Heliyon 8 (2022) e11039

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Robotic construction analysis: simulation with virtual reality

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ARTICLE INFO

Keywords:
Robotic construction
Virtual reality
Drone
Robotic arm
Construction simulation
Assembly

ABSTRACT

Advances in robotic construction are evident and increasing every year, bringing present and potential improvements. However, the economic and social impacts are hard to assess and quantify without physical in situ testing, which is expensive and time-consuming. This paper presents a methodology for the simulation of robotic construction technologies, namely drones, using a virtual reality environment. Our hypothesis is that a virtual reality simulation of a robotic construction (H1) has the potential of increasing the precision of predicting the construction duration and cost and (H2) allows for the detection of construction problems. The study begins with a review of the literature on drones, robotic arms, and hybrid automatic construction solutions, as well as virtual reality construction simulations, summarising the robotic technologies currently being used, mainly in academic research, to assemble construction elements. It then proposes a construction simulation methodology applied to three architectonic elements to analyse different approaches and different scenarios for robotic construction simulation methodology. A construction simulation is tested, and the data is analysed and compared with traditional construction methods, focussing on construction time and costs.

1. Introduction

This paper is part of ongoing research into the use of robotics in the building construction industry which involves investigating the possible use of robotics (drones and robotic arms) in a new building context and using a new methodology. The subject explored in the paper, namely a virtual reality (VR) simulation of a drone building methodology, is presented as the first step towards anticipating and preventing future problems in real-life robotic construction.

Robotic construction is likely to change the current construction paradigm [1, 2]. The new paradigm will prompt the construction industry from the Third Industrial Revolution, closer to the level of automation of other more technologically advanced fields such as the naval and automobile industries. These industries have been using robots for several decades for a wide range of tasks with far-reaching consequences. In the automobile industry, for example, the luxury brand Lexus uses a fully robotized assembly line since 2000 [3].

Despite the transition underway in many industries from the Third to the Fourth Industrial Revolution, referred to as Industry 4.0, the construction industry is still based on traditional building techniques that are time-consuming, expensive, and more prone to error during the building process. In the current economic and ecological context it is vital that more technological approaches to construction start to change the construction processes, introducing more efficient and sustainable methods empowered by modern technologies, allowing for diversity and innovation in the built solutions [4].

In recent decades, major developments have taken place in the world of robotics and technological advances have been employed in a wide variety of tasks. Nowadays, depending on its main function and tasks, a robot can have many forms and operate on scales ranging from domestic to industrial, medical, security/defense, educational or entertainment. These robots may be humanoid robotics, animal robotics, drones, robotic arms and exoskeletons, among others developed for specific purposes [5].

Despite the many technological advances in the field of robotics, their use in most industries still relies on human collaboration in a hybrid assembly line process, although there are some exceptions. After the Second Industrial Revolution, most of the tasks in manufacturing "were arranged and designed according to specific principles such as specialization, simplification, and standardization", making them more efficient with simpler and repetitive tasks for workers [6, 7].

Hybrid assembly lines still widely used today in the automotive, shipyard, textile and other industries, have the advantage of keeping up with industrial needs for advanced production solutions, while improving product quality, production flexibility, cost reduction and ergonomics by robotics. This is supplemented by the human capacity for

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https://doi.org/10.1016/j.heliyon.2022.e11039
Received 7 February 2022; Received in revised form 22 February 2022; Accepted 6 October 2022

rapid problem-solving and on the spot corrections when checking product quality and safety. In the example of the automotive industry, the assembly line is influenced and designed with robotics in mind, although humans are still very much present in the assembly project [8]. According to Tsarouchi et al. [7], while industrial robots are used in many production lines and processes, the close collaboration between robotics and humans still must be perfected to minimize risks to human life [7, 9, 10].

So far, robotics has not been able to replace human capabilities entirely, although a solution can be achieved by combining the capacities of both to create an excellent industrial environment [7].

Regarding robotic construction in AEC, several robotic tools have been used, ranging from “manual manipulated mechanical machinery, or remote controlled semi-automated or automated devices, to more sensible and intelligent autonomous robots” [11]. Examples of fixed and mobile robots include robotic arms to build walls using various materials and techniques, as in the ETHZ Informed Wall project and the robotically built wall from NYU Abu Dhabi [12, 13], and the use of vehicles to mark or screw, as in projects developed by the University of Michigan [14], The Hong Kong Polytechnic University [15] and the Takenaka Corporation [16]. In the latter cases, robotics relying on vision and sensors are programmed to perform plot markings, nailing and screwing.

Two main technologies have been extensively tested and explored in architecture, namely the robotic arm and the drone, each demonstrating great flexibility and advantages for the construction industry and for exploring advanced architecture design.

The constant evolution of technology enables us to envisage that in the future drones will both replace part of the manual work and work side by side with humans in construction, bringing advantages as well as threats. This study aims to analyze the potential for the future of robotic construction.

1.1. Goals and hypothesis

The theme of this paper is the use of drones in construction, specifically with regard to their potential to autonomously assemble parts of a building. It focuses on the role of computer simulation of a robotic construction process, in particular the interaction between humans and robots, using VR. We begin by developing a methodology for the simulation process, and then we present an analysis of a building process simulation. This process is designed to identify and prevent construction errors, whilst enhancing efficiency in the construction of complex architectural shapes.

The use of computer simulation in VR for robotic construction is an important aspect of the future use of robotic construction technologies.

Simulation processes are used in many areas of the architectural and construction industries to analyse the building, from the beginning of the design stage and throughout its entire life span. Among the diversity of construction simulations possibilities, this paper focus on buildability analyses, in which simulations of machine placement, for example, and the possibility of machinery movement in terms of material arrival, placement, and distribution, are analysed [17, 18, 19, 20, 21, 22].

Our simulation process focusses on the processes cited above to accomplish the following: in the initial stage, a visual analysis of the predefined structures and an evaluation of whether the designed shapes can be built without the use of binding materials; and in the second stage, an analysis of the constructability of the structures by simulating the robotic building process, trajectories and building space.

Our goal is to explore how a computer simulation using VR of an environment makes it possible to simulate the entire constructability of a dynamic process. For the designer, the use of VR simulation has the advantage of providing real scale, so that he can observe the construction from any perspective with a feeling of being present. This type of visualization enables the user to check the feasibility of the model and quickly make changes and corrections.

Our hypothesis is that a VR simulation of a robotic construction (H1) has the potential of increasing the precision of predicting the construction duration and cost and allows for (H2) the detection of construction problems.

To test these hypotheses, we simulated three experiments in robotic construction using VR: (i) the construction of a small architectural element composed of six overlapped bricks; (ii) the construction of a simple linear wall; (iii) the construction of a complex double coverture wall. We assess and quantify robotic construction using drones through VR rather than through physical in situ testing.

1.2. Organization

This paper is divided into six sections. The introduction presents the research gap and the goals of this research, while the second section presents the state of the art regarding the construction of complex geometries, robotic construction and construction simulation using virtual reality. The third section explains the methodology used for the robotic construction simulation experiment reported in this paper. Section four describes the experimental design stages and the final simulation and section five presents the results. The paper ends by presenting the discussion and conclusions, focusing on the key questions in the study regarding the advantages of simulating robotic construction by means of VR.

2. State of art

2.1. The construction of complex geometries

According to the Cambridge Dictionary, complexity is “the state of having many parts and being difficult to understand or find an answer to” [23]. The concept of complexity can be applied to all fields of knowledge, from mathematics to art: ever since the first structures built by men, the search for complexity has been unending.

The concept of complexity in space geometry has been studied and experimented with in architectural design by numerous architects, including the present-day offices of Zaha Hadid, Frank Gehry, and Rem Koolhaas, among others.

Nowadays, the once challenging task architects face when designing complex architectonic shapes has become an easier and simpler process thanks to advances in recent technologies and parametric design software. The widespread use of these design tools has made it possible for architects to experiment and design these shapes, which have become one of the most sought-after forms of architectural expression, previously only developed by a small number of avant-garde architects. Physical built elements, such as a geometrically complex skin for a facade, are nowadays parametrically designed using a computer so that changes in inputs (parameters) produce different outputs which, after comparison, lead to the selection of a design solution.

The use of parametric design processes associated with Computer Aided Manufacturing (CAM), at a time where architectonic design is pushing the boundaries of construction, has become one of the most important ground-breaking processes for the construction industry, forcing it to adapt and change to efficiently produce the buildings of tomorrow. According to D'Uva, the possibilities that technology brings to design and construction allow for greater freedom in designing complex shapes than the one that traditional approaches to design would allow [24].

