Automated Localization of UAVs in GPS-Denied Indoor Construction Environments Using Fiducial Markers

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Abstract

Unmanned Aerial Vehicles (UAVs) have opened a wide range of opportunities and applications in different sectors including construction. Such applications include: 3D mapping from 2D images and video footage, automated site inspection, and performance monitoring. All of the above-mentioned applications perform well outdoors where GPS is quite reliable for localization and navigation of UAV's. Indoor localization and consequently indoor navigation have remained relatively untapped, because GPS is not sufficiently reliable and accurate in indoor environments. This paper presents a method for localization of aerial vehicles in GPS-denied indoor construction environments. The proposed method employs AprilTags that are linked to previously known coordinates in the 3D building information model (BIM). Using cameras on-board the UAV and extracting the transformation from the tag to the camera's frame, the UAV can be localized on the site. It can then use the previously computed information for navigation between critical locations on construction sites. We use an experimental setup to verify and validate the proposed method by comparing with an indoor localization system as the ground truth. Results show that the proposed method is sufficiently accurate to perform indoor navigation. Moreover, the method does not intensify the complexity of the construction execution as the tags are simply printed and placed on available surfaces at the construction site.

Keywords –

Indoor localization; construction performance monitoring; Building Information Model (BIM); AprilTags; Automated monitoring; Facility Management;

1 Introduction

Unmanned aerial vehicles (UAVs), also known as drones, have recently attracted attention from various industries including construction. Employing UAVs equipped with visual sensors for construction site monitoring is beneficial due to the vehicles' maneuverability and rotary features. UAVs can access points that are inaccessible or unsafe to be reached by humans. UAVs may also be equipped with other devices such as a laser scanner, thermal sensors, or hyperspectral/multispectral sensors that can be used for acquiring further insights and then generating very informative analytics about the status of the construction component being monitored. Specific applications in the construction industry include 3D mapping for dimensional measurement of construction components [1], visual progress monitoring, and visual inspection [2].

The key capability of UAVs that makes them useful in so many industries is their ability to be programmed to perform tasks autonomously. One critical module of such autonomous robots for automated task performance is the localization system. For outdoor environments, autonomous flight planning is less challenging, because the localization module is based on global positioning systems (GPS), which is accurate and reliable. Localization results are then fed to the control systems as the state sensing component (feedback loop). Navigation and path planning can then be performed based on the accurate and reliable localization results obtained in outdoor environments. However, indoor localization using GPS is not sufficiently reliable because of the weak signal and other interferences present in indoor environments such as walls and other interior components under-construction.

Using reliable indoor localization systems that already exist commercially, such as wireless networks, UWB, or vision-based positioning cameras (e.g. Vicon system) intensifies the complexity of construction sites and, indeed, requires additional costs for deployment. This paper investigates the use and employment of fiducial markers (AprilTags, in particular) for potential deployment in GPS-denied indoor construction environments. The 3D coordinates of fiducial markers are hardcoded into 3D CAD drawings integrated with the building information models (BIM). Camera-equipped UAVs can identify their relative pose to the tags and then calculate their location in the global coordinate frame give the tag's location.

2 Background

The related background information is investigated from three different perspectives: (1) indoor localization state-of-the-art, (2) fiducial markers for indoor localization, and (3) localization of construction equipment and materials. These areas are extensively discussed in the following sections.

2.1 Indoor localization state-of-the-art

Indoor localization and the related research area is used when objects are to be detected in a location where a global localization signal such as GPS is not reliable [3,4]. According to Ibrahim and Moselhi (2016) [5], indoor localization techniques can be divided into three major categories:

