A New UAV-based Module Lifting and Transporting Method: Advantages and Challenges

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Abstract –

The modular construction technique is the one key technology that can substantially advance the competitiveness of the construction industry. However, the industry is having difficulty creating an optimum environment for broader and more effective use of modularization due to one key barrier: implementing a modular construction technique, that is, shipping modules from the fabrication shop to the build site. Multiple issues are potentially challenging to overcome, such as module size and center of gravity, rigging, tie-down, site access, site congestion, and transportation regulations, as well as the availability of local heavy lift equipment. The researchers propose to implement drones as a way to address module transportation challenges and innovative logistics of modules. The primary research objectives are to innovate logistics with a new drone-based module lifting/transporting method, consisting of a drone lifting/transporting a module from below, similar to a pallet. In this paper, the researchers present key challenges and potential advantages, which have been identified from a manual test flight of the new method, with a drone lifting/transporting an acrylic cube box from below. The key challenges identified from the manual test flight are 1) limited payload, 2) limited power supply, 3) dynamic properties of a module; 4) agility/instability of unmanned aerial systems (UAS), and 5) regulations. Through the use of the drone-based module method, the researchers expect that lifting/transporting times and costs can be significantly reduced, eventually diminishing total installation costs, and expediting the overall construction process. This study will lead to the development of a drone-based module transportation framework for practitioners in the construction industry.

Keywords –

Modular construction; Modularization; UAS; Drone; Logistics; Module transportation; Lifting

1 Introduction

Modular construction is a manufacturing and installation technique that specializes in exporting site-based development to an offsite location. The modular construction technique has been utilized for centuries. Yet, in the past, modular construction was limited to lower levels of modularization. Moreover, many modular projects failed to achieve expected levels of performance or full benefits due to poor planning, poor management, late scope commitment, design changes, union jurisdictional problems, and/or module shipping failure. However, thanks to the advancement of robotics, information technology (IT), and Building Information Modeling (BIM) technologies, as well as an increased awareness of green construction and lean principles, the modular construction technique has rapidly evolved. This has enabled practitioners to plan and manage a modular project better, fabricate modules more precisely, and apply the modular technique to bigger and more complicated projects. It is now evident that practitioners and researchers in the construction industry recognize the value of modular construction. The potential of the modular construction technique will continue to grow [1] as the productivity growth of fabrication shops increase [2].

An inevitable disadvantage of the modular construction technique, compared to the conventional stick-build method, and one key barrier to implementing this technique is shipping modules to the build site and lifting/placing modules at final installation locations [3–6]. Multiple issues, such as module size and center of gravity, rigging, tie-down, site access, site congestion, onsite storage areas, transportation rules, regulations, delivery time restrictions, traffic, and local heavy lift equipment availability can potentially add costs for module transport and lift [3,6]. If the construction industry can innovate module logistics and shipping processes, the industry may accomplish broader and more effective use of modularization.

For the first time, the researchers propose to implement drones as a way to address module transportation challenges and innovative logistics (lifting/transporting) of modules. The primary research objectives are to innovate logistics with a new drone-based module lifting/transporting method, consisting of a drone lifting/transporting a module from below, similar to a pallet. In this paper, the researchers present key challenges and potential advantages identified from the literature review, as well as a manual test flight of a new drone-based module lifting/transporting method, with a drone lifting/transporting an acrylic cube box (a module) from below.

2 Methods

This research process for this paper is as follows: 1) problem identification with the process of module logistics; 2) extensive literature review on modular construction and drone applications; 3) development of a new method of a drone lifting/transporting a module from below; 4) fabrication of a prototype unmanned aerial vehicle (UAV); and 5) manual test flight of the new UAV-based module lifting/transporting method. Detailed research steps are described below.

First, the researchers identified the need for innovation of module logistics in modular construction in order to accomplish more effective uses of modularization. One of the researchers' past findings showed that one key barrier to implementing the modular construction technique is shipping modules to sites and lifting/placing modules at final installation locations [3,4]. Additionally, executing a preliminary transportation evaluation based on a full understanding of module limitations is the most critical success factor (CSF) for modularization [1].