The traditional methods for building complex architectonic shapes are complex, difficult, time-consuming and require the use of auxiliary structures. In the process of building a simple circular brick wall, for example, the builder first needs to create a layout for the structure on the ground using geometric techniques to design the circle (in this case a spike and mason line), then place the bricks in the right place until the wall is completed. In the case of building processes for certain more complex shapes, such as the one explored in this paper, the geometric technique applied to help the builder would be very complex. In fact, the example of the double curvature wall with an alternating brick pattern, shown in Figure 1, could be built in several ways, usually using different series of pikes and lines in different places and heights, as illustrated. The more complex the shape is, more complex and unusual the auxiliary structures need to be. The use of complex shapes combined with the demand for fast, efficient construction creates the need for new tools to control the process, from the design to the building stage.

2.2. Robotic construction

Robotic Arms (RA) mimic the performance of human arms since they can perform a substantial variety of movements. They can work either autonomously or as a part of a more complete robot. RA are programmable manipulators, composed of rotational/linear segments that control the precision of their movements [25]. At the end of an RA there is a tool which can move, position, and manipulate objects, which may include a milling tool, for example, to cut or drill, claws or suction cups to grab objects, or a tube to deposit construction materials such as concrete or glue. Drones are unmanned aerial vehicles. They may be commanded manually by a human using a remote control in real time, or via pre-programmed and pre-planned trajectories using integrated digital control systems such as sensors, radars and GPS to perform specific, predefined tasks [26]. Although RAs and drones are very rarely used in construction sites, research in architecture is underway in the laboratory and in the form of real-life scenario prototypes, as reported next.

In 2006, the Informed Wall Project was developed in ETH Zurich, led by Gramazio and Kohler with the collaboration of postgraduate students. The goals were: to test the architectonic potential of RA by building brick walls; to use varied materials, processes, and shapes. The construction was designed with no exogenous interference such as wind loads, spatial obstacles, and human intervention. The RA to reach any point in the three-dimensional space and execute all the tasks as defined in the Edeffector programme [12]. A claw was attached to the RA so that it could grab, lift, and set traditional bricks in their correct place. A computer script capable of translating CAD data into coordinates was developed using the MAYA software. Several wall prototypes were produced, concluding that RAs can be used in the construction of brick walls with little error.

In 2017, the Institute for Computational Design and Construction (ICD), in cooperation with the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart, completed a new research pavilion with the main goal of exploring building-scale fabrication with glass and carbon fibre reinforced composites. The lightweight nature and high tensile strength of these materials allow for a different approach to the fabrication process, combining low-payload, long-range machines such as Unmanned Aerial Vehicles (UAVs) with strong, accurate industrial robots, thus allowing for object fabrication on a larger scale [27]. In order to create structures larger than the standard industrial fabrication equipment workspace, a collaborative setup involving multiple robotic machines communicating with each other was required. In addition, to ensure a continuous material structure and create a seamless fiber laying process, the fiber had to pass between multiple machines. Two stationary industrial RAs with the precision required for the fiber winding work were placed at the ends of the structure, while an autonomous, custom-built UAV (with a long range but less precise positioning) transported the fiber between the two RAs [28].

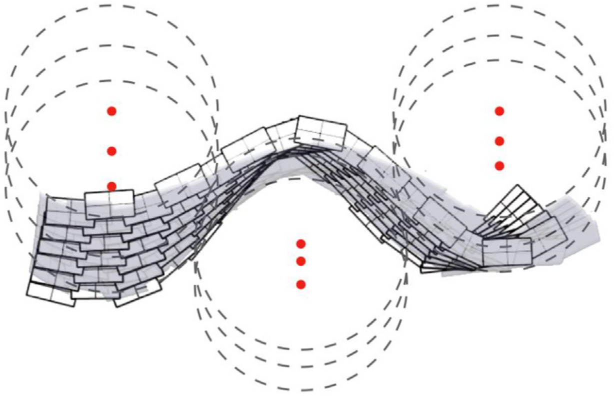

Figure 1. Process for designing the layout of the wall on the ground so that manual builders would be able to construct it: in black, the desired shape; in dark grey, the closest shape possible using this method.

In 2017, the Chinese University of Hong Kong developed the Ceramic Constellation Pavilion, a robotic assembled structure made with RAs 3D-printed clay bricks, each with a unique shape [29]. The main goal of this project was to overcome the constraints of standardized mass production objects and allow for some creative flexibility. The resulting 3.8 m tower structure is a load-bearing timber pavilion fully built by RAs — from brick production to brick and wood beam placement— on which the 2000 terracotta bricks, all uniquely designed, are dry stacked to create a twisted façade [29].

Nowadays, semi-automated mason robotic technologies, based on RA, are being deployed and studied for future construction in real life scenarios such as SAM, a robotic assistant mason that, is able to pick bricks, add mortar and place them in their right coordinates. The final wall element is achieved by the brick laying RA in cooperation with a human worker, a skilled mason that follows behind the RA to strike the joints and finish the wall [30].

In 2012 Gramazio, Koehler and D'Andrea programmed drones capable of lifting and assembling thousands of bricks, one by one, in the FRAC Centre in Orleans, France. The Flight Assembled Architecture project was a pioneering drone assemblage project. A 6-meter-high structure that was 3 m in diameter was built using 1500 polystyrene parallelepipeds (weighing around 100 g and measuring 10 × 30 × 15 cm [31]). The project aimed to verify the feasibility of the construction of buildings by drones. Four drones were necessary (each equipped with servo-powered pins to cut a hole through a brick and hold it during the flight), as well as a blueprint, a foreman and a construction team. It was verified that if the flight was faster, there were fewer external disturbances, such as turbulence and collisions, and the error margin was also lower. When the speed was reduced and the landing was softer, the error margin was higher [32].

In 2013, another ETHZ project, Aerial Construction, was undertaken, involving close collaboration between the Institute for Dynamic Systems and Control and the Architecture and Digital Fabrication Department at ETHZ, with the main goal of investigating and developing new construction methods for aerial machines, or drones. The main experiment was to build a bridge with nine 120 m Dyneema ropes between two scaffolds standing 7.5 m apart. Two drones were equipped with rope dispensers and the trajectory of each drone was planned in order to accurately create all the connections and nodes needed for the final object [32, 33]. This project was the first to prove that small drones can autonomously assemble a real-scale load-bearing structure. Although the project was based in a lab environment, its successful execution presupposes the possibility of building a similar bridge between two points that are difficult to access [15].

These projects explored RA, both RA combined with drones, and drones alone and their ability to build complex shapes. The ETH Zurich team concluded in 2006 that greater investment in software and hardware would be needed to execute more complex geometric shapes. Also, that the building process and the range limitation of the RA have to be considered in the project stage and strategies in order to overcome the limitations in future [34]. To overcome such limitations in 2017 the ICD/ITKE Pavilion the teams worked with a combination of RAs and UAV which enabled to complement each other in different sorts of work. The precision of the RA was highlighted while its limitations were canceled by the use of a UAV that served as a mere way of material transportation, not fully exploring it's potential. Also, in 2012 the ETHZ concluded that the speed in which drones fly had a relevant impact in the error margin of the construction. The experiment from ETHZ in 2013 also with drones constituted a next step in demonstrating the capability of drones to build in difficult geometric scenarios.

After analyzing the use and performance of both technologies, their variants and their advantages and disadvantages, the drone was the selected technology over the more studied and well tested RA. Still with some drawbacks in terms of size, battery and load capacity, its freedom of movements, the larger working area it can cover, the lack of special constraints, the various configurations it provides, the inflight and coordinate precision it provides as well as the lack of additional structures to work, give the drone a bigger advantage when compared with RA for this research. Although the RA has a higher precision, and the number of possible tools and tasks are larger, its limited working area and need for additional structures, such as tracks, makes it fit less in this research.

2.3. Construction simulation with virtual reality

Virtual reality (VR) is something that is perceived as near-reality by means of simulation. According to the Handbook of Simulation, simulation is “the imitation of the operation of a real-world process or system over time” [35]. A computer-generated simulation is a three-dimensional image or environment that allows individuals using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors, to explore and interact with it in a seemingly real or physical way. The user of a VR system becomes immersed in the virtual environment (VE) and may interact with it in several ways e.g., by manipulating objects with a simple joystick or performing a series of actions in a natural way through gesture [36, 37].

Immersiveness and presence are concepts that translate into a complete virtual experience of space and have been studied by several authors. Both concepts are closely linked and are responsible for our perception of reality/virtual space. Immersiveness is a key concept related to the quality of the system's virtual environment (VE) technology, while the concept of presence refers to the psychological experience of being present in a specific virtual place.

Many projects and experiments have been developed by several researchers investigating the use of immersive VR and the awareness of space and shapes, including work by Slater and Spanlang [38], D'Uva et al. [39], Li et al. [40], Sampaio et al. [41], Navon and Retik [42]. They offer examples of how VR construction simulation can serve as a reliable tool for the construction industry. In this study, our research focuses on five of the construction simulation case studies mentioned above, regarding the construction of complex and technologically demanding projects.

