, row houses, coach houses, etc. This is achieved through pick-and-place operations of prefabricated assemblies, driven by a novel end-effector allowing for the multi-rotational positioning of building elements. In addition to presenting the CDPR prototype, the paper will also address the creation of a novel software tool for the control, simulation and verification of the CDPR in order to facilitate architectural design-fabrication exploration.

The work presented herein contributes to the continued development of CDPRs for automated construction applications. Although early in its design and development, it offers insight into the advancement of a CDPR build, as an opportunity to share information to a larger audience interested in its potential as an alternative method for in-situ construction.

BACKGROUND

Prefabricated Architecture - Historical Context

The development of a CDPR as an alternative method for in-situ construction is centered around a prefabricated and modular construction methodology. Despite the perception of being a contemporary method of fabrication, factory-made housing has a long history within architectural practice. During the 1920s and 30s, influenced by the modernist drive for efficiency and practicality, Le Corbusier championed the utopian vision of the home as a living machine, with his focal point being the Dom-Ino House Concept. Conceived in the late 1920's, Buckminster Fuller's Dymaxion House aimed to facilitate rapid assembly, making it suitable for prefabrication in a factory and easy transportation to the construction site. Fuller envisioned that a team of three individuals could assemble the house in under 24 hours. In 1949, Charles and Ray Eames created a custom-designed, prefabricated residence and studio that catered to their unique requirements. They constructed this structure using readily available steel components from steel fabricators, showcasing a model of industrial production. The "Packaged House," a system of prefabricated modular construction, was conceived by Konrad Wachsmann and Walter Gropius in the 1940s. This system consisted of a collection of components that could be assembled in numerous configurations. The method for connecting these components relied on two, three, and four-way connections between panels [4] where every building surface was intended to be constructed using the same panel typology. Despite the inventiveness displayed in the aforementioned precedents, each project faced several challenges that contributed to their limited success. The state of technological progress, perception and stigma, limited design options and resistance from the traditional construction industry were all contributing factors that stifled their implementation at a much larger scale.

Current State of Prefab

Due to the shortage of skilled labor, escalating labor costs, a declining appeal for construction careers among young individuals, and the constraints of short construction seasons in northern regions, the construction industry urgently requires a transformation. This change requires a comprehensive investigation into innovative construction techniques through the adoption of technological advancements.

Other nations have recognized this necessity for change and have initiated the adoption of offsite construction. The United Kingdom, Japan, Sweden, Germany, and the Netherlands have all embraced prefabrication technology, with Japan and Sweden leading the way for the past two decades. In Sweden, it's been estimated that as much as 90 percent of single-family homes are manufactured in factories [5]. In Japan, the principles of manufacturing originally developed by the Toyota Car company to eliminate waste and enhance productivity, have gradually been applied to the efficient production of buildings, with a strong emphasis on the process as a means to enhance the final product.

The research presented in this paper is inspired by a platform approach to design for manufacture and assembly, a concept originally introduced in the manufacturing industry, focusing on two key design aspects: the manufacturing process of a component and how it can be integrated into a final product during assembly. As traditional construction focuses on a "design for use" methodology, these two considerations would require a radical yet attainable retooling of how we design and construct buildings, with focus placed on enhancing production efficiency which ultimately translates to lower construction costs.

Unlike architecture, most industries have embraced technological advancements to increase efficiency and production. In 1908, Ford introduced the Model T, an inexpensive car produced on a Detroit assembly line. The price point of the Model T held particular significance for Henry Ford, who aimed to create a car that could be afforded by the very people working in his factory. He was the first automobile manufacturer to pioneer interchangeable modular components and implement assembly line production techniques. These innovations completely transformed the way automobiles were manufactured and set a precedent for mass production that has been imitated in the automotive industry for a century.

In 1926, the architect Margaret's Schutte-Lihotsky was best known for the Frankfurt kitchen, a system mass-produced and installed in thousands of homes across Germany. Based on a framework of efficiency and workflow, every element was designed to be as compact and economical as possible where units and sizes were standardized. Despite the level of standardization, it used a repeatable "chassis" that allowed for customization and accordingly set the criteria for how kitchens are designed and produced today.

Cable Robotics and Construction

As mentioned previously, the development of a CDPR as an alternative method for in-situ construction is centered around a prefabricated methodology. Its intended goal is to automate the assembly/construction process as a means to significantly reduce construction costs by minimizing construction timelines, reducing labor costs and overall waste generated on-site.

