Exploratory Research towards Automated Masonry Construction using UAVs

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Abstract. Unmanned autonomous vehicles (UAVs), also known as drones, are pervasive in modern society for both recreational and business purposes. Construction sites routinely employ UAVs to capture imagery used for photo documentation, progress reporting, surveying, and inspection. Drones can also carry infrared cameras and LIDAR, increasing opportunities for their use on construction sites. They are not limited, however, to remote sensing and photogrammetric applications. Research is pushing the boundaries to explore other UAV opportunities, such as material deliveries and physical construction. This paper reports on exploratory research to investigate current efforts in automated construction of masonry walls using drones and drone swarms. Masonry was chosen due to the repetitive nature of the processes, which increases the probability of successful implementation. The results of a literature review are first presented to establish the state of the art in this area. The proposed approach will be evaluated based on the construction quality in accordance with standards, entailing both accuracy and precision requirements in the laying process. Approaches for continuing research in drone-based masonry construction automation will be outlined and discussed in the conclusion.

1. Introduction

The construction industry global market is expected to be a total worth of $15 trillion by 2025, a projected increase of 70% compared to its worth in 2013 [1]. Investments in the construction sector are projected to continue to increase steadily in the near future beyond 2025 as global economic growth expands. In Western nations, this growth is hindered by challenges with labor availability. To advance the industry capabilities, professional societies have been proactive in recruiting and training. Material suppliers introduce products with less labor demand for installation, such as self-consolidating concrete. Prefabrication and off-site manufacturing further reduce on-site labor requirements. Accordingly, there is a need for continuous innovation to support and enable the industry to match the rising demand.

Furthermore, current construction practices depict a rising demand for skilled laborers. With the construction industry shift towards high-rise structure development, workers' safety and health risk have undoubtedly escalated. Consequently, construction workers have a 1 in 200 chance to die or get severely injured from the job on the field over a 45-year career span period [2]. Robotics and the use of technologies, such as UAVs, for physical construction, can provide further positive benefits by eliminating risks associated with workers' safety. This is a further additional benefit complementing projected improvements in quality and productivity.

The incorporation of off-site manufacturing and just-in-time delivery has enabled construction innovators in China to build commercial structures in days as opposed to months. Robotics and automation promise the ability to bring techniques commonplace in manufacturing to the construction site. Significant research in this area has been done at the Technical University of Munich and
throughout Japan and Korea [1]. Moreover, these techniques tie to the broader field of construction automation (CA), which is considered an integral technological advancement to the development of construction 4.0 practices – practices that promise to revolutionize the industry.

Building construction includes many disparate activities, such as site surveying, excavation, bricklaying, concrete casting, tiling, painting. Construction robotics can incorporate the latest technologies, such as sensors, cameras, mapping, planning tools, to allow enhanced control and efficient task execution. CA and robotic systems development are seen to be able to highly contribute to the development of safer construction, with lower cost, better quality, and reduced duration [3]. In regard to autonomous on-site construction, three families of robotics can be recognized: 3D printers, mobile robots, and unmanned aerial vehicles (UAVs). Construction 4.0 incorporates all three of these families; however, each has limitations that must still be overcome by research and development. 3D printers, for instance, are restricted because they need to be on a gigantic scale and are often larger than the structure to be constructed. Mobile robots are restricted in their movement space, which results in construction progress disruption. Finally, UAVs are limited to their payload capacity and the required accuracy imprecision in the elements' placement.

It is beyond the scope of this paper to investigate the current state of the art for all three of these areas. Thus, this research explores how to un-tether an automated process using UAVs for construction activities and assistance in construction activity completion. UAVs are becoming more common worldwide and frequently used for surveying, documentation, communication, and recording site conditions [4]. Each iteration of drone advancement incorporates more sensors allowing for safer flight coupled with software advances that allow for ease of use and autonomy [4]. Furthermore, drone technology has advanced to allow for interchangeable and increasing payloads, supporting several construction applications. This research summarizes activities completed and published to date and develops a conceptual framework for furthering knowledge in this area through additional research.

2. Objectives

Significant research involving UAVs has been identified in the literature in recent years. Some of this research involves using drones for the delivery of the actual construction for a given activity. Where this has been examined, the approaches were tested and validated under controlled environmental conditions and generally focused on the use of single drones. Accuracy limitations were observed and documented in the assembly process in most research activities. This research recognizes these challenges but also recognizes that tools and techniques continue to advance, which will address the precision in future iterations and with the coupling of drones with alternative location systems, such as Vicon and Optitrack - motion capture systems and Real-Time Kinetic (RTK) systems.

