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Unmanned Aerial Manipulator (UAM) in Construction: Opportunities and Challenges

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Unmanned Aerial Vehicles (UAVs) have been utilized as an alternative medium to human workers in data collection processes in various industries. The capabilities of UAVs are now being extended from passive tasks of data collection to active tasks of interacting with the environment by equipping them with manipulators and robotic arms to function as Unmanned Aerial Manipulators (UAMs). Research on UAMs has been growing in the last few years. The applications of UAMs have been studied including sensor installation, inspections, door opening, valve turning, pick and drop, etc. for the oil and gas industry and civil applications. However, there is a lack of studies in understanding the potential applications of UAMs and their capabilities in construction and in augmenting construction activities. The goal of this research is to identify potential opportunities and challenges of the application of UAM in construction projects. The study undertakes a literature review followed by semi-structured interviews with industry experts to identify the potential areas for the UAM application and possible challenges towards the adoption of technology in the field. This study contributes to the introduction of a new research area in contact-based UAV-guided technologies in construction processes.

Key Words: Aerial Manipulation, Aerial Robots, UAV, UAM, Construction Drones

Introduction

Unmanned Aerial Vehicles (UAVs) when equipped with a robotic arm, have capabilities to grasp, interact, hang, and manipulate performing as an Unmanned Aerial Manipulator (UAM). Several capabilities of UAMs have been used to assemble and disassemble, install, and retrieve, tool operations, pick up and drop and valve turning, etc. They have been used for installing and retrieving sensors (Hamaza et al., 2019), contact-based structural inspection (Jimenez-Cano, Braga, Heredia, & Ollero, 2015), constructing simple truss-like structures (Lindsey, Mellinger, & Kumar, 2011; Yun, Schwager, & Rus, 2011), and some more challenging tasks such as peg-in-hole and valve turning tasks (Orsag, Korpela, Bogdan, & Oh, 2017). The ability of the UAMs to perform simple manipulations and inspections provides a safe alternative to complete the tasks that are considered dangerous for humans. Research has been conducted where a system has capabilities to inspect pipe surfaces using contact-based electrical conductivity sensors, (Tognon et al., 2019), and a system with capabilities to deposit liquid expansion foam for repair work (Chermprayong et al, 2019). Most of these inspection and repair work are traditionally carried out by humans in hazardous conditions (e.g., at heights) using safety gears such as anchor belts, scaffoldings, cranes, etc. which are still hazardous conditions and even expensive to deploy. UAMs provide opportunities to work in such environments as a safer alternative to human intervention. The application of UAMs in these scenarios shows that they can play a significant role in construction and there is a need to identify potentials of UAM applications in the construction processes.

Although existing UAMs are capable of performing tasks like installation, retrieval, tool operations, pick up and drop, peg in the hole, and valve turning, etc., there is a lack of studies in understanding applications of UAMs and their capabilities in construction processes and in augmenting construction activities. Therefore, this research focuses on identifying potential applications of UAM in construction indicating their potential capabilities and adoption challenges in the construction processes. Specifically, current body of knowledge focuses on the development of UAMs and capabilities of the UAMs to perform manipulative tasks but does not encompass construction activities that can be completed through the application of UAMs and their capabilities. The goal of this research is to identify potential opportunities and challenges of the application of UAM in construction projects. To achieve the study goal, this research first investigates current application of UAM in other domains that can be potentially applied in construction to establish fundamental knowledge on the use of UAMs. Then, through semi-structured interviews, the study has identified opportunities and challenges of the application of the UAM systems in construction processes.

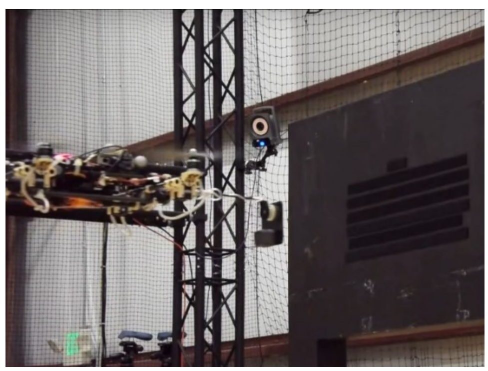

Figure 1. A UAM developed for push and pull task (Anderson, Marshall, L'Afflitto, & Dotterweich, 2020)