CDPRs comprise a Mobile Platform (MP) connected to a fixed frame via multiple cables controlled by actuating winches. They offer several advantages over traditional industrial robotic arms, including their capacity to cover extensive distances, enhanced mobility, ease of transport, and lower associated costs. While historically employed in tasks such as material/cargo handling, high-speed tracking photography, and live broadcasting (e.g. Sky-Cam) [6], CDPRs have been rarely explored in architectural applications, despite their enormous potential to transform current methods of construction. Prior initiatives, such as the COGIRO cable robot, developed by TECNALIA and LIRMM [7], have demonstrated the potential in industrial settings, while the research conducted by the Institute for Advanced Architecture of Catalonia (IAAC) using this same aforementioned CDPR, focused its efforts on construction tasks, and more specifically large scale adobe 3D printing [8].

In contrast, this research documents the design and development of a CDPR centered around a pick-and-place framework for the semi-automated positioning of prefabricated assemblies. Unlike using CDPRs for other applications, such as those mentioned earlier, adapting this technology for the precise needs of handling prefabricated building components requires a specialized approach in developing the CDPR's architecture and its associated components. This tailored approach introduces its own distinct set of challenges and, simultaneously, opens the door to unique solutions in addressing them.

METHODS

Course Integration

The introduction of the CDPR took place within the context of the M.Arch Craft and Tech Design Studio in the Fall of 2023. This studio was uniquely positioned at the crossroads of technology, ecology, and housing, providing a platform for students to explore innovative housing solutions within an advanced technological framework.

Within this studio, students explored three distinct yet interrelated areas of study: "Prefabricated Architecture," focusing on factory-made building components as a means to expedite and enhance the construction process; "BioBased Materials," exploring natural and renewable materials to effectively decarbonize