Second, to define the research problem clearly and to find gaps in the existing knowledge, the researchers conducted a review of the literature on modular construction methods as well as drones. In this paper, the researchers summarized the current applications of drone in the construction industry and the challenges of module transportation.

Third, the researchers proposed and developed a method of implementing drones as a way to address module transportation challenges and innovative logistics (lifting/transporting) of modules. To better understand the new method's potential and challenges, the researchers developed/fabricated a small-scale prototype and tested it. The details of the proposed method, the development process of the prototype, and the specifications of the prototype can be found in the Results and Discussion section.

Finally, the researchers conducted a manual test flight of the new UAV-based module lifting/transporting method, with a drone lifting/transporting an acrylic cube box (a module) from below. A discussion of the identified potential and challenges are summarized below.

3 Results and Discussion

An unmanned aerial vehicle (UAV) is defined as:

> "an aircraft which is designed or modified, not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an onboard autonomous flight management control system that does not require flight controller intervention." [6, p.7]

While flying robots/aircraft are commonly referred to as UAVs, a term, unmanned aerial systems (UAS) (typically referred to as *drones*), is used to indicate the entire infrastructure, systems, and human-machine interfaces required for autonomous operation [8]. UAS are classified as fixed-wing UAS (FW-UAS) and rotary-wing UAS (RW-UAS). FW-UAS tend to use the most power efficient flying principles, while RW-UAS are tailored to increased maneuverability and stationary vertical flight [8]. This research implements an RW-UAS, as it has higher maneuverability and stationary vertical flight ability.

3.1 Current Applications of Drone in the Construction Industry

Currently, drones have been deployed in [8]:

1. remote sensing – pipeline spotting, power line monitoring, volcanic sampling, mapping, meteorology, geology, agriculture, unexploded mine detection, pipeline risk assessment and repair, power line maintenance, real-time mapping, crop care and mine defusing;
2. disaster response – chemical sensing, flood monitoring, wildfire management, infrastructure repair, flood mitigation, and wildfire fighting;
3. surveillance – law enforcement, traffic monitoring, coastal and maritime patrol, border patrols, crowd control, traffic redirection, and inspection of maritime and trucking containers;
4. search and rescue – assessing the care and delivering first-aid support;
5. image acquisition – inspecting industrial and civil structures, and conducting maintenance work tasks;
6. communications;
7. transportation – small- and large-cargo transport and passenger transport; and
8. payload delivery – firefighting or crop dusting.

Numerous researchers have demonstrated drone applications in the construction industry as well, such as drones to assemble structures (proof-of-concept) [9,10], with manipulators [11–15], and to probe and repair civil infrastructure [16,17]. Lindsey et al. [9] and Willman et al. [10] demonstrated proof-of-concept of workpiece pickup and drop-off (with self-connect, using magnets or pre-machined joints) to defined locations. Some researchers are equipping RW-UAS with manipulators to illustrate more dexterous tasks like inserting, screwing, and removing workpieces [11–15]. Darivianakis et al. [16] and Marconi et al. [17] have presented drones that can physically probe bridges, pipelines, and power lines to repair and replace parts. These efforts led to the inspection of a real power plant boiler using a multirotor vehicle and tightly integrated visual-inertial algorithms [18]. Many practitioners have also shown interest and participated in large consortia to implement drones in the construction industry (e.g., Petrobot Project [19], Aerial Robotics Cooperative Assembly System [20], European Robotics Challenges [21], ARGOS Challenge [22]).

3.2 The Current State-of-the-art of Heavy Aerial Lifting by Drone

Scientists in the UAS domain have demonstrated a system like a flying taxi, which will be commercially available shortly. EHANG 184 has test-flown successfully in Dubai in 2017; it is designed to carry a 100 kg payload for 25 minutes [23]. The Boeing company just conducted first test flight with their Air-Taxi prototype design in January 2019. The specifications are not open to the public yet, but they are planning to launch air-taxis operating in Los Angeles, and Dallas Texas by 2023 [24]. Lastly, Bell Helicopter unveiled a full-scale air taxi concept in 2019 at Las Vegas. The concept is designed to carry one pilot and four passengers [25]. The current state-of-the-art of heavy aerial lifting is described in table 1.