- Wave characteristics and propagation: various ultrasonic and sound waves and receivers such as radio frequency (RF), ultra-wideband (UWB), and wireless local area network (WLAN) are used for indoor localization [3,6,7]. Indoor localization using ultrasound waves may result in 9 cm accuracy, however, it requires direct and interference-free access to the objects. Other techniques such as UWB and RFID have reported accuracy of 5-9 m, which is insufficient for high accuracy applications and analyses. Localization systems with such low accuracies are used for sensing and roughly locating materials in warehouses and other indoor environments.
- Image-based/vision-based localization: image-based localization uses computer vison to identify the location of objects in the global coordinate system. Image-based localization has been categorized in two major groups: (1) global feature detection, identification and localization such as edge and corner detection, and (2) local feature detection such as fiducial tag and marker detection and localization. Image-based localization requires line-of-sight to extract features; therefore, it is significantly impacted in dynamically changing environments and also by markers' deterioration throughout the project lifecycle. Recently, simultaneous localization and mapping (SLAM) has been found to be capable and reliable for indoor localization and mapping [8]. The method proposed in this paper belongs to this category and aims to investigate and overcome some of the existing challenges using fiducial markers.
- Inertial navigation systems: indoor localization can be performed, given an initial location and navigating using on-board accelerometers, inertia measurement units (IMU's), and other motion sensors. Inertial navigation and IMU-based indoor localization drifts from actual measurements as movement progresses, if motion components are not appropriately updated. Ibrahim and Moselhi [5] developed an IMU-based localization technique combined with a Kalman filter, which was found to be more accurate compared to the wave-based method. However, relying on IMU for UAV navigation is very risky and may lead to serious hazards such as loss of control and subsequent collision with objects in the environment. SLAM [8] may also be used with inertia measurement units (IMU's) or some other motion sensors for facilitating the localization. In such cases, processing is less computationally demanding and therefore closer to real-time.

2.2 Fiducial markers for indoor localization

Visual tags are designed to be easily detectable by camera systems. If a camera system is well calibrated, the relative pose of the camera with respect to a tag can be calculated, and therefore the camera system can be localized with respect to the tag's coordinate frame. Challenges for employing and implementing fiducial markers include: (1) the processing cost for decoding the tags, and (2) the difficulty of generating template tags that are orthogonal with each other [9].

Among fiducial markers, AR Tags were found to be very easily detectable and quickly decodable. AprilTag Tags were then introduced to overcome the inadequacies of AR Tags, which included the accumulated error when distancing from the target [10]. AprilTag Tags were proved to be more robust for indoor localization, and, since then, they have been used for many applications such as robot localization and navigation. AprilTag Tags are used in this study to investigate the localization of UAVs using their on-board camera systems [11].

2.3 Localization of construction equipment and materials

The previously explained techniques and technologies have been used for locating construction equipment and materials on site. Razavi and Haas [12] presented a method for localizing construction equipment and materials using RFID tags. In another study, indoor localization was tested using passive RFID tags for sensing. Song et al [13] used RFID tags for automating the task of tracking the delivery of materials on construction sites. As reviewed in the literature, localization frameworks are either performed outdoors or only for the purpose of sensing if performed indoors. This study aims to test and assess the performance of AprilTags for indoor localization of UAVs.

3 Methodology

For the purpose of localizing UAVs used for indoor task performance, on-board cameras are employed to detect AprilTag Tags with known locations in the world coordinate frame, and therefore linked to the building information model. On-board cameras are first calibrated to identify the physical and intrinsic parameters required for pose identification. An overview of the proposed framework is illustrated in Figure 1.

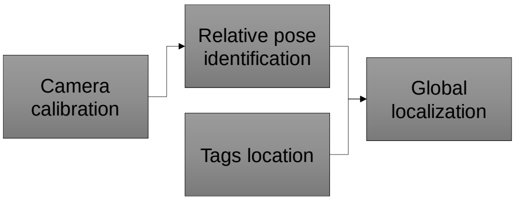

Figure 1: Overview of the proposed framework for indoor localization

3.1 Camera Calibration

Camera calibration is required to estimate the parameters of a lens and image sensor of an imaging system. Camera calibration parameters are thus required for accurately measuring distances to perceived objects. The Robotics operating System (ROS) package for camera calibration is used to estimate the camera parameters using a large checkerboard (8×6) with known dimensions (108 *mm*) for camera calibration.

3.2 Tags location

UAVs are going to be employed for indoor monitoring of construction elements. To identify the critical elements to be monitored, different filters can be applied on the building information model to extract the world coordinates and assign them to the tags used for localization. For example, a filter can be applied on object types, in case a specific type of object, such as drywalls or electrical outlets, is to be monitored. The construction of some objects may become behind schedule; they are the purpose of task monitoring using UAVs. In that case, a filter on object status can be applied to the BIM objects to extract the critical locations in the world coordinate system. Moreover, project managers might be interested in tracking and monitoring the tasks performed by specific subcontractors or vendors.

In summary, filters can be applied based on the search criteria in order to extract critical locations to be monitored by the UAVs employed in indoor environments. Extracted coordinates are assigned to tags, which are then employed for the localization of UAVs. Tags link the UAV's location to the world coordinate system as explained in the following section.