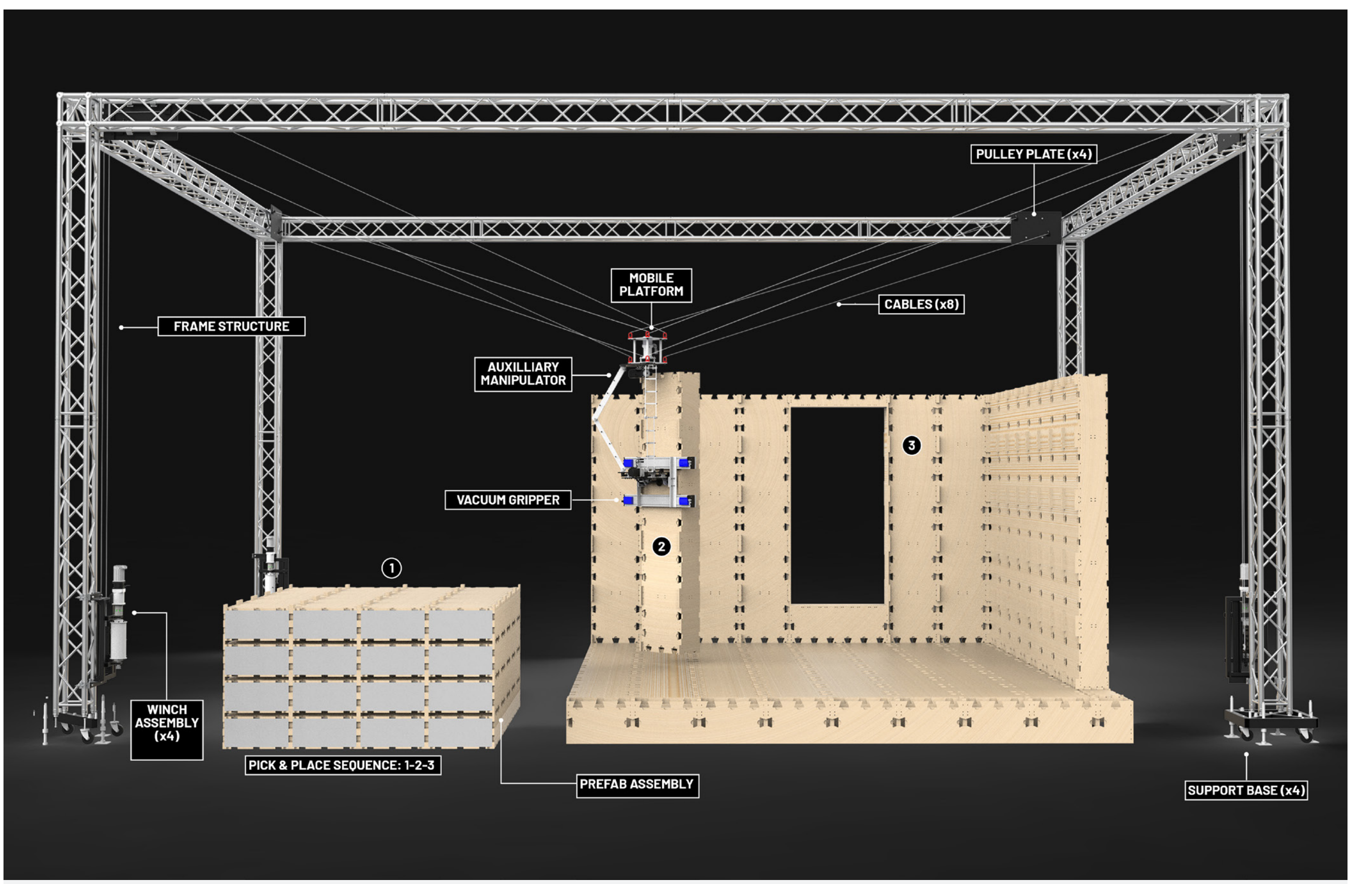


Figure 1. Targeted Prototype (10 meters x 6.67 meters x 6.67 meters). Image by author.

our built environment; and "Construction Automation," which emphasized the integration of advanced technology and robotics, such as the CDPR, to streamline manufacturing and construction processes. By combining these three domains of knowledge, students were encouraged to think holistically about the design and construction of housing. The CDPR served as a practical and tangible embodiment of these interdisciplinary principles, offering an exciting avenue for architectural explorations rooted in advanced technologies.

Accordingly, the technical research efforts, spanning a two-year period preceding the commencement of the Graduate studio, are presented in the following section. These efforts centered on the intricate design and construction of the CDPR, a project that was made possible through cross-disciplinary collaboration between engineering science and architectural research units.

Frame Design

The choice of an aluminum truss structure as the framework for the CDPR stems from its numerous benefits. The aluminum truss components are known for their lightweight nature, simplifying the assembly and transportation of the frame. Additionally, the modular design allows alterations to the frame's size and configuration as needed. Furthermore, readily accessible standard components like clamps, feet, and other accessories add to the convenience of using aluminum truss structures. Consequently, these structures are the preferred choice in the design of CDPRs due to their ease of assembly and wide availability.

The targeted CDPR frame takes the form of a rectangular prism with dimensions of 10 meters in length, 6.67 meters in width, and 6.67 meters in height (Figure 1). In the early stages of our research, we established certain requirements, which included enabling the MP to position assemblies measuring 1.2 meters[4 feet] x 2.4 meters[8 feet] in any orientation while avoiding collisions. To achieve this, the robot had to operate at a height of 4.5 meters. Additionally, the robot was mandated to handle a maximum expected payload of 100 kg, encompassing the weight of the assembly, the MP, and the end-effector.

Owing to spatial constraints in our lab, the Work in Progress (WIP) prototype was confined to a workspace measuring 6 meters x 3.5 meters x 3 meters. Nevertheless, all auxiliary components were strategically designed and manufactured to meet the aforementioned criteria. Once tested and validated in a controlled environment, our intention is to deploy the full-scale CDPR in an unrestricted outdoor setting.

Winch Design

CDPRs, which are a type of parallel robot, differ from serial robots in that they employ flexible cables instead of motor-driven joints for their operation. These flexible cables are controlled by multiple winches, enabling the MP to move in three-dimensional space by adjusting the lengths of the cables. Given that a CDPR relies on cables to navigate in 3D space, it's crucial to maintain tension in all the cables within a certain range to prevent the MP from becoming under-constrained.

The cable actuation system (Figure 2), often referred to as a winch, consists of a motor-driven drum and a level winding mechanism, responsible for regulating the active lengths of each cable to achieve the desired motion of the robot's MP. The chosen robot architecture requires pairwise actuation of the cables in a specific parallelogram arrangement.