In their research, Slater et al. [38] compare immersive VR with other display modes for visualizing complex 3D geometry. The main focus of their study was to determine whether immersive VR technologies offer advantages for users in terms of the visualization of complex geometries, when compared with conventional visualization methods. The study concluded that the head-tracked immersive VR adds a statistically significant advantage in comparison to the joystick-controlled display mode, especially when the VE is displayed in real scale [38].

Sampaio and Martins [41] researched on the use of VR applied to the construction simulation processes of two frequently used bridge construction techniques, namely the cantilever method of bridge deck construction and the incremental launching method of bridge deck construction. The aim was to analyze the use of such technologies and how they can provide support for civil engineering classroom-based education, particularly relating to bridges and construction processes. The knowledge each student and teacher could extract from the construction simulation was considered to be informative, both in terms of bridge construction techniques, supporting the study of the type and method of operation, and the necessary equipment for the construction methodologies in question. The research demonstrated how VR can bring new perspectives to the teaching and study of complex sequence construction and how it can be used for design and material selection in AEC [41].

In 2003 Li et al. research on the advantages of the use of VR in experimental processes for innovative construction operations was developed at the Hong Kong Polytechnic University [40]. According to the authors, VR allows planners to interact with the VE, a completely immersive 3D computer-generated construction simulation, and the objects inside it as if in real life [40]. For this experiment a case study from the municipality of Hong Kong was chosen, involving a group of three 41-storey public housing blocks, to demonstrate the advantages and possibilities of VR construction simulation for research in new construction methodologies and technologies. This experiment showed that the use of VR promotes: (i) a better understanding of complex construction systems and shapes for every individual, whether expert or non-expert, in building and construction systems; (ii) the evaluation of various different scenarios, while limiting expenses and construction efforts; (iii) a realistic assessment of automation processes [40].

Adami et al. [43] research focused on the impact of VR tools exploring their possible use in the training of construction workers, testing their impact knowledge acquisition, operational skills, and safety behavior. According to the authors, VR-based training is a safe and cost-effective training that allows workers to be exposed to normal construction environments as well as to hazardous/negligible tasks and safety risks. Fifty construction workers were assigned a task, either VR-based or in real life training, to be carried out using a demolition robot. This experiment showed that VR-based training had a significant increase in knowledge, operational skills, and safety behavior of the construction worker when compared to in-person training [43].

In 2021 after analyzing the wood construction sector and determining a shortage in well-trained construction workers, Osti et al. [44] research focused on developing a VR based learning environment to help train a new generation of workers. In order to analyze and explain and test a construction shape was selected (a timber wall), a 3D model of a construction site and a video tutorial in a VR Head-Mounted Display (HMD) where developed. A set of participants were selected and divided into two groups, the full VR training group was compared with participants that had access to a 2-D instructional video. With this research it was evident that the VR training group had resulted in better retention, task performance, learning speed, and engagement than their video learning counterparts, therefore demonstrating that VR technologies and environments are a viable training tool for the construction sector [44].

Based on these research projects, it may be considered that the use of VR for construction simulation has been acknowledged as a powerful tool, not only for understanding architectonical spaces but also for testing and experimenting with different construction methodologies and technologies.

3. Methodology

The main references for our study are the ETH Zurich methodological process used to develop two drone construction experiments in robotic flight assembly and aerial construction, as well as the two experiments by the University of Stuttgart, which used a combination of robotic arms, a drone and a dynamic shade system controlled mainly by drones [28, 34, 45].

Despite the differences in the final architectonical objects produced in each of these experiments, all followed a similar methodological framework and main tasks. Their methodology is divided into four main steps: (i) Definition of the building process and architectonic object – choice of technologies, materials and modules; (ii) Definition of the robot building trajectories and building order - firstly the architectonic objects are identified as independent modules and assigned a construction order, and secondly the drone trajectories are planned and studied; (iii) Simulation of the building process - the result of the previous steps is simulated in order to prevent construction problems (e.g. drone collisions, collisions with the architectonic element, inefficient trajectories), and

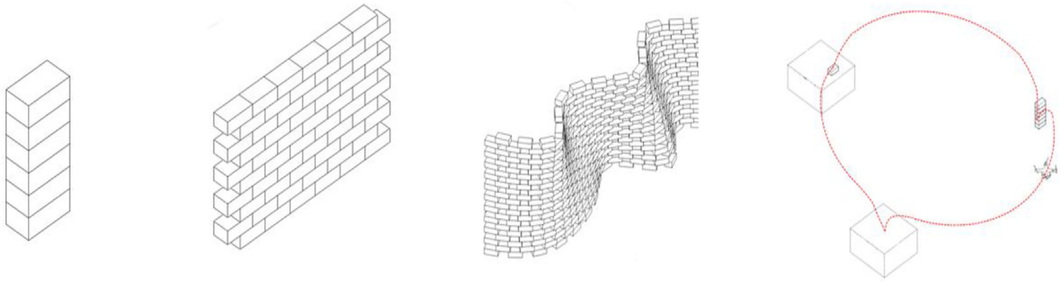

Figure 2. The three designed walls. From left to right: Wall 1; Wall 2; Wall 3; the landing position, brick deposit, construction plane with the wall being built, and the drone flight path. The brick dimension is constant; models are not to scale.

construction time is also analyzed, among other tests that may prove important for the construction specifications; iv) Robotic building experiment - the real construction is executed and analyzed.

Throughout the building process problems not foreseen by the simulation may occur and will require a re-evaluation of the previous steps and, in some the cases, a process of trial and error to successfully build the desired architectonic element [28, 34, 45].

The methodology chosen for this study follows the methodology described above by including four steps. In the scope of this paper the authors developed a methodology for the simulation of robotic construction in IVR. This methodology includes three main steps: (i) definition of the experimental settings (here presented in Section 4.1); (ii) development of the simulated model (here presented in Section 4.2); (iii) VR simulation and analysis of the building process (here presented in Section 4.2); (iv) Analysis of the results (here presented in Section 5). Our proposal also adds assessment of the efficiency of the robotic construction, i.e. viability, duration of construction, and cost.

4. Experiment

This section presents a robotic construction simulation experiment using VR and analyses the potential of such a simulation in the pre-construction phase. It involves a VR simulation of the construction of three different dry staked masonry walls, performed by drones. The use of VR simulation aims to (i) visually highlight the weaknesses and strengths of the building process, (ii) obtain measurable results that enable the efficiency of robotic construction to be assessed, i.e., viability, duration of construction, and cost.

4.1. Definition of the experimental settings

We started by defining the experimental settings, namely how the simulation of the building process was developed. For the simulation, each artefact involved in the scene is identified as an independent module, the drone building trajectories are defined, as well as the construction/assembly sequence.

Three dry staked walls (no mortar is used) with varying complexity shapes were designed, so that their visualization and analysis through VR would allow a broad discussion regarding the potential of visualization, with view to anticipating robotic construction [43].

The first wall consists of a simple ten-brick-high vertical tower (see Figure 2). The bricks, drones and each of the trajectories were defined for the simulation of this wall, as well as the departure point of the drone, the place where it arrives at the dispenser (where it grabs a new brick), and its landing position (where the brick is placed). The construction sequence for the first geometry is the following: a drone takes off from the departure point and travels to a dispenser, where it grabs a brick using its claw, then takes off for the brick destination coordinate, where it lands again and releases the brick. It then goes back to the dispenser and repeats the process with a second brick, until all six bricks are in place. The route is circular, avoiding collisions between the two drones. The drone goal is to build the tower and land in a specific location at the end of the process.

The second experiment involves the construction of a vertical brick masonry wall in mismatched rows, supported only by the blocks' self-weight (Figure 2). This experiment shares the premises defined in the first wall experiment, differing only in terms of the construction co-ordinates and dimensions of the final built object. In the previous model, the construction coordinates in X and Y axis are constant, while Z changes. In this second model, the bricks are placed in different Y and Z coordinates, maintaining the X axis. In order to create the rows, the drones pick up the bricks and position them side by side, mismatching the bricks in the second row using the same process.

The third wall has a more complex geometry based on double-sided curvatures. The bricks are also held up by gravity and the wall is composed of rows of bricks laid with spaces between them and on top of one another (Figure 2). This more complex geometry was made using parametric design software. For this wall, first a series of parametric points were added and linked together by a curve, secondly the curve was divided into several points and bricks elements were added in each of them. The final shape was finalized by multiplying the number of curves and by moving each point 2 cm in the opposite direction (points in the outside of the curve moved inwards and points inside moved outwards) creating a opposite curve in the top face of the wall.

This experiment follows the same path as the previous one. In this model, each brick has different X, Y and Z coordinates in order to create the curvature of the wall. Each brick is placed according to its spatial coordinates. The drone's action is identical to those described above.