Table 1. The Current State-of-the-art of Heavy Aerial Lifting by Drone

Name	**EHANG 184**[23]	**Boeing Air Taxi**[24]	**Bell NEXUS**[25]
Test Flown	2017	2019	N/A
Weight	260 Kg	N/A	2720 kg
Capacity	100 Kg Payload 1 passenger No pilot	2~4 passengers No pilot	272 kg Payload 1 pilot, 4 passengers
Flight Range & Speed	Time: 25 minutes Speed: 100 km/h	Range: 80 km	Range: 240 km Speed: 240 km/h

Considering the speed of recent technological advancements of UAS, as scientists have demonstrated, a system like a flying taxi will be commercially available shortly, a drone will be available for heavy aerial lifting in the near future.

3.3 Problem Identification with the Process of Module Transportation

Compared to the conventional stick-build method, the process of module transportation, including rigging, lifting, and installation is unique to the modular construction method. According to two recent surveys [4,26], this process was selected as one key barrier to implementing the modular construction technique. There are many issues related to modules that need to be considered, such as design/fabricate/install strategies, module type, number of modules (one box or multiple assemblies), contract, supply chain, transportation restrictions (length, height, width, and weight), and critical constraints (water access, road access, and overhead obstructions) [1]. Additional issues, such as module size and center of gravity, rigging, tie-down, site access, site congestion, onsite storage area [27], can be potentially additive and more difficult to overcome for transporting and lifting modules. Proper engineering, planning, and project support are required for a successful module transport effort. However, planning module transportation is a very complex task [28]. Because many municipalities, counties, and townships have their own restrictions, without an experienced shipping and traffic coordinator, transport is not easy to manage [29]. In particular, transportation restrictions determine maximum module sizes [30,31] and that fact can impede the implementation of modularization.

3.4 A New UAV-based Module Lifting/ Transporting Method

The researchers propose a new method (hereafter known as *the new UAV-based module lifting/ transporting method*) of *a drone lifting/transporting a module from below* like a pallet, as illustrated in **Error! Reference source not found.**, to replace the traditional modular transportation process.

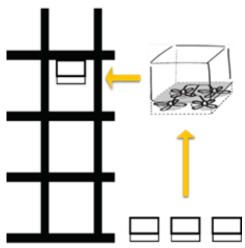

Figure 1. The new UAV-based module lifting/

transporting method

As Figure 1 illustrates, in this study, the researchers focus on transporting and lifting a cube shape, light building/facility module (i.e., HVAC and utility skids) with one UAS.

3.5 Development of a Prototype UAV

To test-and-evaluate the UAV-module, the off-the-shelf component Q450 V4 glass fiber frame is selected. The UAV-module consists of a Pixhawk autopilot controller and four 920kv (RPM/V) brushless motors fitted with 9.5-inch propellers. The selected battery (3-cell, 2.2 A, 11.1 V lithium poly) yields a UAV that can carry up to a 4.5 kg payload. The size of the UAV-module is 0.45m by 0.45m. A cubic-foot sized acrylic box was chosen for transportation. Lastly, a 3D printer is used to customize a suitable holder for the battery and acrylic cube box (Fig. 2). The UAV-module is manually deployed by FrSky Taranis X9D plus a transmitter (Fig. 3).

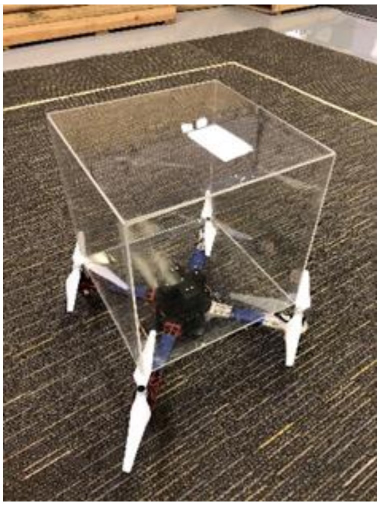

Figure 2. Prototype UAV with an acrylic cube box (a module)

Figure 3. Prototype in-flight testing

3.6 Manual Test Flight

The researchers conducted a manual test flight of the new UAV-based module lifting/transporting method, with a drone lifting/transporting an acrylic cube box (a module) from below (see Figure 3). The key challenges that have been identified from the manual test flight are 1) limited payload, 2) limited power supply, 3) dynamic properties of a module, 4) agility/instability of UAS, and 6) regulations.