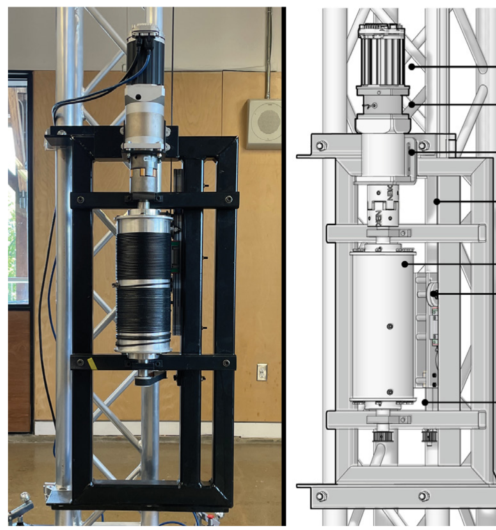


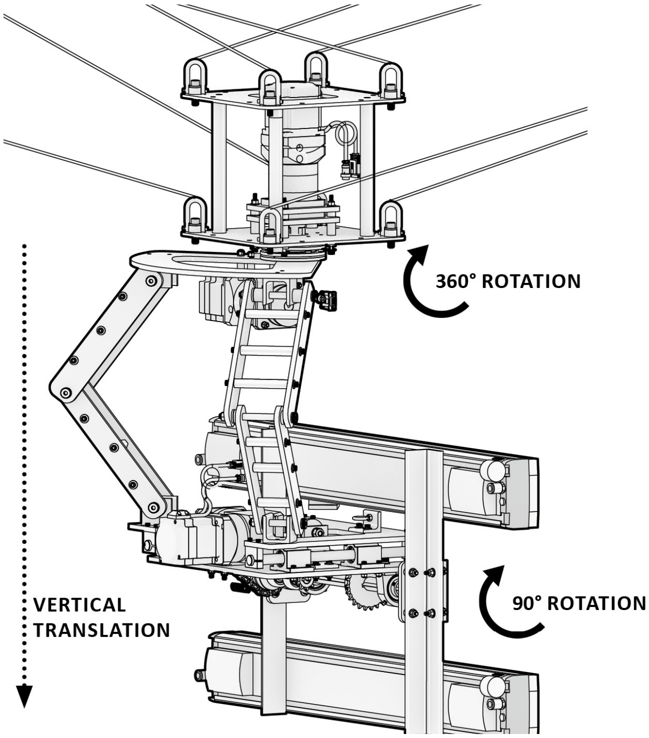
Figure 2. Cable Actuation System. Image by author.

Reorientation Mechanism

As previously mentioned, the CDPR's cables are arranged in pairs, forming parallelograms, with each pair controlled by a single motor-driven winch unit. This arrangement limits the robot's capacity to provide rotational motion. Given this limited ability to generate significant rotations, an auxiliary mechanism attached to the MP became necessary for reorienting panels during assembly.

Although the current CDPR prototype can tolerate external disturbance moments, such occurrences are undesirable due to the potential for uneven cable tension within a specific parallelogram. To mitigate these disturbances, it is essential to maintain the horizontal position of the combined center of mass of the gripper and assembly along a vertical line passing through the center of the MP while manipulating the panel. This prevents any disturbance moments from affecting the MP, making it the primary objective in designing the reorientation mechanism.

Various commercially available manipulators, such as collaborative and small industrial robots, were explored as potential auxiliary mechanisms. However, they were deemed unsuitable