4.2. Development of the simulated model

In this step the drone trajectories, the 3D model of the walls and the VR visualization are developed. Rhinoceros 3D[1] and Grasshopper[2] visual scripting languages were used to model the experimental objects (parametric walls, drones and tables) and a Grasshopper script was developed for each wall definition (Figure 3, right). This script enabled us to explore different shapes and became an important step in the design and decision-making processes for the shape of the walls to be simulated and potentially built. After the wall design, three points were defined: the drone landing point, the brick deposit point and the construction start location (Figure 3, left). The three points represent the location of each phase in the building process, beginning with the drone departure and loading location, passing through the brick disposal position to pick the brick, then placing each brick in the correct coordinate, repeating the cycle until the construction is complete.

4D Cinema (C4D)[3] software was used to develop the animation of the construction process. After importing the final objects into C4D, each one was turned into an individual object and each wall component was

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[1] http://www.rhino3dportugal.com/site/.

[2] https://www.grasshopper3d.com.

[3] https://www.maxon.net/en-us/products/cinema-4d/overview/.

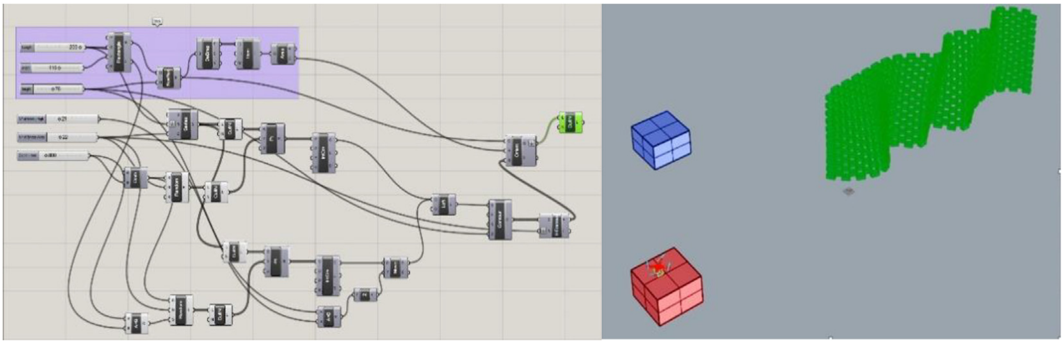

Figure 3. Definition of the wall in Rhino and the drone landing point (red) and brick deposit (blue) (left); Grasshopper geometry definition (right).

separated, brick by brick, from the main object. This software was chosen to obtain the correct coordination for each element for the animation process. In order to start the animation process, the numerous steps in the building progress were split into keyframes (Figure 4) using a recurrent animation technique to make each of the bricks and drone move through space, then deconstructing (instead of constructing) the shape using the construction building order in reverse to obtain each brick's final position. This technique was chosen as an initial approach to the robotic construction simulation process because it was easier to extract the object coordinates. The deconstruction technique obtains the coordinates of the existing 3D models, allowing for easier trajectory planning. The result was a backwards animation of the building process, which was then reversed. Each point on the blue line in Figure 4 represents a step in the trajectory.

Since two or more drones worked in chains, it was essential to create a route script that avoided collision. A circular route was designed (Figure 5), enabling the second drone to place a brick in the correct coordinates while the first moved to the dispenser to grab the next brick. The brick dispenser is in a defined location and all bricks have the same coordinates, so that the drone can arrive, grab a brick and take off. Drones are initially placed on a table, in a start location that also serves as battery charging and resting area.

Starting off from the table, the first drone sets out on its flight path by heading to the brick dispenser, where it lands on the brick and grabs it. When the first drone takes off with its first brick, the second one takes off from the table and heads for the dispenser, while the first heads to the building coordinates, places the brick in its location and returns to the starting point. The drones repeat this sequence until the wall is finished. This circular route was chosen to ensure that the drones were always on opposite sides of the course, meaning that they did not collide. When the wall is complete, each drone heads to the starting point and lands on the table.

The Unity[4] game engine was used to render the experience in the Oculus Rift 2 VR device.[5] When all the components were finalized, each 3D model was uploaded with the specific animation into Unity. It was necessary to add more components to each of the objects in the scene, i.e. drones, tables and bricks, to create a realistic VR environment that simulated the construction of the wall. Colliders and a modifier were added to give them physical properties, as well as an avatar with a first-person camera in the scene to allow for the use of VR technologies. After completing these steps, each Unity file was transformed into an executable VR file, a process that turned each of the finished experiments into a simple executable file that was then uploaded into the Oculus Rift where the VR experience was tested.

4.3. *Simulation and analysis of the building process*

To visualize and analyze the simulation process and its results a wide variety of software and methodologies can be used, from simple 2D simulations to VR experiments, each presenting a set of different advantages and disadvantages.

VR simulated environments, as opposed to other less graphical, realistic, and immersive simulations, enables the user to perceive the experiment from within, in an almost real experiment, allowing for a better and easier understanding of the simulation. Such experiments are inclusive representations for they do not require knowledge about drawing and codes for a user to understand what is happening in the virtual environment. For the broad study that is under development and for the particular study presented in this paper, VR was chosen as the means to experience the space due to the reasons mentioned above. VR in this paper was used as a steppingstone for future in development simulations on human/robotic cooperation experiments.

During the simulation in VR (Figure 6) the user can navigate freely through the ongoing construction process and visualize the whole process, including how the drones grab and deposit the bricks as well as how the wall is built, step by step. This can be visualised from all sides of the building site as well as at any level of approximation to it, although the user cannot interfere with the construction process or its speed.

The assessment criteria was divided into three main items: (i) viability; (ii) duration; (iii) cost. The VR simulation outcomes and resulting analyses are the basis for evaluating the robotic construction simulation methodology, identifying the main differences between robotic and traditional construction, highlight and prevent construction error beforehand.

5. Results

5.1. *Construction viability*

In the first two experiments (Walls 1 and 2), neither external, natural, human, nor physical interferences change the way the structures should be built. Their simple shape and simple means of assembly pose no problem, either in the construction phase or in the final element, since in the first experiment each brick rests perfectly, one on top of the other, and in the second one some of the bricks rest half on top of the next at both ends, as shown in Figure 7. However, in the case of the third experiment, namely the double curvature wall with the alternating brick pattern, the VR visualization highlighted several problems.

In the third wall, the imbricated pattern created a problem for the building process, since the final brick in each row rests over only 1/3 of the previous one and therefore is left hanging, as shown in Figure 8. The analysis of the results showed that the more complex the shape, the more precise and correct the 3D mapping of the building space and building coordinates must be, to allow each brick to rest in the correct place and reduce placement errors, therefore creating a structurally more stable

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[4] https://unity.com/.

[5] https://www.oculus.com/rift/?locale=pt_PT.

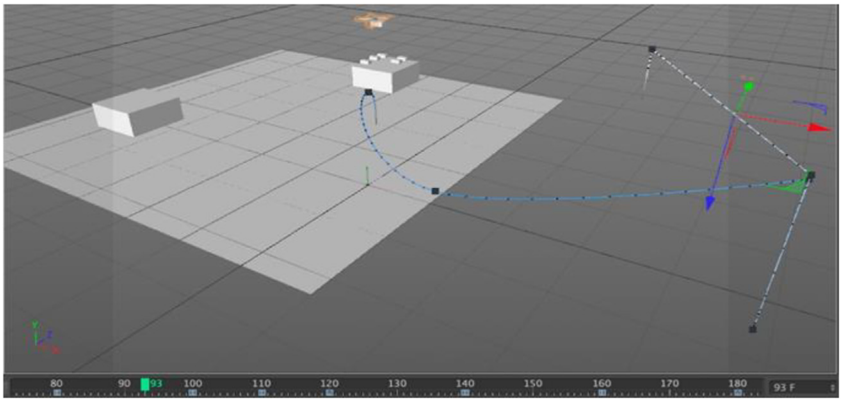

Figure 4. Screenshot from C4D showing a segment of the animation process in the virtual reality experiment.

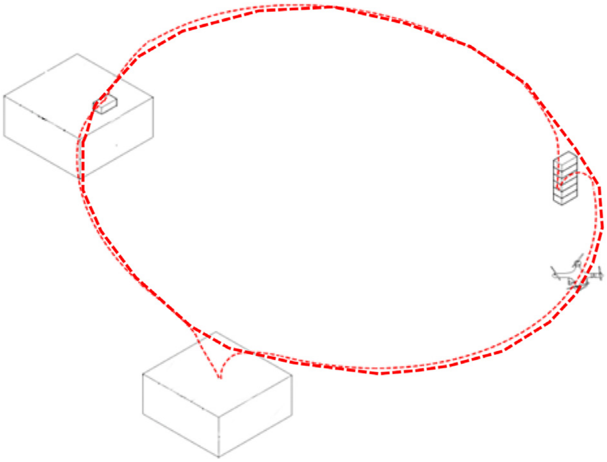

Figure 5. Circular trajectory diagram and plan of the flight, from the moment the drone (4) takes off from the platform (1), then goes to the brick disposal (2) and on to the construction site (3).

architectonic object and a correct/realistic robotic construction simulation.

