Tag-based Indoor Localization of UAVs in Construction Environments: Opportunities and Challenges in Practice

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ABSTRACT

Automated visual inspection and progress monitoring of construction projects using different robotic platforms have recently attracted scholars' attention. Unmanned/Unoccupied aerial vehicles (UAVs), however, are more and more being used for this purpose because of their maneuverability and perspective capabilities. Although a multi-sensor autonomous UAV can enhance the collection of informative data in constantly-evolving construction environments, autonomous flight and navigation of UAVs are challenging in indoor environments where the Global Positioning System (GPS) might be denied or unreliable. In such continually changing environments, the limited external infrastructure and the existence of unknown obstacles are two key challenges that need to be addressed. On the other hand, construction indoor environments are not fully unknown, as a progressively updating building information model (BIM) provides valuable prior knowledge about the GPS-denied environment. This fact can potentially create unique opportunities to facilitate the indoor navigation process in construction projects. The authors have previously shown the potentials of AprilTag fiducial markers for localization of a camera-equipped UAV in various controlled experimental setups in the laboratory. In this paper, we investigate the opportunities and challenges of using tag-based localization techniques in real-world construction environments.

INTRODUCTION

Building information models (BIMs) play a pivotal role in the design and management of projects in the architecture, engineering, and construction (AEC) industry. Numerous benefits of BIM, such as clash detection, 4D modeling (i.e., 3D + schedule), 5D modeling (e.g., 4D + cost), and automated quantity take-off have been widely exploited. However, the majority of the developed models lack a vital perspective, "the reality", also referred to as "as-is" and/or "as-built". In fact, updating the BIM is an essential task for aiding both the inclusive objective assessment of under-execution AEC projects and the decision making process throughout the whole lifecycle (Chen et al. 2015). Nevertheless, reflecting the actual progress status is still challenging in many cases. Thus, automated methods and technologies aim to facilitate such a laborious, time-consuming, and error-prone task.

As illustrated in Figure 1, a robust BIM updating practice for under-execution AEC projects is a cyclic process that is composed of three main phases, namely, data capture, data processing, and information modeling. The required data is obtained from sources including images from cameras (El-Omari and Moselhi 2008)(Golparvar-Fard et al. 2009), laser scanners (Bosche et al. 2009), 3D point cloud (Pətrəucean et al. 2015), and RGB-D cameras (Izadi et al. 2011). In processing input data for BIM updates, various processing techniques are employed. As an example, many promising studies have been conducted using vision-based techniques (Hamledari et al. 2017a; Kim et al. 2013) to extract the required information. Information modeling, finally, can be performed whether with (Hamledari et al. 2017b, 2018; Son et al. 2015) or without (Cho et al. 2019) an as-designed 3D CAD/BIM. However, a systematic, automated, and centralized data capture approach for under-execution AEC projects still requires more attention, especially for indoor environments.

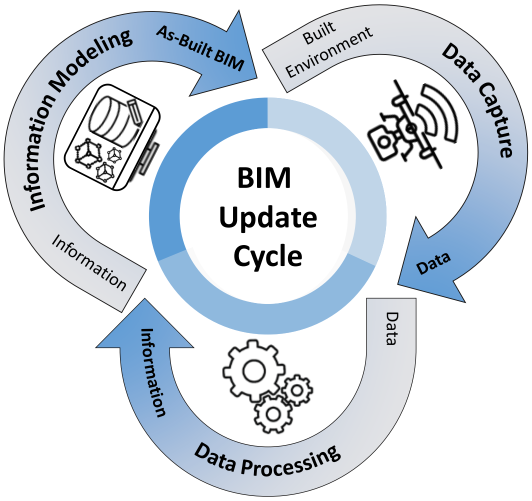


Figure 1. A robust cyclic BIM updating process for under-execution AEC projects.

Robotic platforms are beneficial devices for improving the efficiency of the data capture phase for either BIM updating or automated monitoring and inspection purposes (Mantha et al. 2018). In this regard, the broad and promising applications of light-weight unmanned/unoccupied aerial vehicles (UAVs), also known as drones, have been studied in the AEC industry (Lin et al. 2015; McCabe et al. 2017; Siebert and Teizer 2014). Not only are light-weight UAVs able to perform where it might be unsafe or inaccessible, but they also provide maneuverability and perspective advantages over ground robotic platforms. For instance, aerial robots can provide a broader range of points of view (e.g., different elevations and angles), mainly when images and videos are the primary type of data to be acquired. Indoor construction environments, in general, and multi-story buildings, in particular, may incorporate physical barriers (e.g., stairs) that may degrade the performance of ground robots. To further boost its data acquisition capabilities, the UAV can be equipped with one or more sensors. Exploiting multi-sensor autonomous UAVs can yield substantial benefits in the collection of informative data in congested and continually changing work sites.