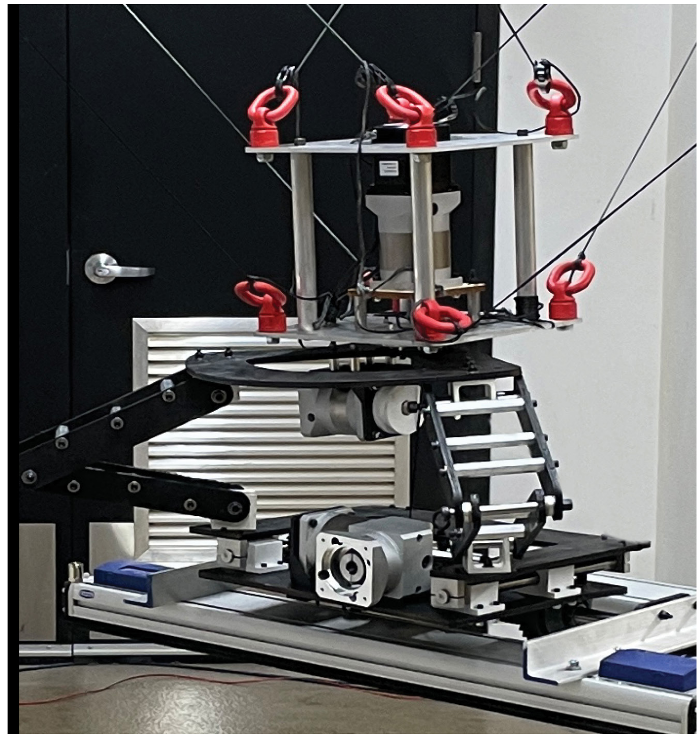


Figure 3. Reorientation Mechanism. Image by author.

for this application. While they could provide the necessary Degrees of Freedom (DoFs) for translation, they couldn't maintain the center of mass constant during the pick-and-place operation. Moreover, they would limit the size of the assembly and overall design possibilities when rotating a panel from a horizontal to a vertical position thus restricting the size of the panels that could be accommodated.

Consequently, a bespoke mechanism was developed to facilitate translational motion while meeting the specified goals (Figure 3). The subsequent stages focused on the development of this reorientation mechanism, which is an integral part of the robot's effectiveness in panel assembly. The selection of the auxiliary mechanism's configuration is guided by the need to provide the requisite DoFs for the designated tasks. As illustrated in Figure 3, to enable the CDPR to perform its intended function effectively, this mechanism must offer 2-DoFs for panel rotation using a vacuum gripper, with one axis oriented vertically and the other horizontally. Additionally, it should provide 1-DoF for vertical translation, allowing the panel to be lowered to avoid potential collisions with the CDPR's cables.

Controller Integration

In this system, the controller plays a pivotal role in managing the movement of the cables. It receives data about the cable's path from a connected computer and translates this data into step and direction signals, which are then relayed to the motors. These motors are equipped with integrated drivers that interpret these signals to determine the necessary motor positions, speeds, and accelerations to precisely follow the desired path. Furthermore, the controller is equipped to receive feedback from the motors, including information about motor torque and any deviations from the intended path.

CDPR Studio

Simulating the CDPR in a design environment before its physical implementation is a crucial step in integrating it into architectural design processes. Software plugins such as Kuka|PRC [9], have empowered designers who may have limited experience with robotics, offering them immense design exploration capabilities. To foster innovation in architectural fabrication while addressing the intricacies associated with parallel robots, a design tool for the control, simulation and verification of the CDPR was developed.

CDPR Studio (Figure 4) was developed as a plug-in for Grasshopper (GH) within McNeel's Rhinoceros software. An earlier version of CDPR Studio was crafted in GH CPython, running on the Anaconda Python distribution. This enabled the use of the NumPy Python library [10] for crucial trajectory and wrench feasibility calculations. However, the Python components in CDPR Studio were found to be performance-constrained, making real-time algorithms unviable. Consequently, an enhanced version of CDPR Studio was fashioned in C#, featuring a suite of GH components. These components are capable of generating trajectories for various fabrication applications, computing forward and inverse kinematics, kinematic sensitivity, and cable tensions within an acceptable range. Furthermore, they provide users with tools to create custom CDPR configurations, including the frame, MP, and end-effector. CDPR Studio also facilitates the visualization of Cartesian space and joint-space trajectories, identifies out-of-range cable tensions, and calculates cable lengths and length changes at every point along the Cartesian space trajectory.

The core components of CDPR Studio comprise the robot builder, trajectory planner, simulation previewer, and trajectory sender. Each of these components accepts specific inputs and generates new data types necessary for the analysis, verification, and simulation of desired fabrication applications, such as pick-and-place or 3D printing.

Robot Builder Components: The Robot Builder allows users to select a predefined frame configuration, MP, and end-effector. It also offers the flexibility to create custom CDPR configurations as needed. Inputs, including DoFs, allowable tension, anchor points, and mesh geometry selection, contribute to generating a preview of the CDPR system. This component assembles the robot system and outputs the system parameters, as well as the mesh geometries of the CDPR components.