Background

UAVs have been equipped with visual cameras, infrared cameras, LiDAR, etc. for visual data collection and processing on construction sites. Such UAV applications collect images, conduct visual inspections, and create 3D models. In fact, application of UAS in construction ranges from performing vision-based pre-construction operations like surveying and site planning (Rawat & Lawrence, 2014; Siebert & Teizer, 2014), to monitoring real-time condition of job sites during construction including progress monitoring (Moeini, Oudjehane, Baker, & Hawkins, 2017), quality inspection (Eschmann, Kuo, Kuo, & Boller, 2012), and safety management, as well as completing as-built documentation using drones equipped with laser scanning technologies (Bosché, Ahmed, Turkan, Haas, & Haas, 2015). In addition to construction management, Liu et al. (2014) have summarized other opportunities of UAVs for seismic risk assessments, data collection on transportation projects, assisting in disaster response, flood monitoring and assessment and surveying and mapping. Despite the benefits of UAVs in the construction process, legal issues pertaining to Federal Aviation Administration (FAA) rules and regulations have been a roadblock to their deployment in the field. Lu et al. (2015) also identified other challenges regarding the use of UAVs in construction such as technology features, organization characteristics, project characteristics, workforce training, and perception towards technology acceptance. Liu et al. (2014) in their study also identified similar challenges such as real-time communication concerns, and information dissemination among stakeholders. Irizarry & Costa (2016) found evidence to these factors where a database of visual assets was evaluated through interviews with project staff of the test sites.

UAM Systems

Aerial manipulation is an emerging field that has introduced new solutions, using UAVs as an aerial medium to navigate through the environment and perform manipulation tasks. A UAM system broadly is comprised of three elements: a UAV as a base for aerial movement, a robotic arm or a manipulator which interacts with the environment, and sensors that include data collection agents such as scanners, cameras, etc. (Ruggiero, Lippiello, & Ollero, 2018). Figure 1 (Anderson, Marshall, L'Afflitto, & Dotterweich, 2020) and Figure 2 show a typical example of a UAM. Equipping a UAV with an arm or a robotic arm enables it to function as a UAM, hence the design of the manipulator is a crucial factor to be considered while categorizing the UAM systems. In a study by Ruggiero, Lippiello, & Ollero (2018) UAMs have been categorized based on the following factors.

1. Degree of Freedom (DoF) of the manipulator such as single DoF (Lindsey, Mellinger, & Kumar, 2011; Hamaza et al., 2019; Augugliaro et al., 2014), dual DoF (Tognon et al., 2019), and more DoFs (Chermprayong et al., 2019)
2. Mechanics of the joint, such as the work by Hamaza et al. (2019) that had a prismatic joint, and the work by Chermprayong et al. (2019) had a parallel joint.
3. Configuration of the system, for example, Chermprayong et al. (2019) proposed a manipulator with a delta-like structure.
4. Motor controlling the system.

Figure 2. An example of a UAM developed with a static manipulator

Current Applications of UAM

Current UAM applications include systems that are applied for three major purposes: contact-based inspection, manipulation, and grabbing and assembly.

Inspection

Studies have shown promising results in using UAMs for inspection and maintenance tasks. For example, under the AEROARMS project for robotic inspection, a platform AEROX aerial manipulator has been developed specifically for inspection tasks (Ollero & Siciliano, 2019). This UAM system has the capability to maintain the force required to keep the sensor in contact with the surface, calculate the position of the arm with respect to the UAV, and maintain stability by overriding the errors due to wind and force generated due to contact (Ollero & Siciliano, 2019). These capabilities are used in conjunction with a contact-based inspection device which uses ultrasound and eddy current sensors.

Manipulation

Autonomous UAM systems are also developed for valve turning tasks in the gas and pipeline industries to eliminate errors during emergencies (Orsag, Korpela, Bogdan, & Oh, 2014). Valves with different colors have different functions and the developed UAM system recognizes valves based on their colors, detects spokes in the valve, and uses a gripper to turn them on or off (Orsag, Korpela, Bogdan, & Oh, 2014). In another research a static manipulator has been used to install and retrieve monitoring sensors in indoor and outdoor environments (Hamaza et al., 2019). The tracking in indoor environments is guided by VICON, a motion capture technology, and GPS for outdoor environments (Hamaza et al., 2019).