One of the fundamental prerequisites in achieving a level of autonomy wherein the UAV can get from point A to point B with no human control commands is the estimation of the UAV's state. The state of a UAV includes its 3D pose (i.e., x, y, z, *roll* (θ), *pitch* (ϕ), and *yaw* (ψ)), linear and angular velocities (i.e., $\dot{x}, \dot{y}, \dot{z}, \dot{\theta}, \dot{\phi}, \dot{\psi}$), and linear and angular accelerations (i.e., $\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\theta}, \ddot{\phi}, \ddot{\psi}$). The state estimation of UAVs is more challenging than ground robots because: (1) as UAVs have a limited payload capacity, only light-weight sensors are usable; (2) as they have fast dynamics, the sensing is noisy; (3) as their motion is continuous (UAVs cannot just stop, sense, and estimate), the estimated state is associated with more significant errors; and lastly (4) the UAVs 3D motion requires the estimation of more variables. The estimation of 3D position and orientation of a UAV is called pose estimation or simply localization. The UAV pose estimates are also used in motion planning and the control loop.

In summary, previous research conducted by the authors in tag-based indoor localization (Kayhani et al. 2019; Nahangi et al. 2018) showed a proof-of-concept that an off-the-shelf camera-equipped UAV can be localized in a controlled lab setup. However, tag-based localization in a real construction environment may be accompanied by unique conditions that are inconspicuous in lab settings. Thus, the objective of this paper is to investigate the opportunities and challenges in tag-based indoor localization of an off-the-shelf UAV in dynamically changing actual work sites. First, however, indoor localization techniques in robotics, tag-based localization, and the authors' research in tag-based indoor localization of UAVs are briefly reviewed.

INDOOR LOCALIZATION OF MOBILE ROBOTS

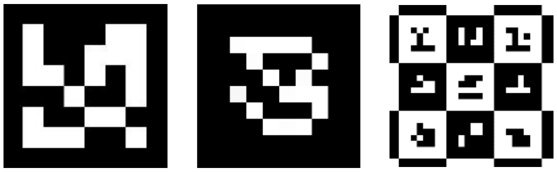
Autonomous aerial robots typically take advantage of robust and accurate external sources of pose estimation information, such as the Global Positioning System (GPS) outdoors and motion capture systems (e.g., VICON and Optitack) indoors. Even though GPS is reliable in many outdoor environments, it may suffer from multi-path inaccuracies in highly congested urban areas with a dense distribution of high-rises (i.e., urban canyons). Thus, the localization of mobile robots may be challenging even outdoors. Since GPS signals are not sufficiently reliable for indoor navigation, such environments are usually referred to as being GPS-denied.

Autonomous robots operating in GPS-denied environments may rely on dead-reckoning techniques for localization. For example, inertial measurement unit (IMU) (Taneja et al. 2012), which consists of inertial motion and rotation sensors, is traditionally used in aerial vehicles for dead reckoning. However, such measurements are subject to drift over time. On the other hand, although motion capture systems can provide millimeter level of accuracy in their estimates, they cover a limited indoor workspace of operation, require repetitive calibrations, and are extremely costly. Similarly, because they impose extra costs, logistics, complexity, and distraction into the job site, they are considered an impractical solution for indoor construction applications. Other localization methods mainly employ technologies such as wireless local area networks (WLAN) (Deasy and Scanlon 2004), radio-frequency identification

(RFID) (Liu et al. 2014; Razavi and Moselhi 2012), ultra-wideband (UWB) (Shahi et al. 2012; Yassin et al. 2017), and machine vision (Liang et al. 2013). However, due to the radio-frequency interference with metallic materials (e.g., RFID (Mainetti et al. 2014) and UWB (Xiao et al. 2016)), variations in propagation conditions (e.g., UWB (Witrisal and Meissner 2012)), imposing external infrastructure, and more importantly the inadequate accuracy of such systems (Ibrahim and Moselhi 2016), they are often unsuitable for indoor localization of UAVs during construction. For all these reasons, localization is still recognized as a primary barrier to autonomous navigation of UAVs in GPS-denied indoor environments, particularly under-execution AEC projects.

TAG-BASED LOCALIZATION

As illustrated in Figure 2, fiducial markers are artificial landmarks represented as patterned tags printed on paper. These tags can be used to provide accurate global six-degree-of-freedom pose estimates for a mobile robot equipped with a camera even when the tags are rotated or placed in different lighting conditions. Prevalent examples of fiducial markers include ARTag markers (Fiala 2005), CalTag markers (Atcheson et al. 2010), and AprilTag markers (Olson 2011; Wang and Olson 2016). These markers are designed to be efficiently detected and distinguished by computer vision algorithms while remaining robust to misidentification. Other vision-based localization algorithms and methods typically obtain three-dimensional information by matching features between images from either different cameras or different frames in consecutive time steps. The information provided by a tag is much richer: the full 6DOF pose estimate is obtained from a single image of the tag. Despite their low price, AprilTag markers are proven robust fiducials for indoor localization of mobile robots (Olson 2011).