In this specific example, in order to execute the construction and avoid bricks falling (as seen in Figure 8) certain options would have to be considered, being the first and the second the ones with higher potential of working:

- Addition, by drone, of an auxiliary structure (a smaller brick, Figure 9) that would be placed in advance under the "falling brick" to stabilize it; this structure would be removed when the brick was in position or when the entire wall was built.
- Addition of the same auxiliary structure by a human that would collaborate with the drone.
- Use of a fast-drying mortar or bricks with an incorporated gluing mechanism that could support the cantilever until the next brick placement.

5.2. Construction duration

This experiment considered the use of two DJI MATRICE 100 drones (with diagonal dimensions of 650 mm, weighing 2355 g), with a 30-minute battery life when carrying small objects and a max predefined flight speed of 58 km/h (max 79.2 km/h and min 50 km/h). For carrying this experiment, we simulated that the chosen drones were complemented with mechanical four-fingered claws, similar in function to The Flight Assembled Architecture, consisting of four metal pins each actuated by a single servo controlled and powered by a circuit board that supplies signal and power to the claw element [31]. Such process reduced the amount of energy needed for the claw to work since only a small signal was needed to make the claw closes and opens, locking it in these positions, and therefore not requiring energy during flight. The small power consumption required by the claws was therefore not considered for the current simulation process. The drones trajectories and precision are defined by the speed of the flight (varying from 0 to 58 km/h). During the flight, when only carrying a brick in a simple and straight trajectory, the drone can maintain an almost constant speed of 58 km/h. In other cases, such as in more complex and difficult tasks, such as grabbing and placing the bricks, the drone reduces its speed in order to successfully complete the task.

The drone starts the trajectory by taking off from the charging platform, accelerating from 0 to 58 km/h, until it reaches a 3 m height, at this time the drone continues its horizontal trajectory to the brick dispenser coordinates (provided by the script), in this step the drone stops in mead air and slowly descends (at a rate of 5 km/h to 1 km/h) to slowly stop over the brick, an electrical impulse closes the mechanical claw (adjusting it to the edges of the top face of the brick), and once more the drone slowly takes off (from 0 to 58 km/h until a 3 m height) and continues the horizontal trajectory until it reaches the brick final placement coordinates at this stage the drone slowly descends once more, carefully lands, the claw opens to release the brick in the accurate place.

In order to manage a constant construction flow using only two drones, they were interspersed: once the first drone reached half of its battery life, the second one began operating. During this part of the work, both drones worked simultaneously, but when its battery began to run down, the first drone would rest and recharge, while the second one

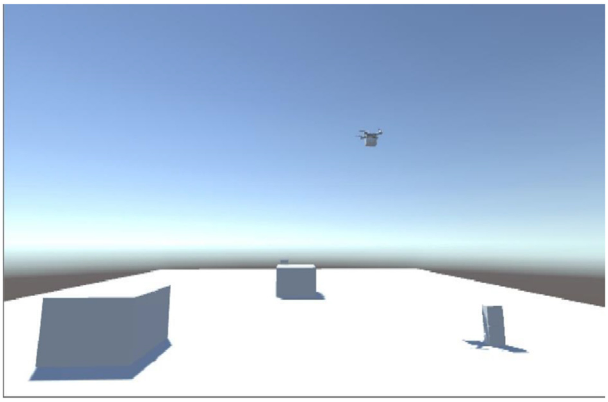

Figure 6. VR environment: on the left, the table where the drones land; in the center, the place where the bricks are grabbed; on the right, the wall being built.

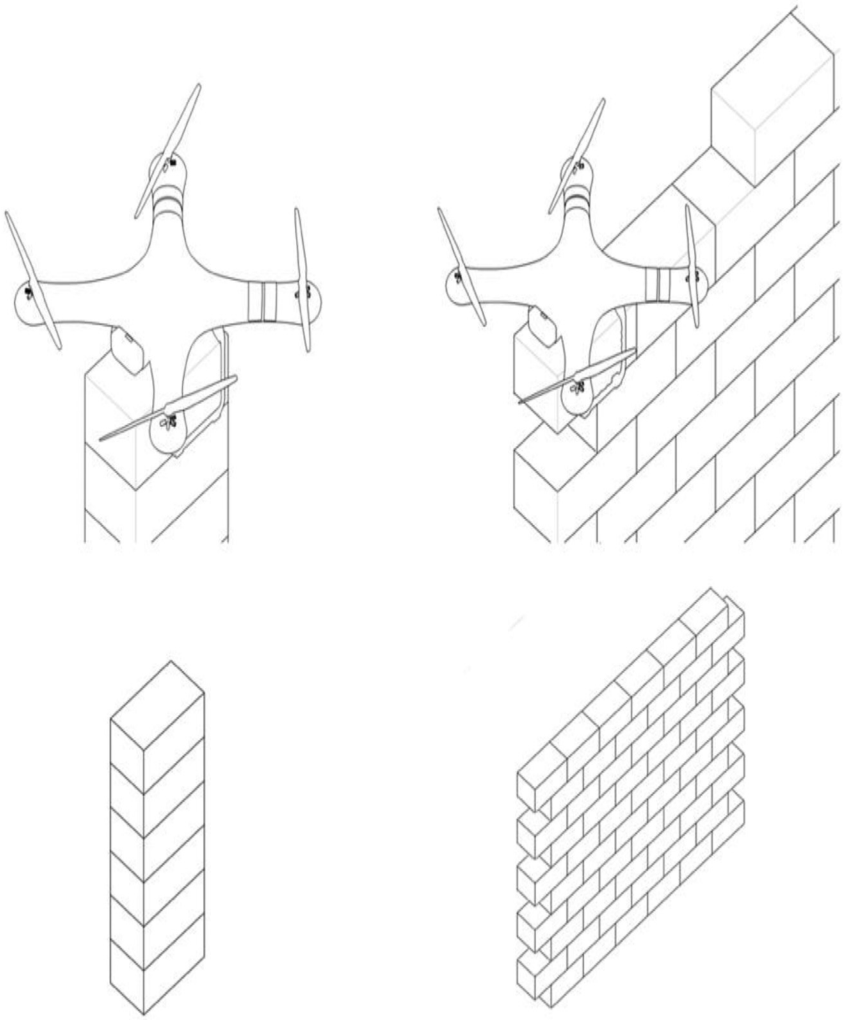

Figure 7. Diagrammatic representation of the positioning of the bricks in experiments 1 and 2.

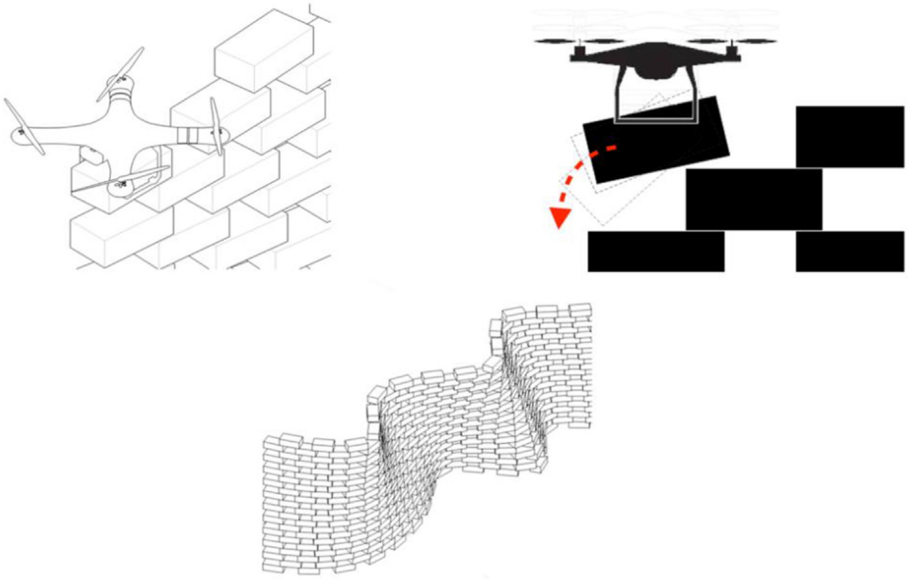

Figure 8. Diagrammatic representation of the positioning of the bricks in the third experiment, and the main design issue.