3.3 Relative pose identification

Once the on-board camera on the UAV is calibrated and tags locations are identified, UAVs can be localized with respect to the tags placed on construction sites. The relative pose is reported as a relative translational vector (x, y, z) and a rotational vector $(roll, pitch, yaw)$. These two vectors are reported as a relative transformation denoted as T_t^l, which relates the position of the UAV measured locally and in the tag's local coordinate system. Given the transformation that relates the position of the tags in the global coordinate system T_g^t, the UAV can then be localized globally. The required transformation for localizing the UAV in the global coordinate system T_g^l is calculated as: $T_g^l = T_t^l \times T_g^t$.

4 Design of experiments and results

An experimental setup is designed to collect the required data for verifying the accuracy of UAVs under various circumstances. A Parrot Bebop 2 equipped with a camera and on-board accelerometers is used as the UAVin this study. Detailed specification of the vehicle is provided in Table 1. AprilTags of type *36h11* printed at two different sizes are used to identify the impact of the tag's size on the accuracy of detection and pose identification. For integrating the on-board sensors of the UAV used in this set of experiments, a ROS driver for the Bebop device is used [14].

Table 1: Parrot Bebop 2 technical specifications

Feature	Specifications
Video resolution	14 MP
Image resolution	1920×1080 pixels, 30 frames/sec
Flight time	~ 25 min
Networking	Wi-Fi Dual Band 2.4 & 5GHz
Weight	500 g
Operation range	Up to 2km (Wi-Fi controller)

4.1 Effective variants

Four parameters are investigated to identify the accuracy of the proposed indoor localization framework:

1. Tags' placement orientation: construction sites and environments are dynamically changing during the projects' lifecycle. If the tags are planned to be placed on vertical walls, there might be a delay on the deployment of tags when a new floor is being inspected. On the other hand, tags placed on floors may be covered by building materials and elements. Both situations are tested to better understand the limitations.
2. Tags' size: the accuracy of the detection and pose identification with respect to the size of the tags is investigated. Larger sizes are more visible and therefore their detection accuracy is expected to be higher; however, smaller sizes are more practical to implement and deploy on construction sites.
3. Distance from tags: the UAV must see at least one tag at all times during the flight. This is crucial because if no tag is, the navigation control switches to on-board odometry which is neither reliable nor safe. The reason is that the UAV may lose its pose and location in the world coordinate system. In order to identify the threshold distance at which the UAV has a sufficiently accurate level of pose identification with respect to the tags, the impact of distance on localization should be investigated. The results can then be considered as a constraint in optimizing the tag placement plan on a building map.
4. Angle of view: similar to the previous variant, the angle of view is also of crucial importance in pose identification. The threshold angle value for which UAVs are localized with sufficient accuracy should be identified and considered in the tag placement optimization plan.

4.2 Experimental setup

An experimental setup is designed to measure the accuracy of the tag-based localization system. Tags are placed at previously known locations linked to the world coordinate system in the BIM. Figure 2 illustrates how world coordinates are calculated using the tag locations and how they are measured with the ground truth indoor localization system (Vicon cameras).

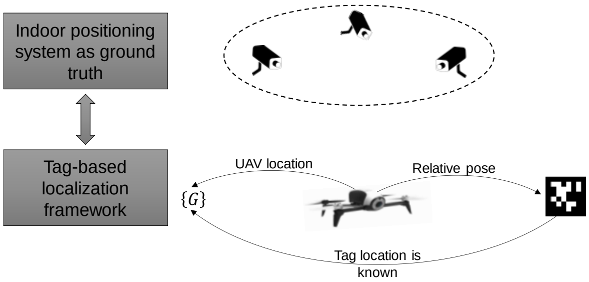

Figure 2: Tag-based indoor localization. For verification and validation of the calculated location, the results are compared with ground truth indoor positioning system. Tag-based localization results are compared with the Vicon system used as the ground truth (Section 4.3).

4.3 Ground truth indoor positioning system

An overhead camera system is used to assess the accuracy of the proposed tag-based localization framework. The overhead camera system detects markers that uniquely identify various objects. Once markers are detected, the position of the object is estimated as the ground truth. In the laboratory setup, the Vicon system is integrated with the ROS and the localization results are reported in a *rostopic* recorded for further result analyses.