Grabbing and Assembly

Researchers have been able to develop a system in which multiple quadrotors with grippers assemble a simple truss-like cubic structure, with magnetic members (Lindsey, Mellinger, & Kumar, 2011). The grippers are enabled to pick up, transport, and assemble the members to present a proof of concept that such systems can construct Special Cubic Structures (SCS) which can be replicated in real-world structures such as towers, scaffoldings, trusses, etc. In a similar study, a system of UAMs was able to incorporate cooperative transportation, where two UAMs grab, transport, and release a 4.23 m (13.9 ft) long bar, as a part of a structural assembly experiment (Ollero & Siciliano, 2019). In that study (Ollero & Siciliano, 2019) two UAMs cooperatively grab a long bar, transport the bar through an environment with obstacles, and places the bar at the required location. In another study, researchers performed an experimental investigation on the use of UAV systems that can assemble a 20 feet high tower of foam bricks (Augugliaro et al., 2014). In that study (Augugliaro et al , 2014), the UAVs are equipped with puncturing pins turning them into a UAM system. Four UAMs then flew autonomously and were guided by motion capturing cameras installed on the ceiling.

Methodology

To address the study objectives, this research used two distinct research methodologies: review of the existing literature and semi-structured interview with construction industry experts. The literature review led the identification of the basics of the UAM design and established a knowledge base on how the capabilities of the UAMs are being utilized across industries. The current state of the art, including the mechanism of UAM systems, their modeling and control, applications in the industry, and the trends and challenges were investigated. These findings contributed towards developing the questions for the semi-structured interview. The gap in the knowledge was addressed by semi-structured interviews with the construction industry experts who have prior experience and knowledge of construction technologies such as UAVs in their projects. Interview participants with prior experience or knowledge of using UAVs on construction projects were recruited through emails. Each interview started with the presentation of study findings on the current applications of UAM and showing example images and videos to the study participants. The videos and examples of various experiments collected during the literature review were shown to the interviewees to provide them with a context of how the UAM technology has been utilized in other domains. Then, the interview was guided by the following pool of questions:

1. What are some potential construction applications of the capabilities we saw in the presentation?
2. UAMs, in general, are being used to carry out tasks at heights (situations hazardous for humans), what are some other situations where UAMs can assist humans to reduce their vulnerability to accidents?
3. Can you think of another type of UAM (a drone integrated with arms or manipulator) in addition to what you just saw in the presentation, that would help construction tasks?
4. What do you think are the challenges of applying UAM in construction? Can you give some examples?
5. What are some limitations of using the capability of UAM in construction we discussed earlier?
6. What are some tasks that can still be performed but do not need as accurate positioning as in tasks discussed earlier?

Recorded interviews were transcribed for content and descriptive analysis. An online software ‘Trint’, was used to transcribe the videos, and QSR NVivo was used for descriptive analysis and text analysis of the interview data. The questions framed for the semi-structured interviews helped to streamline the coding procedure of the data. The interview questions intended to identify opportunities and challenges of the application of UAM in construction processes. So, the questions were broadly divided into two categories, focusing on opportunities and limitations. In the initial round of coding, instances where the interviewees touched upon applications, limitations, challenges, and scenarios of application, were collected. These instances were then categorized into more meaningful and broad themes such as inspections, trade activities, safety and tool operation under “applications” category.

Results

The 30-minute online interviews were recorded on zoom in compliance with the approved IRB protocol (#20-664) and total of six participants were interviewed in this study. The participants represented different construction companies and held different positions in their companies including project managers, superintendents, and executive-level employees (see Table 1). This ascertained that the study participants have a different perspective towards the technology and the feedback on the UAM technology is received from professionals in several levels across different expertise in construction.

Table 1

Details of the study participants

Company Rep	Type of company	Rep’s Position in Company	Years of Experience
Participant 1	Owner’s Representative	Associate Director	27
Participant 2	General Contractor	Senior Project Manager	13
Participant 3	Owner’s Representative	Senior Building Tech Consultant	24
Participant 4	General Contractor	Superintendent	13
Participant 5	Owner’s Representative	Service Executive	24
Participant 6	General Contractor	Superintendent	12

After the initial coding of the interview transcripts, the specific instances are categorized into three broad groups, Opportunities, Challenges in implementing UAM in construction, and Limitations of UAM technology. These categories are further broken down. 'Applications' category is broken down based on the area of application, i.e., whether it is used for inspection purposes, for safety setups, or to conduct construction trade activities. Similarly, 'Limitations' and 'Challenges' categories were broken down into the UAM system design limitations listed under the limitations, implementation challenges such as administrative challenges, the ability to seamlessly integrate the UAM technology in construction processes, and technology perception challenges. A detailed breakdown of the categories is illustrated in Figure 3.