AprilTag ARTag CalTag

Figure 2. Instances of AprilTag, ARTag, and CalTag markers.

The use of fiducial markers, especially AprilTag markers, may be accompanied by a number of challenges that need to be addressed. First, the position and orientation of each tag must be known precisely, requiring calibration procedures. Second, the distribution of tag locations must be well-planned to reduce the number of tags required while still achieving sufficiently accurate localization. It has been showed that the accuracy of the pose estimate provided by the AprilTag makers generally degrades with increasing distance and angle from the camera (Kayhani et al. 2019; Nahangi et al. 2018; Wang and Olson 2016). Finally, tags are susceptible to damage or occlusion, which must be taken into account in the tag placement planning.

TAG-BASED INDOOR LOCALIZATION OF UAVs IN CONSTRUCTION ENVIRONMENTS

An updated BIM provides prior knowledge about the workspace or built environment. Therefore, a progressively updating BIM can be utilized in tag-based localization and for tag placement planning purposes.

In this regard, authors showed a proof-of-concept that an off-the-shelf UAV equipped with an onboard camera and IMU could be localized in a GPS-denied indoor environment using AprilTag markers, given the tags' pose are known in BIM (Nahangi et al. 2018). Having used an extended Kalman Filter (EKF), we were able to improve the previously proposed single-tag localization framework (Nahangi et al. 2018) by accounting for uncertainty and fusing data from multiple sources, namely, multiple tags and the onboard IMU (Kayhani et al. 2019). Both studies were tested in the laboratory and under controlled experimental settings.

Applying such a method in dynamic and ever-changing construction environments, however, provides unique opportunities and challenges. Thus, this study aims to identify and discuss challenges and opportunities for the full implementation of tag-based indoor localization in real-world construction environments. Moreover, it seeks to discuss some potential solutions to address identified challenges.

CHALLENGES IN PRACTICE

In addition to what was discussed about general and inherited challenges in tag-based indoor localization of UAVs, construction environments (e.g., high-rise buildings) themselves raise challenges. Construction sites may be subject to significant changes during short spans of time. Thus, a visible tag at the current stage may be out of sight later. For instance, assume that a drywall partition was supposed to be erected between two scheduled data capture visits, and that the partition ends up on top of one of the previously available tags. This change in the availability of visible tags could affect the UAV's localization performance, autonomous navigation, and its ability to capture reliable data. Moreover, appearing or temporary obstacles may be introduced into the environment, which may affect the UAV's navigation, whether directly or indirectly by blocking the tags line-of-sight.

Tags are also susceptible to deterioration, occlusion, and unintentional displacement in such an environment. It is crucial to limit the number of tags and the frequency of the tag placement, as tag placement itself could adversely affect the efficiency of the whole process. Thus, a robust tag placement strategy is required to not only optimize the number and location of required tags in the BIM but provide on-site personnel with reliable placement instruction in practice. By considering general and construction-specific requirements, such instruction must enable workers to effectively, efficiently, and effortlessly place the tags in the environment according to the identified and planned locations.

Safety concerns are another set of challenges in using autonomous UAVs in an indoor construction environment. To avoid any disturbances or disruptions to field personnel and workers, we envision using the UAV when the environment is entirely unattended. Thus, the UAV will work over weekends or at night.

The processing unit for an autonomous UAV may be external or onboard. Although external processing units, such as a PC, may handle more computationally expensive algorithms in less time than onboard processing, data transformation needs an external infrastructure. Since the majority of off-the-shelf lightweight UAVs (e.g., Parrot Bebop 2 or DJI Mavic Air) support Wi-Fi data transfer, external processing is a viable solution. For instance, the UAV directly connects to a laptop to transmit data. However, as the Wi-Fi range is limited, a signal booster network may be needed.

OPPORTUNITIES IN PRACTICE

Nevertheless, there are several unique opportunities in AEC projects equipped with BIM that can be seized. Any localization problem assumes that the workspace's map is given. In many applications, such as disaster rescue scenarios, the workspace is an unknown and unstructured environment where the map is not available in advance. An updated 4D BIM, on the other hand, can be utilized as a rich source of spatial information, such that the exact pose of each tag is identified and annotated in the BIM. Given accurate tag placement, the UAV, which is able to estimate its relative pose, can be localized in a global coordinate system (Kayhani et al. 2019; Nahangi et al. 2018).