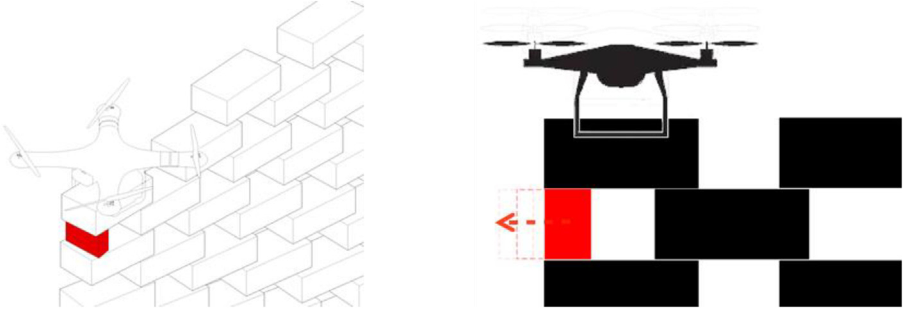

Figure 9. Diagrammatic representation of the use of an auxiliary object (in red) to support Brick 1 until the one above it is placed.

(which had started later) continued the construction process. This process was repeated until the wall was completed.

The time taken by the two drones to build each wall was calculated from the computer simulations and is indicated in Table 1. The same table also presents an estimate of the manual construction time, calculated after interviewing and experimenting with a set of experienced construction workers.

After analysing and examining the three drone building simulation results, it was concluded that the building time varies, depending mainly on the size and complexity of the desired shape and the number of bricks (related to the need to recharge).

In the first experiment – the 10-brick dry staked vertical tower – the simple shape, the constant XY coordinates, and the absence of recharging time resulted in a faster construction time in comparison to the second and third experiments.

In comparing the second and third experiments, which both involved the same number of bricks and rows, the construction time was found to be almost the same, with only a slight time difference of 7/10 of a second between them, varying according to the complexity of the wall shape. The simpler shape of the second wall, a straight-line regular wall, enabled the drones to work faster in placing the bricks since the rotation of each block is always the same and each brick is placed next to the previous one.

The third, more complex wall geometry, a double curvature wall with spaces between bricks, was the slowest and most complex of the three experiments to build. The different placement coordinates and rotation of each brick meant that the building process and trajectory calculation took a little longer, since the drones had to adjust the rotation angle for each brick placement and the total recharging time increased.

These results can vary depending on the speed and autonomy of the drones used, as well as the number of drones.

In order to understand and have a comparable analysis between manual and robotic construction a group of seven people in the construction industry were asked to share their experience by assessing the possibilities of building the three defined architectonical elements. For this study five construction workers with a large experience in the field (all with a work experience of between 15 to 25 years) a foreman and an architect where selected.

The five construction workers were asked three tasks (i) to build Wall 1 using 10 bricks, (ii) a meter long by a meter high section of Wall 2, using bricks (30 bricks held in place by gravity) and (iii) for Wall 3, due to the complexity of the element, the seven intervenient were asked to find a building strategy to build it but the building itself did not took place (Figure 1). To obtain an accurate approximation of construction time, the five workers were asked to build the elements as they regularly would, a set of different timelines were obtained and an average time for manual construction was stipulated. The real experiments allowed to time how much a meter long by a meter high manual wall construction would take, originating a time estimate for a complete construction of the second wall.

When comparing the robotic construction with the manual construction, the major difference between them is in time and speed of construction: for the two first experiments (Walls 1 and 2) the construction is faster due to their simpler, standardized shapes. A construction worker can build these simpler walls more quickly since they do not need special auxiliary construction structures and, unlike the drone, can pick up and transport more than one brick at a time, thus resulting on a faster time per linear meter.

Regarding the most complex wall, Wall 3, due to its irregular shape, the group of construction workers estimated they would take around five full days, equivalent to 40 h, to complete this intricate shape, requiring a set of complete and highly detailed drawings with each brick position and rotation or an alternative construction methodology. However, this manual building would not be completely accurate, as the intricate process would be prone to human construction errors in terms of wall geometry, therefore resulting in a wall whose geometry would not be completely correct. In case of Wall 3, the robotic process is more efficient regarding construction time.

Table 1. Construction duration for each of the three simulation experiments, using manual labour and a drone.

	Number of rows [units]	Bricks per row [units]	Total number of bricks [units]	Row length [m]	Total length [m]	Number of stops to charge battery [units]	Time per row [min]	Total Time [min]	Time per linear meter [min]
Wall 1									
Manual	10	1	10	0.30	3.0	–	–	4.61	0.65
Drone						0	1	10	3.33
Wall 2									
Manual	22	30	700	9.3	204.6	–	–	240.70	0.85
Drone						24	30	660	3.22
Wall 3									
Manual	22	31	700	11.5	253	–	–	2400	9
Drone						34	40	1240	3.40

5.3. Construction duration with natural external factors — simulation with wind

For a second assessment of the construction duration, we considered the same experimental settings with the only difference being the addition of an external natural factor, a wind force. The main purpose of this second assessment is to evaluate the interference of a horizontal force, simulating wind, on the speed and accuracy of the robotic construction process.

In this simulated environment the drone is programmed to follow the exact same construction trajectory by constantly compensate the wind force, the drone augments its speed/force in the opposite direction of the horizontal force, decreasing battery life, to follow the same circular trajectory and place the bricks in the exact same coordinates as shown in Figure 10.

The time taken by the two drones to build each wall was calculated from the computer simulations with the introduction of a wind force and is indicated in Table 2. The same table presents the time of construction with two different forces, the first one a force of 1 unit and the second one with a force of 5 units.

With the simulation concluded, and after analyzing the previous results (with no external factors) and comparing them with this second set of simulations, we can conclude that the building time and accuracy varies not only depend on the size and complexity of the desired shape, number of bricks or even the charging time but also on the external factors. In this case the addition of wind, its force and direction, where determinant factors in the construction time and drone energy/battery live.

By increasing the shape complexity and adding external factors such as wind, within the simulation environment, we concluded that the drone battery life was affected, reducing in proportion to the drone behavior/trajectory corrections. The amount of propeller force/rotation needed to generate more lift, the amount of time needed to correct the wind force and return to the trajectory, and the time to stabilize the drone to land in the correct coordinates demanded more airborne time and therefore more energy, reducing the battery life from 10 to 25%, and augmenting the number of recharging needed. The faster the propellers spin the more energy is needed for the flight.

In this second simulation the addition of a 1 unit of force made the construction process slower 0.2 min per row and with no more charging stops were needed. In the simulation with 5 units of force the result was an increase of 2 min per row with the need for 4 total charging stops when compared with the no wind simulation environment with 0 stops.

The simple shape of Wall 1, and the constant placing coordinates and reduced number of bricks resulted in construction simulation very closer regarding duration to the one simulated without wind.

In the case of Wall 2 and Wall 3, both with 700 bricks, the addition of the wind force largely altered the construction time, augmenting the difference between the two walls construction. Not only the complexity of the shape affected the construction time but also the different wind force that were added into the simulation environment.

The simpler and straight-line regular shape of Wall 2, enabled the drones to predict and correct the building trajectory faster, allowing it to accurately place each brick in their correct coordinates. In the case of the force of 1 unit the construction process took mor 9 min per row while in the force 5 units simulation it took 66 min more per row.

Wall 3 was still the slowest of the three experiments to build. The different placement coordinates, rotation of each brick and building trajectory correction for each brick makes it a more complex process to correct and therefore longer. In Wall 3, for each brick the drone not only had to adjust the rotation angle but also to constantly correct the building trajectory, increasing the total placement time and recharging time. For the 1 unit of force, the building time augmented by 19 min per row, while in the 5 units of force scenario the construction took more 84 min per row.

In this simulation external factors were introduced in order to evaluate their impact on the building process. Results can vary depending on the speed and autonomy of the drones used, as well as the number of drones. Notwithstanding, this simulation with horizontal forces (wind), enables us to conclude that the time of construction of each architectonical element can vary not only depending on complexity and number of drones but also depending on an external natural factor.

5.4. Construction costs

Table 3 shows a comparison between the current cost of manual construction, based on the average price of construction in the EU according to the European Construction Costs [46], and an estimate for the cost of using robotic technologies (using the construction data without wind interference) in the building process. The prices assume that both constructions would take place in the same site and use the same materials. The current manual construction time and costs was estimated on the basis of interviews with construction workers and companies. In this table, the prices set for the robotic construction are calculated as if for a stable technology, excluding the research and testing phase, and are based on current international drone rental with professional drone operator.

For the purpose of our analyses the cost was calculated through the definition of a basic, comparable and measurable set of parameters common in construction and shared by both approaches: a) the cost of the chosen building material (the brick); b) and labour, eighter a construction worker or a drone with operator; allowing to estimate and calculate the quantity of material and time needed as well as cost per hour of construction and per unit of construction material.

This approach, use of comparable parameters, was selected for it alone can portray a simple yet real cost comparison between a stable technology and an in-development one.

From the estimated construction costs shown in Table 3 it may be concluded that the robotic construction method would only be beneficial when applied to complex elements such as Wall 3, but not if more simple structures were built, as in the case of Walls 1 and 2. In both the simpler examples, manual construction is faster, representing less than half the time spent to build the same structure with a drone, and therefore costs less to build.