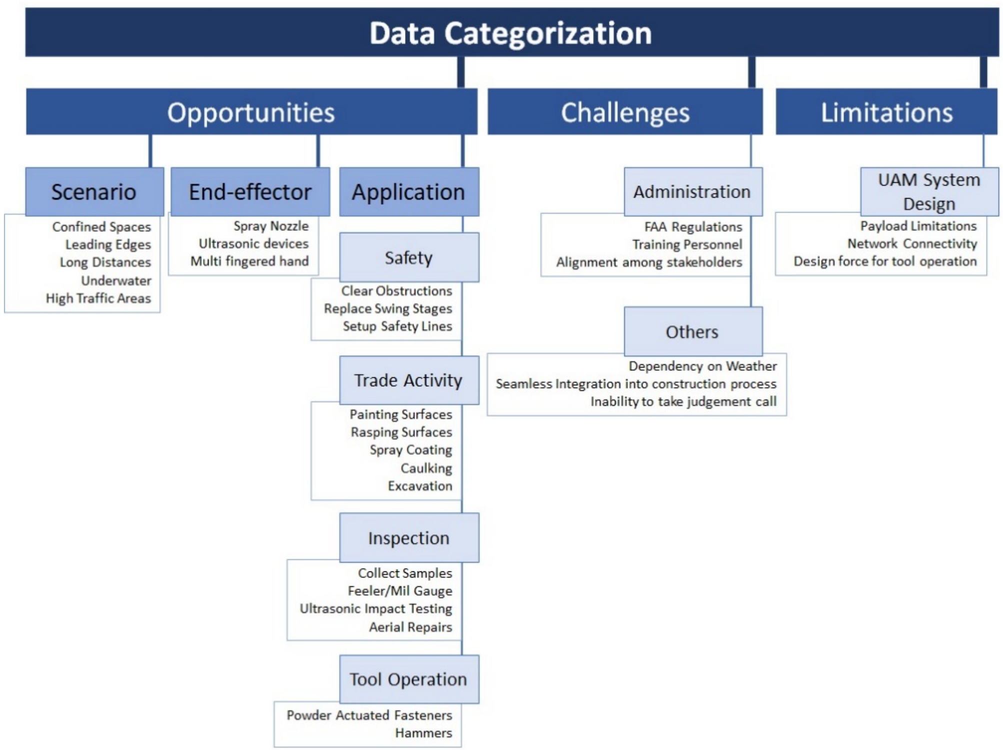

Figure 3. Categorization of data collected from the interviews

Discussion

The opportunities for the UAM application in construction processes identified in this study were divided into three major categories based on (a) applications in carrying out trade activities, conducting inspections, ensuring safety carrying out trade activities, and (b) tailor-made end effectors which is the device connected to the end of the UAM arm to interact with the environment, and (c) their use in scenarios other than heights. Considering UAMs to carry out trade activities, tools operation for surface manipulation (painting, rasping, grating, etc.), and pairing them with spray nozzle (for weather coating) were some of the applications that were unanimously suggested by the participants. This aligns with some of the alternate end effectors that were identified in the literature review section. Participant 2, Participant 4, Participant 5 suggested using the UAM for spraying liquid, Participant 3 discussed equipping the UAV with a spray nozzle as an end effector. In addition to spraying using UAMs for grating and rasping (surface preparation), and caulking was a common theme among Participant 2, Participant 4, and Participant 5. However, limitations of the UAM pertaining to its low payload capacity will have to be addressed before a UAM can be used for these applications. These applications also present an opportunity for the swing stages scaffolding to be potentially eliminated from the construction sites. Swing stage is a platform that is suspended from the building to transport workers, tools or materials to a higher point and eliminating the need for the platform swing can eventually improve workers safety. Some of the study participants suggested that the UAMs can be used to set up safety lines, or barriers on leading edges on construction sites. Although accurate tracking and control of the system has been a categorical problem with UAVs, some of the common applications that came up in the study suggested that the UAM can still be used for activities such as removing obstructions, fixing clogs in pipelines, assisting workers in post demolition cleanup that require lower levels of accuracy.

Using UAMs to conduct structural inspections was another area that was identified in the study. Suggestions from Participant 5 categorically focused on conducting inspections and ties in with their work as a consulting firm. The suggestions included feeler and mil gauges, inspecting surface preparedness for painting by conducting tests on surface samples, and conducting Ultrasonic Impact Treatment (UIT) on steel structures.