Each UAV site visit should yield new information about the progress of the construction activities and update the BIM to yield a more comprehensive map. Although an updated 4D BIM model ideally provides a comprehensive map of the environment in the last UAV site visit as well as the planned progress for the current site visit, the spatial information for the current site visit is uncertain. There might still be some tasks that had been planned to be completed in the current site visit yet were uncompleted. In this case, even though we are not certain about the possible changes in the map, we are already alerted about the location of such obstacles. This can be handled by generating a probabilistic map for tag placement and navigation purposes.

Figure 3 - Formed and stripped floor hallways before and after drywall erection.

Although a robust data capture system should cover the majority of indoor tasks during construction, the necessity of automated data capture varies through different stages of indoor construction. For instance, data capture should be performed more frequently on finished and stripped floors during the forming stage and in the early stages of finishing, when drywalls are erected, and where a significant amount of plumbing, mechanical, and electrical work are performed (see Figure 3). In this period, the pace of change and the number of installed items that have to be investigated provide significant incentives to automate data capture. So, not only can data capture using an autonomous UAV be effective and useful at this stage, but it provides us with versatile options for tag placement.

According to the Occupational Safety and Health Administration (OSHA) mandates and provincial regulations in Ontario, hallways and corridors are to be kept clear of obstruction (Figure 3) and provided with proper illumination ("1926.56 - Occupational Safety and Health Administration" "O. Reg. 213/91 s. 45 and 72 (1): construction projects - housekeeping"). This not only significantly mitigates the safety risks in autonomous flight in confined environments but also allows the use of vision-based techniques such as tag-based localization.

Due to rapid changes in indoor construction environments, it is vital to identify best practices for tag placement. Tags may be placed on the floor, the ceiling, or mounted on the walls. The regulations for under-execution corridors and hallways make the floor the most reliable option. The reason is that these places are well-illuminated and less likely to be occluded or covered. Moreover, concrete walls are usually left untouched until later in the project except for minor grinding. With ample space for multiple tags at different heights, wall-mounted tags can be used in suites that need to be inspected. Ceiling utility runs, ceiling heights of 6m or more, and aerodynamic effects on the UAV make the ceiling less reliable for tag placement.

Accurate and versatile tag placement is another challenge that has to be addressed. Versatility allows the tag to be installed, reinstalled, and removed as needed, and accuracy is required for autonomous navigation. In Figure 4, design gridlines are accurately highlighted on the ceiling to facilitate the placement of interior elements. They can also be exploited as a locational system for tag placement and replacement.

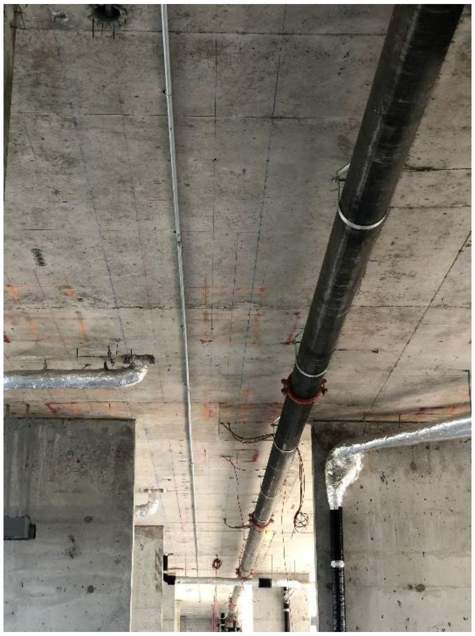


Figure 4- An example of a construction site with gridlines on the ceiling.

In order to achieve a versatile tag placement best practice, fixed benchmarks can also be added to the structure. For instance, surveying markers and tags, shown in Figure 5, can be placed around the space and mapped into the BIM model. Fiducials, such as AprilTag markers, can then be glued or attached to the walls by matching pinpoints on the survey tag and the fiducial marker. By so doing, they are less subject to unintentional displacement, the tag placement becomes more convenient and accurate, and calibrations are dramatically reduced.

Figure 5 - Survey tags can be used as fixed and accurately localized benchmarks.

CONCLUSION

Although the authors had previously shown the potentials of tag-based indoor localization of UAVs in an experimental setting (Kayhani et al. 2019; Nahangi et al. 2018), the opportunities and challenges in practice remained untouched. This paper investigated and discussed opportunities and challenges of tag-based localization employment in indoor under-execution construction sites. It also proposed some potential solutions for those challenges. A tag-based localization system assumes that the UAV can continuously see a tag. When the UAV is not able to see any tags, it has to switch to dead reckoning (e.g., IMU), which is highly prone to drift over time. Thus, a robust tag-based localization system needs to be supported by a reliable backup system (e.g., visual-inertial odometry). Finally, localization based on a known map is not sufficient because there might be unforeseen obstacles that must be avoided. Thus, a reliable autonomous navigation system needs to be equipped with an obstacle avoidance system as well.

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