This research will build upon the state of the art as identified in the literature to investigate how UAV-based drones and drone swarms can be utilized for construction. Furthermore, the research aims to develop a new construction process by building further promising studies in this field. Specifically, the research will focus on masonry blocks and brick walls, which involve significant task repetition. UAVs facilitate enhanced construction efficiency with lower costs and allow new shapes and materials to be realized with the new way of thought resulting from such technological adoption [5]. The research will address drone technology and UAV development, the construction elements, and the construction process in terms of sequencing. The proposed approach will be evaluated based on the construction quality according to standards specified for masonry construction. Accordingly, tolerances and sequencing are critical facets relating to the elements and the process, which will be addressed in this research.

Furthermore, the research hypothesizes the cooperation of several UAVs or a swarm of UAVs acting in parallel to attest to its presumed increase in overall construction efficiency in terms of cost and time. Experimentation will first be performed in controlled, indoor conditions. Then, research results will be extended to outdoor environments to investigate the role of wind and other environmental factors on the resulting techniques.
3. Literature review

UAVs ability to physically interact with the real world; allows them to contribute to construction directly and not just perform inspection applications. Seminal research in this area was carried out by a joint effort between MIT and UCL [6]. The team explored using structural elements of different shapes and sizes, including conical-shaped bricks developed to build circular columns and rectangular bricks as typically used in current practice. Ultimately, the team developed "Droxels" reimaged masonry units that can overcome mortar use and accommodate complex and intricate architectural designs. However, while MIT and UCL team reimagined the concrete masonry unit, introducing such units in the marketplace has significant barriers to implementation. For these reasons, this research will be performed using traditional masonry units and shapes currently available in the market. The rest of this section reviews three major studies in this area (Table 1) and highlights significant findings and achievements.

Table 1. Related research methodologies and aspects

| Research team               | Reference | Structure constructed | Task sequence | Guidance system                                | Grasping Mechanism          | Payload |
|-----------------------------|-----------|-----------------------|---------------|-----------------------------------------------|-----------------------------|---------|
| Kohler and Raffaello d'Andrea | [7]       | Polystyrene foam brick tower | -             | FMA - motion capture system                  | Electromagnetic gripper     | -       |
| MIT and UCL                 | [8]       | Prototypes using dricks and droxels | CAD to UAV instructions | Image recognition, laser, GPS/RTK, and GPS/automatic theodolite RGB-D detection of plate, GPS & down-pointing Garmin LiDAR lite v3 sensor | Specially designed grippers | -       |
| CTU, UPenn, and NYU         | [10]      | Dropped bricks on a wall | Special algorithm |                                          | Electromagnetic gripper     | 1kg     |

3.1. The flying machine arena platform

The flying machine arena (FMA) platform is a vision-based autonomous system and is considered the benchmark for future innovations and designs in UAV construction applications. In research led by R. D'Andrea, the FMA platform was also demonstrated in 2011 at Orleans, France exhibition (Figure 1), where 4 UAVs were utilized to construct a 6-meter-high composed of 1500 polystyrene foam brick tower. This experiment is considered the first architectural construction assembly with UAVs. Other demonstrations for the FMA platform were carried in 2012 Zurich - Hannover Messe in San Francisco and in 2013 at Edinburgh TED Global events.

The platform is equipped with 19 Vicon T40 cameras to cover the arena flight space capacity of almost 720 m³. The reported system setup time for the platform is between four and six hours [7]. The designed system can record measurements at a rate of at least 300 Hz (200 Hz typically required). Measurements inside the FMA are taken with respect to a user-defined coordinate frame. The core system components include global sensing (motion capture system), on-board sensors, off-board control/estimation modules, wireless command interface, state machine, and actuator. The object's positions (x, y, z) are tracked with the help of the cameras imagining sensor/optics capabilities along with near-infrared strobes and 3–4cm retro-reflective markers. Moreover, a calibration algorithm is utilized to take account of the cameras and other benchmark positions. The data is then reused by the camera simulation tool to calculate required adjustments from the current motion capture coordinate and accurately mirror the arena.