Payload capacity was the most common limitation that concerned the study participants. The applications such as painting, and spraying insulations suggested earlier in this section will require the UAMs to either have a container attached to it or it needs to be attached with some hose hooked on to the source of the material. In any case, the design of the UAMs will be instrumental in defining their capability to carry out such tasks. Participants also mentioned workforce training and argued that it is easier to train specialty trade workers to carry out these tasks rather than train a UAV pilot to accomplish the task. At the moment, it seems more convenient to get the specialty workers to carry out these tasks manually compared to process of the paperwork for FFA regulations required for flying a UAV system on the construction site. Appropriate weather and alignment in adopting new technologies are some other factors that play a categorical role in determining the application of the UAMs on the construction site. However, surprisingly none of the participants pointed out issues related to using a swarm of UAMs on the site. In a situation where, multiple trade contractors have their respective UAMs flying around on the site, the issue of UAM swarm seems to pose a serious problem on the jobsite performance and safety. Multiple UAMs on site will be a challenge as it might interfere with construction operations and equipment.

Overall, two groups of participants were interviewed in this study, participants from (a) General Contractors (GCs) including superintendents, and project managers, with comparatively less experience in the construction industry, and (b) owner's representative firms with more experience in the construction industry. Therefore, the participants' input towards the research on the UAM applications and limitations that they suggested were different and related to the kind of work their organization is mainly responsible for. For example, the applications suggested by the GC representatives were focusing more on trade activities with limitations pertaining to UAM design limitations, and the suggestions by the study participants from the owner's representative group focused on inspection and identified the acceptance of technology in the industry as the primary challenge.

Moreover, the study participants from owner's representative firms showed more enthusiasm towards the technology than the GC representatives. The participants from owner's representative firms used UAVs in some form on their projects and therefore, they were more cognizant of the problems that come with the technology, yet when asked about the UAMs in particular and possible opportunities of this technology, in addition to suggesting the applications, they spoke about automation, as a whole. For instance, Participant 3, suggested using UAMs to transport other drones or robots over the construction sites. Participant 5 suggested that UAM-like systems for underwater application in construction can be a potential area in construction automation. In addition to discussing the identified scenarios, the tone and the language used by facility owner's representatives was more positive during the discussions. Statements such as "clearly, drones have a good role there", "you do a lot of work in construction that's in the water…I know that submersible drones, that's exciting to bring them in…", "I could definitely see a drone doing a similar thing", "I could definitely see a drone with that technology…" are some instances where the participant showed enthusiasm towards construction automation using drones. Compared to the participant from owner's representative firms, the participants from the GC firms limited their applications to specific trade activities, but they did point out that the UAM technology will face pushback from trade partners and every opportunity they suggested was followed by the limitation or challenges that this technology will potentially face.

Conclusion

This research identified the opportunities and challenges of the application of UAM systems in construction processes. The study contributes to the introduction of a new research area in contact-based UAV-guided technologies within on-site construction activities. The study participants suggested several opportunities for the implementation of UAMs such as (a) various scenarios including confined spaces, high traffic areas where they can be used to reduce the vulnerability of the human workers to safety hazards and possible accidents, (b) types of end-effectors that can be used to carry out different tasks and, (c) various applications and tasks that can be conducted with UAMS including safety setup, trade activities, conducting inspections on structures, and tools operations. The study findings that delineate the design limitations of UAMs and their application challenges on construction sites include UAV's low payload capacity, network connectivity issues in indoor environments and the challenges that come with using them on construction sites such as, the FAA regulations that restricts the use of UAVs on construction sites, skilled workforce as pilots for UAMs, and finding alignment among the project stakeholders to implement UAMs in their project lifecycle.

Limitations and Future studies

This study was limited to interviewing participants using the result of the literature review and knowledge of previously conducted research to identify the opportunities and challenges the UAM technology can introduce to the construction industry. Also, this study has included a limited number of interview participants conducting only a qualitative study. Future work could include more interview participants. Future study can alternatively conduct a survey study prior to the interview phase to first map the acceptance of UAMs in the industry, providing a quantitative element to the study and then including a higher number of participants to elaborate the study results. Even with a limited number of participants a substantial pool of opportunities and challenges have been identified in this research and with more study participants, the body of knowledge can be extended. The survey design that could complement this research can use the findings of this research including the identified opportunities and challenges and verify with more details through focus group study with industry professionals. Using the identified opportunities in this research, future study will develop a use case with a prototype of a UAM with an application in construction as a proof of concept which can then be tested and presented to construction experts for further study.

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