Solver Component: The solver component conducts a simulation of the robot before executing the trajectory, producing the CDPR geometry as a mesh and cables as curves. While collision detection was a part of the previous CDPR Studio, it has yet to be implemented in the updated version, owing to development priorities and time constraints. However, it is slated for reintroduction in future updates.

Trajectory Planner Component: CDPR Studio offers two trajectory planning methods. The first, “Curve Trapezoidal Constant-Orientation,” involves moving the MP along a user-defined curve using a trapezoidal velocity profile. Users specify the curve, acceleration, and target coast velocity (in mm/s), with positions and orientations calculated through linear interpolation and spherical linear interpolation, respectively. The second method, “Linear Trapezoidal,” moves the MP between frames using a trapezoidal velocity profile. Users provide a list of frames to traverse, along with acceleration and coast velocity values, and positions and orientations are calculated using linear interpolation and spherical linear interpolation. This component generates a list comprising a series of states required for the CDPR to follow the specified trajectory.

Trajectory Sender Component: The trajectory sender component is responsible for transmitting a cable trajectory to the CDPR Studio firmware, initiating the physical movement of the CDPR. Users simply select the BAUD rate and COM port to set the CDPR in motion.

The ability to simulate CDPR within a design environment, prior to its physical implementation, is a pivotal step in its adoption within an architectural design setting. This software plugin addresses the inherent complexities associated with parallel robots while fostering architectural fabrication innovation. As we continue to refine and expand CDPR Studio, it has the potential to be a valuable asset in the toolkit of architects and designers, enabling them to push the boundaries of CDPRs within an architectural fabrication framework.

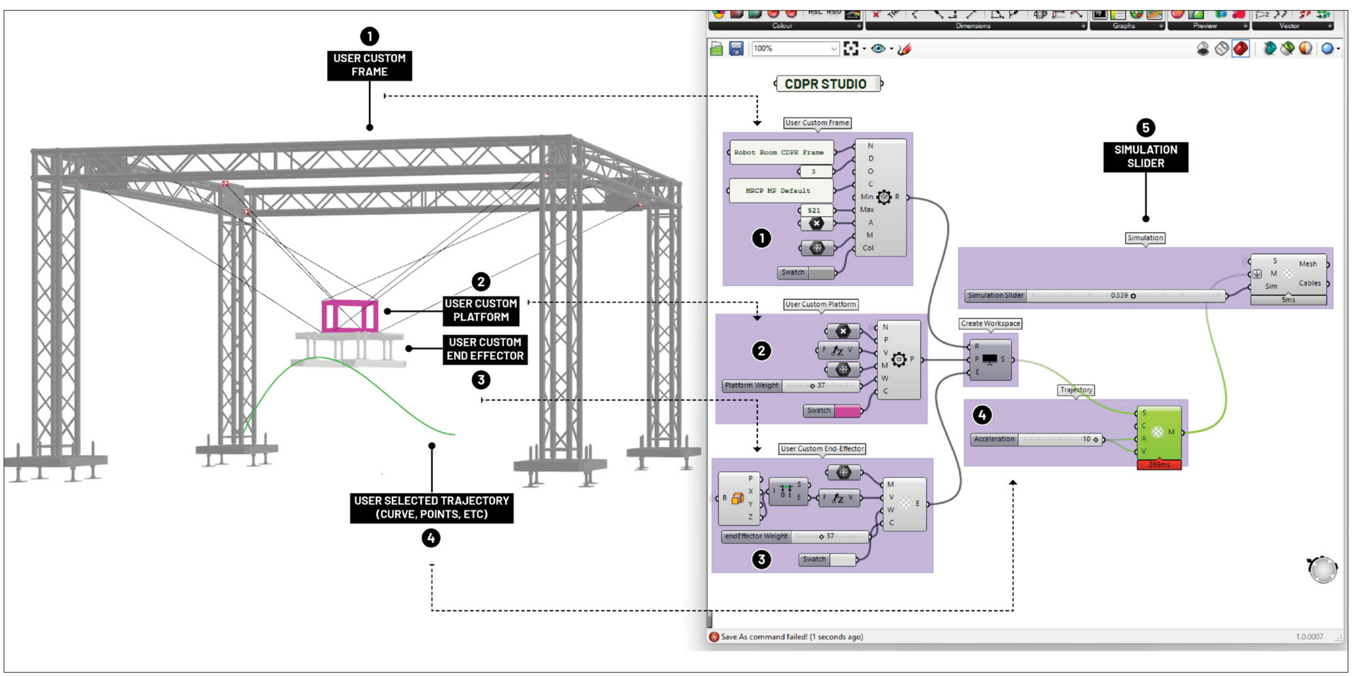


Figure 4. CDPR Studio Plugin. Image by author.