It is typically mandated to simulate the exact flight plan multiple times; however, it is challenging to realize this in an asynchronous simulation [7]. The simulation was performed mathematically with nominal equations of motion, using input from the on-board control/estimation and state machine. Parameters that can alter the UAV simulation's flight control include disturbances (wind), sensor inaccuracy, and simulation speed. To consider the average deviance in control of the UAV flight, simulation calculations are performed on the expected flight state.
3.2. MIT & UCL collaboration

In aims to present an alternative to additive manufacturing building scale limitation. A research collaboration between MIT and UCL; investigated the feasibility of constructing real building scale structures using UAVs. Traditional masonry wall construction requires accuracy in the brick assembly of less than 1 cm [8]. Therefore, the team explored several guidance systems: image recognition and color tags, laser system mounted on the UAV, GPS coupled with RTK, and GPS coupled with an automatic theodolite instrument (Figure 2). Nevertheless, to overcome UAVs’ flight placement imprecision, the study took a different direction by modifying the building's structural components to better fit UAVs' construction limitations. The research team came up with four families of bricks (a portmanteau of "drone" and "brick") and droxels (a portmanteau of "drone" and "voxel"); geometrically modified bricks with defined grooves to enable easy sliding and alignment. Furthermore, they enable the design of complex 3D structures such as curved walls and cantilever. Both bricks advancements, i.e., designed indentations, guide the bricks to slide in place and allow a placement position inaccuracy of almost 5 cm.

Additionally, the team demonstrated CAD benefits and its feasibility in being utilized to formulate UAV flight instructions. The CAD drawing is transformed into a ".dxf file" extension compatible with the C++ subroutine, which translates each brick on the line into x-y coordinates. A "txt file" is then accordingly generated, holding the UAV flight instructions between the loading bay and the required position of the brick's placement (Figure 3).

Further renovations were presented by the research group a year later [9]. The authors confirmed the feasibility of constructing a real scale structure, i.e., concrete precast column using UAVs (Figure 4).
large-scale drone testing was performed using a custom-built UAV with a 40kg payload capacity. The study implemented manual piloting of the UAVs as a proof of concept pertained by the allowed position inaccuracy due to the introduced bricks. The column was constructed by stacking 15-20kg cylindrical bricks (with a metallic plate on top) designed with an allowable position inaccuracy of 6.5cm. The UAV used in this experiment was equipped with an electromagnetic guidance cone for enhanced grip and placement mechanism.

![Figure 4. UCL drone assembled precast concrete column][6]

Among the introduced developments are new brick designs, i.e., Drick60. Nevertheless, the introduced bricks still had drawbacks, including required complex formwork and weakness of the brick's thin sides. Similarly, other dricks introduced had other complex issues, i.e., requiring different types and sizes of bricks based on their application (walls and corners). Correspondingly, to ease the complexity of the several dricks introduced, the authors designed dronicks software that automatically portrays the required dricks types at each location of the wall structure.

3.3. CTU, UPenn, and NYU collaboration

The discussed system is a joint research between CTU, UPenn, and NYU, designed for Mohamed Bin Zayed International Robotics Challenge (MZIRC) 2020. The challenge consisted of picking and placing bricks by a UAV team on a highlighted wall pattern. The presented system was the best performer in the competition, with correctly dropping ten bricks. The designed system can scan an area to locate the loading bay and placement location, precisely grasp the bricks, and drop them in position. Accordingly, one of the UAVs in the swarm is responsible for site scanning and creating a topological map (highlighting the brick stack and the wall planned to be constructed). Subsequently, the map is shared with the rest of the UAV swarm. Three UAVs were employed for the joint wall construction; however, only two UAVs were allowed to fly simultaneously to mitigate collisions. Additionally, predicted trajectories were utilized to ensure the UAVs do not cross pass within their planned routes.

Among the research challenges was establishing proper navigation to effectively grasp the bricks from the stack and precisely place them on the wall structure. The study utilizes visual surveying techniques instead of a motion capture system. The experiment guidance system combines Red-Green-Blue-Depth (RGB-D) cameras, GPS, and Light Detection and Ranging (LiDAR) sensors. Robust and prompt brick detection is fundamental for effective grasping [10]. The bricks need to be grasped from their center of mass; to prevent the additional torque from the additional mass and allow for stable flight control and accurate placement. RGB-D cameras can precisely allocate the brick position and the constructed wall while hovering over the site area. Moreover, the bricks are amended with ferromagnetic plates on their top; to allow for better grip using UAV. Nonetheless, it should be noted that the established accuracy for brick placement is not appropriate to constructing a real-wall structure. Blocks were dropped onto any position on the laid-out wall structure and used no glue or mortar to secure the brick in place. Another challenge with the process is that the grasped bricks slightly impact the wall detection and placement process where the brick covers the sensors during its travel.