As shown in Table 3, for the three simulated situations, the cost of drones is always higher than the cost of manual work. Nevertheless, as

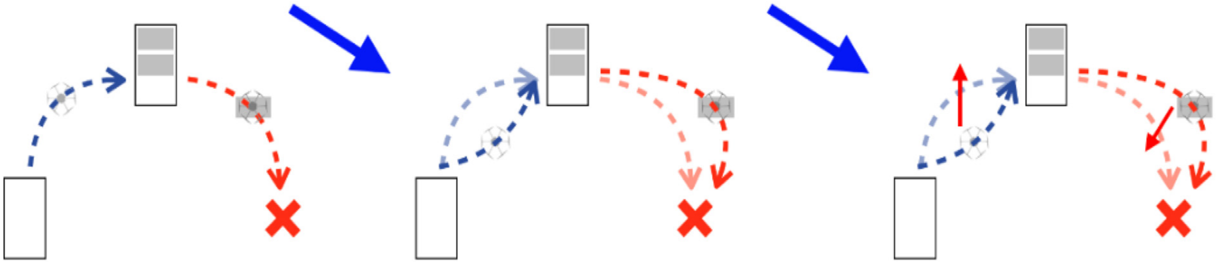

Figure 10. Diagram of the trajectory correction of the simulation process with horizontal forces (wind).

Table 2. Construction duration for each of the three simulation experiments, using a drone and a 1 and 5 horizontal external force (wind).

	Number of rows [units]	Bricks per row [units]	Total number of bricks [units]	Row length [meters]	Total length [meters]	Number of stops to charge battery [units]	Time per row [minutes]	Total Time [minutes]	Time per linear meter [minutes]
Horizontal Force of 1 unit	Wall 1								
	10	1	10	3.0	3.0	0	1.20	12	3.6
	Wall 2								
	22	30	700	9.3	204.6	29	39	858	4.19
	Wall 3								
	22	31	700	11.5	253	40	59	1298	5.10
Horizontal Force of 5 unit	Wall 1								
	10	1	10	3.0	3.0	4	3.2	32	9.06
	Wall 2								
	22	30	700	9.3	204.6	40	96	2112	10.32
	Wall 3								
	22	31	700	11.5	253	56	124	2728	10.78

Table 3. Table showing the possible future differences between current construction costs and robotic construction costs.

Wall 1		Quantity	Cost p/hour	Cost p/item	Total
Manual	Bricks	10 units	0.48€	4.8€	6.3€
	Labor	6 min	25€	1.5€	
	Drone	–	–	–	
	Drone Operator	–	–	–	
Drone	Bricks	10 units	0.48€	4.8€	12.30€
	Labor	–	–	–	
	Drone	10 min	25€	2.5€	
	Drone Operator	10 min	50€	5€	
Wall 2		**Quantity**	**Cost p/unity**	**Total**	
Manual	Bricks	700 units	0.48€	336€	398.5€
	Labor	150 min	25€	62.5€	
	Drone	–	–	–	
	Drone Operator	–	–	–	
Drone	Bricks	700 units	0.48€	336€	1161€
	Labor	–	–	–	
	Drone	660 min	25€	275€	
	Drone Operator	660 min	50€	550€	
Wall 3		**Quantity**	**Cost p/unity**	**Total**	
Manual	Bricks	700 units	0.48€	336€	1336€
	Labor	2400 min	25€	1000€	
	Drone	–	–	–	
	Drone Operator	–	–	–	
Drone	Bricks	700 units	0.48€	336€	1836€
	Labor	–	–	–	
	Drone	1200 min	25€	500€	
	Drone Operator	1200 min	50€	1000€	

previously demonstrated, the use of drones for complex shapes would result in greater accuracy and a faster building time. In fact, the advantage of using the robotic construction methodology for complex shapes is that it cuts the construction time by 50% in comparison to current manual construction methods and reduces the construction error margin.

6. Conclusion and future work

The goal of this study was to explore how a VR computer simulation of an environment makes it possible to analyze the constructability of a building process.

Our hypothesis, namely that an VR simulation of robotic construction (H1) has the potential of improving the precision of predicting the construction duration and cost and allows for (H2) detection of problems in the construction through the simulation, was proved.

The use of simulations to analyze robotic construction methodologies enabled us to analyze the differences in speed (simulation with or without wind) and cost of construction; the data obtained was analyzed and compared with manual construction methodologies. After the data was gathered and analyzed, it was concluded that, in terms of cost, robotic construction was always more expensive than manual construction, especially in the case of the first two geometrically simpler walls, since manual construction was faster. However, in the case of the third wall, which involved a geometrically more complex design, although it was more expensive, robotic construction reduced the construction time by 50%, with a very small error margin which resulted in a near perfect reproduction of the wall that would be very difficult to achieve using manual labor.

When it comes to the interference of external factors such as wind in the simulation environment, we can conclude that the strongest the horizontal force (wind) the more time and battery life a drone will use to not only correct its trajectory but also to complete the building process.

For the second hypothesis, the simulations enabled us to analyse each structure before, during, and after construction and check for any possible construction and structural errors. This allowed us to detect errors, in the third wall, for example, in which the complex geometry created a series of cantilevered blocks at each end where only 1/3 of the brick was supported by the one below it, which would result in it falling due to the force of gravity. In terms of very brick placement deviations, a very small error margin could be found between 0 to 1 mm deviation in some cases/places of the structures and depending on external factors such as wind.

The research shows that the use of 4D simulation and VR offers advantages for the planning and analysis stages of architectural design processes. The use of VR makes it possible and accessible to anticipate future robotic routes and construction problems, enabling the user to rethink the processes at any stage and evaluate costs, time and construction constraints such as collisions, forms of interferences which are physical phenomena not evident in a static visualization. By entering a virtual space, we can fully analyse and detail designs, rendering the result more precisely, with fewer interpretation and construction errors.

The use of this technology has the potential to slowly change the building industry, the way we build and design construction sites and locations.

6.1. *Limitations of the study*

The use of VR enables us to fully simulate the world around us, including the effect of most external natural or human interferences. In this study, certain weaknesses were identified in the analysis of the results. We show that the use of VR in robotic construction processes is essential to analyse their potential, but several other aspects must be taken into consideration in order to fully assess this. External factors and interferences that we did not take into consideration must be accounted for, including: (i) natural factors – such as natural and unstable wind, rain, birds, human intervention, and (ii) physical factors – such as gravity, collision, structural integrity of the elements, physical and mechanical properties of the objects, and (iii) inclusion of a more free and less programmed construction trajectory (with the use of Pathfinding software and AI) that can result in differences of brick placement deviations and (iv) the inclusion of mortar during the robotic construction experiment for a final and realistic element construction. This limitation in our study must be addressed in future research.

Concerning the software and methodology used in the simulation process, the Rhinoceros and Grasshopper tools were chosen for the experiment due to their simpler export process and faultless files between platforms. Nevertheless, this software is not as widely used for construction processes as BIM software, for example. Moreover, in terms of methodology, the chosen framework involves several steps and is therefore time-consuming, requiring future work on automation and integration with current design and construction analysis workflows.

Another of the main issues found in the building process was the strictness of the drone trajectories, which did not take into account the possibility of different drone speeds, alternative trajectories to avoid collision, and smart use of drone battery life and coordinates. To overcome this drawback, we anticipate altering the construction trajectory planning, using a system of NavMeshes to allow the drone to choose the best trajectory for each construction coordinate, while avoiding permanent and dynamic obstacles.

6.2. *Future work*

In addition to the points highlighted in the limitations section, some other aspects of the research need to be developed. Many of the weaknesses, such as physics and the interference of external obstacles, are crucial points that should be addressed in order to fully simulate outdoor as well as indoor drone construction.

In future work, we also intend to simplify the simulation methodology by creating a single algorithm capable of connecting the design software and the simulation, making it possible to create and change the shape of a design, e.g. a wall, and automatically calculate and simulate the construction process in VR environments.

It is also important to evaluate worker safety and trust when sharing a workspace with drones and other robots as well as explore possible Human/Robotic cooperation possibilities. VR simulation is especially well suited for this aim.

The integration of BIM technologies (BIM modelling and time planning software and parametric modelling tools such as Dynamo) is an important step for the future. With the full implementation of BIM, enabling construction objects and the construction environment to be described with a high level of development, the robotic construction simulation may be integrated into the design and construction planning processes.

Regarding the drone trajectory, we intend to change the circular shape in future work by providing the drone with a building area and by the use of "pathfinding" algorithms and AI to enable the drones to choose the fastest and best trajectory for each brick, while avoiding possible spatial obstacles such as other drones and humans.