RESULTS

After two years of research, design and development, the first working prototype was completed in the Summer of 2023 (Figure 5). The introduction of this CDPR marked a significant milestone within the context of the M.Arch Craft and Tech Design Studio. Throughout the studio, students began to merge the three areas of study mentioned above into one focused approach where technology, efficiency, cost-effectiveness, and sustainability become core to their investigations. The merger of these areas empowers students to think critically and innovatively, addressing housing challenges, low-carbon construction, and the need for technological advancement in the AEC sector. The design and development of a working CDPR prototype, as illustrated in this paper, was a key contributor to this exploration, exposing students to the potential of technological advancements in architecture, with emphasis on CDPRs potential for cost savings, improved safety and reduced construction time. As technology and robotics continue to advance, the hope is that CDPRs can become increasingly valuable tools in the construction industry.

HOUSING AFFORDABILITY

According to a Construction Cost Survey conducted by the National Association of Home Builders (NAHB), it was found that in 2022, construction expenses accounted for 60.8% of the typical home sale price [11]. Of the major stages of construction: framing, insulation and exterior finishes (excluding windows and

Figure 5. Functional CDPR Prototype. Image by author.

doors) accounted for approx. 31% [12]. The introduction of a CDPR for the semi-automated assembly of prefabricated panels would significantly impact these specific areas. Given that labor represents 50-70% of the costs in these construction stages, automating these processes would present a substantial opportunity for cost reduction, thus having the potential to make housing more affordable by reducing the overall costs involved in these labor-intensive processes. Nevertheless, the extent for cost savings through reduced labor expenses, particularly with the use of prefabricated components manufactured in a controlled environment, is an area that warrants further investigation. This research, currently underway, is necessary to evaluate the extent by which the financial benefits derived from minimizing labor costs through semi-automated assembly effectively exceed the expenses involved in producing prefabricated elements in a controlled setting. In addition to potential cost savings, the use of a CDPR within a prefabricated framework allows for more accurate material usage, minimizing excess and waste and thus represents a significant step towards more responsible, efficient, and sustainable building practices.

LIMITATIONS AND FUTURE DEVELOPMENT

Designed for a workspace spanning 10 meters in length, 6.67 meters in width, and 6.67 meters in height, the CDPR is geared towards the construction of smaller structures, including single-family homes and row houses. Challenges in vertical construction for multi-unit housing, achieving precise positioning throughout the assembly process, overall speed of assembly across large areas, and the ability to adapt to complex geometries are areas that will necessitate additional research and will be key focuses during the testing phase of the full-scale prototype.

Nevertheless, current developments are underway aiming to combine a motion capture system with a Robot Operating System (ROS), which will enhance the CDPR's control, navigation, and object manipulation capabilities. Accurate motion capture systems can provide real-time information about the robot's position and orientation, enabling it to move more precisely within its environment. This will ensure safe and efficient CDPR operation by helping it avoid obstacles and stick to planned paths. This would also assist the robot in accurately locating unique prefab panels and determining the correct and most efficient sequence for placing them.

CONCLUSION

In conclusion, the housing supply crisis is a pressing challenge that necessitates innovative solutions beyond policy strategies. This paper proposes an alternative approach to construction, driven by technology and automation, to address the housing crisis. The focus is on the development of a CDPR, a novel semi-automated construction platform designed for faster and more cost-effective building processes. Through a two-year cross-disciplinary collaboration between engineering and architectural units, a working CDPR prototype was created, emphasizing flexibility, strength, portability, and modularity, together with a software tool for controlling, simulating, and verifying the CDPR in order to facilitate architectural design and fabrication exploration.

This work contributes to the ongoing development of CDPRs for automated construction applications. While still in its early stages, it offers valuable insights and the potential for a transformative alternative in in-situ construction. By sharing this research, we aim to engage a broader audience interested in the possibilities of CDPR technology as a solution to the housing supply challenge.

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