4. Planned research methodology

The research will investigate possible assembly techniques in laying out the bricks and establishing rules and scenarios to guide the UAVs through their flight assembly (Figure 5); to allow for a better efficient
construction process. A scaled-down experiment "small-scale testing" of the proposed methodology will be initially applied on Styrofoam-shaped blocks conducted under a controlled environment. After that, testing will be carried for the outdoor area to ensure system efficiency in constructing an actual wall. The initial stage of testing aims to determine the appropriate guidance system and establish the path planning algorithms that the UAVs will use. Furthermore, the authors will investigate the coupling and use of traditional cementitious mortars and specialized polymer adhesive to ensure completed construction within the required load-carrying capacity and code constraints. Lastly, swarm drone applications will be explored to establish the work distribution for each drone and discover methods to prevent clash detection, i.e., simulating real-time coordinates of each UAV.

Figure 5. UAV rules for laying out bricks [6]

4.1. UAV construction process
Current technology can transform the bricklaying process and wall building to a completely autonomous approach. First, the process is initiated by scanning the site area and identifying the coordinates for the loading bay and the planned wall structure. Next, each UAV is assigned a brick to grasp from the stack, and an algorithm creates a plan for each UAV routes to place the brick in place. The process is repeated until the wall is constructed as per plan or until the UAV battery is depleted. Intermediate steps include hovering above the loading bay and the planned wall structure to locate the bricks' center while loading and placing.

4.2. Guidance control
This study's planned UAV guidance control is a motion capture system, i.e., Optitrack cameras. The system will utilize reflective markers to compute the UAVs position 100-200 times/sec, allowing precise navigation within the system's frame sight. Furthermore, on-board sensors and GPS could also enhance UAV guidance and act as a backup when the reflective markers fall out of sight. The projected placement accuracy from this system is in order of 3-5 mm.

4.3. Grasping mechanism and path planning
Designing an efficient gripper is highly important in the proposed application's success. The gripper directly relates to the successful grasping of the brick's center of gravity and placement accuracy. The most promising grasping mechanisms discovered in the literature include electromagnet couplers, special transportation grips, and micro-spine grippers. Each will be considered and evaluated with performed experimentation. As for the path planning, Dijkstra's algorithm will be deployed to find the optimum route, i.e., the shortest path between two coordinates (loading bay & planned wall) while avoiding known obstacles.

4.4. Modeling and simulation
Robotics are designed to enable physical world interaction using lines of coding to perform a specific task. The coding varies based on the required task that needs to be executed by the robot. Therefore, the modeling process is vigorous, and effort is required to develop a code that works with the robot size and components and executes tasks depending on the predefined work settings. Construction simulation is a process of replicating reality to extract specific parameters to help refine construction works efficiency. Simulation models seek to refine the defined workflow process by recognizing and eliminating activities that do not add value to the process [11]. Although the simulation process might add more time to the project planning phase, the payoffs are considered rather rewarding with the reduced cost of making unnecessary decisions and their corresponding time. Furthermore, simulation can help identify activities' duration and the optimum resources needed for a particular construction task. These results can be
integrated into construction planning and management to maximize efficiency and reflect better project schedules and budgets.

4.5. UAV swarm coordination
A UAV swarm are a set of aerial robots that collaborate to establish a certain user-defined goal. Swarm utilization enables completing tasks in parallel and therefore results in a more productive, efficient process. Other benefits to multi-UAV systems are that a single drone out of control will not stop the entire process since; other UAVs will operate ordinarily. Designing a good communication architecture will enable efficient coordination between the UAVs in completing the assigned task, help prevent clashes in UAV flights, and classify UAVs’ work distribution. However, the number of control computations required to navigate the UAV does not scale with more deployed UAVs. The form of communication deployed between the UAVs and the control center is determined based on the number of UAVs deployed and the required coverage area. Two main communication approaches were discovered in the literature: centralized and decentralized communication. A centralized communication approach is a system designed with a central station/node "infrastructure" as the only communicator providing control commands to every UAV in the swarm. On the other hand, the decentralized communication is a more complex approach recommended for huge UAV swarms, where the dependence on one central station is eliminated with real-time interactive communication [12]. Both forms of communication are planned to be explored to determine which approach fits the proposed process.

5. Conclusion
The research explores construction applications that take advantage of UAV capabilities in forming an automated construction environment with increased construction value and reduced risks. The anticipated primary benefit that we could obtain from the research is automating the brick construction process and achieving higher productivity and associated cost savings. Significant background work has been performed by researchers from MIT, UCL, ETHZ, Penn State, NYU, and elsewhere with notable efforts summarized herein. These efforts demonstrated the progress that has been made towards the automation of construction activities using Unmanned Aerial Vehicles (UAVs, i.e., drones) and drone swarms. A methodology for using drones to construct masonry walls was outlined, with salient elements of the approach discussed. The approach utilized construction quality as the metric for success, with swarm elements added for productivity and cost elements. The research effort seeks to advance research knowledge towards the ultimate successful implementation of drones for masonry construction on commercial construction sites.

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