For a more realistic construction experiment the use of binding materials and strategies to implement them throughout the building process should also be further investigated and addressed in future work (full robotic construction or human/robotic cooperation strategies).

Declarations

Author contribution statement

Nuno Pereira da Silva, Sara Eloy and Ricardo Resende: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by the Fundação da Ciência e Tecnologia (FCT) PhD grant SFRH/BD/146143/2019, and by the research unit project UIDB/04466/2020, also funded by the FCT.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] F. Augugliaro, R. D'Andrea, A. Mirjan, F. Gramazio, M. Kohlar, Architectural fabrication of tensile structures with flying machines, Green Des., Mater. Manuf. Process. (2013) 2013.

[2] A. Mirjan, F. Augugliaro, F. D'Andrea, F. Gramazio, M. Kohler, Building a Bridge with Flying Robots, Springer International Publishing, 2016.
[3] T.L. Friedman, The Lexus and the Olive Tree, Farrar, Straus and Giroux, New York, 1999.
[4] S. Al Dallal, The fourth industrial revolution and beyond, Int. J. Recent Technol. Eng. (2019).
[5] All Robots, All Robots - ROBOTS: your guide to the world of Robotics. https://robots.ieee.org/robots/, 2019 (accessed Mar. 05, 2019).
[6] J. Lee, et al., A Case Study in an Automotive Assembly Line: Exploring the Design Framework for Manufacturing Gamification 490, 2016, pp. 305–317.
[7] P. Tsarouchi, A.-S. Matthaiakis, S. Makris, G. Chryssolouris, On a human-robot collaboration in an assembly cell, Int. J. Comput. Integrated Manuf. 30 (6) (2017) 580–589.
[8] A. Hentout, M. Aouache, A. Maoudj, I. Akli, Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017, Adv. Robot. 33 (15–16) (2019) 764–799.
[9] P. Tsarouchi, G. Michalos, S. Makris, T. Athanasatos, K. Dimoulas, G. Chryssolouris, On a human–robot workplace design and task allocation system, Int. J. Comput. Integrated Manuf. 30 (12) (2017) 1272–1279.
[10] P. Tsarouchi, S. Makris, G. Chryssolouris, Human–robot interaction review and challenges on task planning and programming, Int. J. Comput. Integrated Manuf. 29 (8) (2016) 916–931.
[11] Y. Yang, M. Pan, W. Pan, Co-evolution through interaction' of innovative building technologies: the case of modular integrated construction and robotics, Autom. ConStruct. 107 (2019).
[12] T. Bonwetsch, D. Kobel, F. Gramazio, M. Kohler, The informed wall: applying additive digital fabrication techniques on architecture, in: Synthetic Landscapes - ACADIA 2006 International Conference, 2006, pp. 489–495.
[13] B.G. de Soto, et al., Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall, Autom. ConStruct. 92 (2018) 297–311.
[14] C.-J. Liang, K.M. Lundeen, W. McGee, C.C. Menassa, S. Lee, V.R. Kamat, A vision-based marker-less pose estimation system for articulated construction robots, Autom. ConStruct. 104 (2019) 80–94.
[15] Z. Wang, H. Li, X. Zhang, Construction waste recycling robot for nails and screws: computer vision technology and neural network approach, Autom. ConStruct. 97 (2019) 220–228.
[16] T. Tsuruta, K. Miura, M. Miyaguchi, Mobile robot for marking free access floors at construction sites, Autom. ConStruct. 107 (2019), 102912.
[17] M.A. Abdelmegid, V.A. González, M. Poshdar, M. O'Sullivan, C.G. Walker, F. Ying, Barriers to adopting simulation modelling in construction industry, Autom. ConStruct. 111 (2020), 103046.
[18] W. Liu, et al., Physical simulation of construction and control of two butted-well horizontal cavern energy storage using large molded rock salt specimens, Energy 185 (2019) 682–694.
[19] S. Salimi, M. Mawlana, A. Hammad, Performance analysis of simulation-based optimization of construction projects using High Performance Computing, Autom. ConStruct. 87 (2018) 158–172.
[20] Q. Zhang, Y. Jiao, M. Cao, L. Jin, Simulation analysis on summer conditions of ancient architecture of tower buildings based on CFD, Energy Proc. 143 (2017) 313–319.
[21] J. Gaspari, K. Fabbri, T. Cancellari, G. Corazzi, V. Vodola, The use of building performance simulation to support architectural design: a case study, Energy Proc. 122 (2017) 205–210.
[22] M.J. Clayton, R.B. Warden, T.W. Parker, Virtual construction of architecture using 3D CAD and simulation, Autom. ConStruct. 11 (2) (2002) 227–235.
[23] Dictionary.cambridge.org, COMPLEXITY | meaning in the Cambridge English Dictionary. [online]. https://dictionary.cambridge.org/dictionary/english/complexity, 2019 (accessed Feb. 19, 2019).
[24] D. D'Uva, A. Rolando, P. Piumatti, C. Zanchetta, A. Janovitz, Definition and Representation of Complex Architectural Shapes, 2009.
[25] T. Harris, How Robots Work," howstuffworks.Com. https://science.howstuffworks.com/robot.htm, 2017 (accessed Feb. 12, 2019).
[26] M. Rouse, What Is Robotics? - Definition from WhatIs.com 10, 2019.
[27] A. Anon, What Is a Robot Arm? Robots.com, 2017. Robots.com (accessed Feb. 10, 2017).
[28] A. Menges, J. Knippers, ICD/ITKE Research Pavilion 2016-17. https://icd.uni-stuttgart.de/?p=18905, 2017. (Accessed 12 March 2019) accessed.
[29] C.J. Lange, D. Holohan, H. Kehne, Ceramic constellation | robotically printed brick specials, in: Robotic Fabrication in Architecture, Art and Designs 2018, 2019, pp. 434–446.
[30] E. Young, "SAM, THE ROBOTIC BRICKLAYER," https://www.dynamicsofmasonry.com/WORDPRESS/sam-the-robotic-bricklayer/?msclkid=fe81bb25d14111ec9d1c3335dc46b8a8, Jan. 12, 2021.
[31] ETHZ, Flying Machine Enabled Construction, Idsc.ethz.ch., 2017.
[32] F. Augugliaro, R. D'Andrea, A. Mirjan, F. Gramazio, M. Kohler, Architectural Fabrication of Tensile Structures with Flying Machines, in: Green Design, Materials and Manufacturing Processes, 2013.
[33] ETHZ, Aerial Construction, Idsc.ethz.ch., 2017.
[34] T. Bonwetsch, D. Kobel, F. Gramazio, M. Kohler, The Informed Wall applying additive digital fabrication techniques on architecture, in: ACADIA 2006: Synthetic Landscapes Digi- Tal Exchange, 2006, pp. 491–494.
[35] J. Banks, Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice, Wiley, New York, 1998.
[36] J. Steuer, Defining virtual reality: dimensions determining telepresence, J. Commun. 42 (4) (1992) 73–93.
[37] A.K. Bashabsheh, H.H. Alzoubi, M.Z. Ali, The application of virtual reality technology in architectural pedagogy for building constructions, Alex. Eng. J. 58 (2) (2019) 713–723.
[38] M. Slater, B. Spanlang, M.V. Sanchez-Vives, O. Blanke, First person experience of body transfer in virtual reality, PLoS One 5 (5) (2010).
[39] D. D'Uva, A. Rolando, P. Piumatti, C. Zanchetta, A. Janovitz, Definition and representation of complex architectural shapes, in: Experiences in Advanced Courses at the Faculty of Architecture in Milano, 2009.
[40] H. Li, Z. Ma, Q. Shen, S. Kong, Virtual experiment of innovative construction operations, Autom. ConStruct. 12 (5) (2003) 561–575.
[41] A.Z. Sampaio, O.P. Martins, The application of virtual reality technology in the construction of bridge: the cantilever and incremental launching methods, Autom. ConStruct. 37 (2014) 58–67.
[42] R. Navon, A. Retik, Programming construction robots using virtual reality techniques, Autom. ConStruct. 5 (5) (1997) 393–406.
[43] P. Adami et al., "Effectiveness of VR-based training on improving construction workers' knowledge, skills, and safety behavior in robotic teleoperation," Adv. Eng. Inf., vol. 50, p. 101431, Oct. 2021, .
[44] F. Osti, R. de Amicis, C.A. Sanchez, A.B. Tilt, E. Prather, A. Liverani, A VR training system for learning and skills development for construction workers, Virtual Real. 25 (2) (2021) 523–538.
[45] D. Wood, M. Yablonina, M. Aflalo, J. Chen, B. Tahanzadeh, A. Menges, Cyber physical macro material as a UAV [re]Configurable architectural system, in: Robotic Fabrication in Architecture, Art and Design 2018, 2019, pp. 320–335.
[46] ECC, Europeen Construction Cost, 2020. http://constructioncosts.e.