First, there is a significant gap between a current drone's payload capability and a typical module's weight. Scientists in the UAS domain have demonstrated a system like a flying taxi [23–25,32], which will be commercially available shortly. However, a module's weight can be heavier than a drone's current maximum payload capacity. The second key issue is the power supply of a drone. Currently, with an 11 Volt, 2.2 Ampere Lithium-Polymer (Li-Po) Battery, a typical hobby quadcopter Q450 can only fly about 15 mins and lift 4.8kg, including the parts. As the flight duration is negatively correlated with the weight of the drone and module, the new UAV-based module lifting/transporting method may able to fly for only a few minutes without an improvement of the battery. Due to these weight and size restrictions, the choice of sensors, processors, and algorithms also impose technical and scientific challenges [8,33].

Third, the dynamic properties of the module, such as length, height, width, weight, and center of gravity, introduce additional technical and scientific challenges for implementation of the new UAV-based module lifting/transporting method. The manual test flight revealed that with the current flight control system, it is very difficult to manually adjust and control the UAV when the center of gravity of the module is not in the center. This issue leads to the problem of enhanced instability of the UAS. A UAS itself is very agile, which means that it is continuously moving and cannot be stopped to acquire sensor readings. For the new method, as the center of gravity of a module is not always in the center, additional technical and scientific challenges are imposed. To solve the instability issues, new algorithms and autonomous navigation systems are needed.

Finally, regulations related to drone application are key barriers to the new method. Regulations are needed for multiple reasons, such as safety, security, and privacy. Currently, the Federal Aviation Administration (FAA) requires the registration of all different UAV types for all purposes. Additionally, some purposes require certifications, training, and permits. For successful implementation of the new method, several requirements must be met: 1) overcome all of the issues and challenges addressed above; 2) demonstrate its application in terms of capability and reliability; 3) obtain advanced permits.

The high maneuverability and stationary vertical flight ability of RW-UAS give engineers the potential to innovate the module logistics. The test flight demonstrates that the module transportation process can be significantly reduced through the implementation of the new UAV-based module lifting/transporting method. With the new method, once HVAC modules arrive on a jobsite, the modules can be transported directly to the installation location, without a need for the workers to set up or hook the modules into a module lift frame or spreader bars. Moreover, there is no need for scissor/boom lifts, tower cranes, forklifts, or transporters. Due to these reasons, the UAV-based module method can reduce transportation, lifting times, and costs significantly, eventually diminishing total installation costs and expediting the overall construction process.

4 Conclusion

The process of module transportation, rigging, lifting, and installation is unique to the modular construction method, one of the critical barriers to implementing the modular construction technique and executed inefficiently by practitioners. If the process is innovated, the construction industry will achieve broader and more effective use of modularization. Recently, drones have drawn increasing attention from researchers and others in the construction industry due to rapid advancements in related technologies and applications.

The key challenges that have been identified from the manual test flight are:

1. limited payload;
2. limited power supply;
3. dynamic properties of a module;
4. agility/instability of UAS; and
5. regulations.

However, if these challenges can be overcome through the use of the UAV-based module method, transportation times, lifting times, and costs can be significantly reduced, eventually diminishing total installation costs, and expediting the overall construction process. This innovative method will help the industry to overcome key barriers of modular construction: site access problems, site congestion issues, and the limited availability of local heavy lift equipment.

To make this new method application viable to the industry, the development of new batteries, motors, and propellers may require the next level of advancement (increasing size and capacity of motors and propellers, and changing power sources) in order to lift heavy modules. The researchers believe substantial efforts are necessary in the future to solve these issues. However, as scientists in the UAS domain have demonstrated, a system like a flying taxi, which will be commercially available shortly, can be solved within five years, considering the speed of recent technological advancements.

This study will lead to the development of a drone-based module transportation framework for practitioners in the construction industry, including but not limited to, general contractors, module fabricators, and module transporters.

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