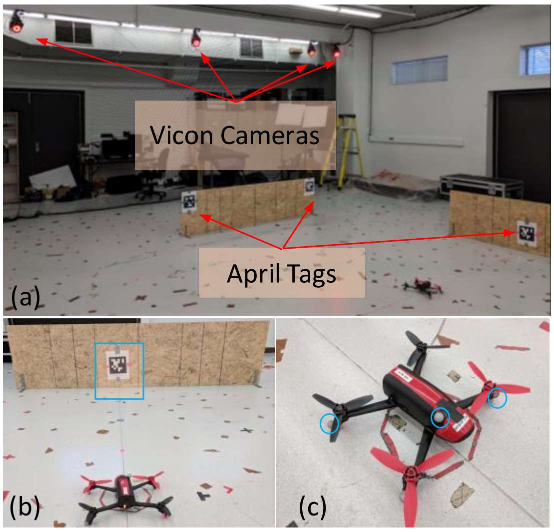

Figure 3: Experimental setup for testing the accuracy of the proposed indoor localization framework. (a) Ground truth system (Vicon cameras) are shown within the laboratory. AprilTags are also placed at various locations. (b) Take-off position where the UAV is faced to Tag-id=0 to be initially localized. (c) Markers are put in a specific pattern on the UAV, so as to be recognizable by the ground truth indoor localization system.

5 Results

In order to investigate the impact of the effective variants, the localization results are compared with the ground truth system under various scenarios. Each scenario is designed to capture the effective variant being investigated.

First, the effect of the orientation of the tags is investigated. For this purpose, localization results for vertical tags placed on walls and horizontal tags placed on the floor are compared with the ground truth system (see Figure 4). Figure 5 illustrates the accuracy of the localization system as the angle from the tag chages for horizontal tags.

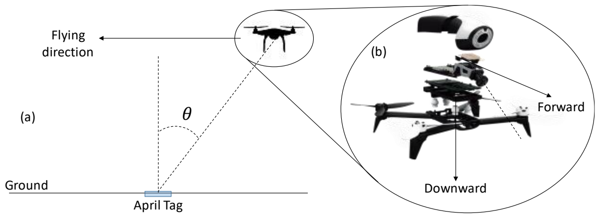

Figure 4: Side view of the experimental setup. (a) Auto-flight plan for calculating the localization accuracy when tags are placed horizontally on the ground. (b) Configuration of the on-board camera of the UAV used in this study. Figure is from Bebop forum [15].

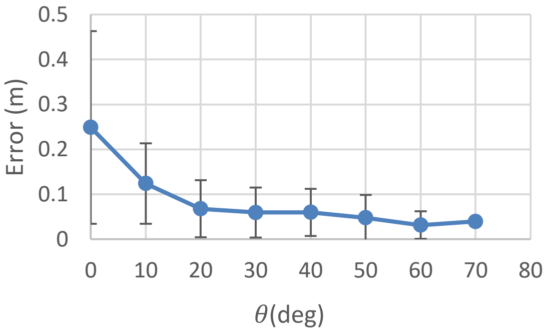

Figure 5: Localization error for horizontal tags placed on the ground. The UAV flight height is fixed at 2 m. Camera angle (θ) with respect to the tag is variable.

As seen in Figure 5, the accuracy of the localization increases as the angle increases. Moreover, the standard deviations (error bars) decrease as the angle increases, which implies more stability in the localization system as the angle increases. This is due to the orientation of the on-board camera used in the experiments. As shown, the camera is angled between forward and downward directions, as shown schematically in Figure 4-(b).

To understand the effect of distance from tags, the UAV is programmed to fly at different distances perpendicular to the tag's plane. Figure 6 schematically shows the automated flight plan programmed to investigate the effect of distance on the localization results. Figure 7 shows how accuracy changes while the UAV is flying at various distances with respect to an AprilTag.

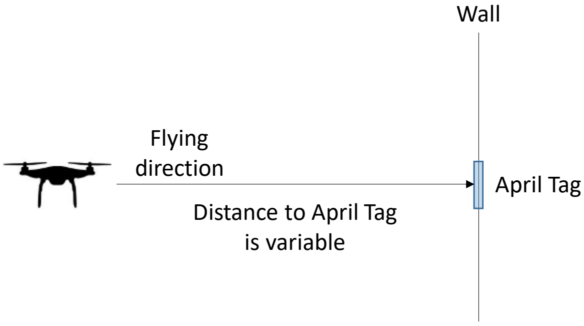

Figure 6: Automated flight plan for investigating the effect of distance to an AprilTag on the localization results

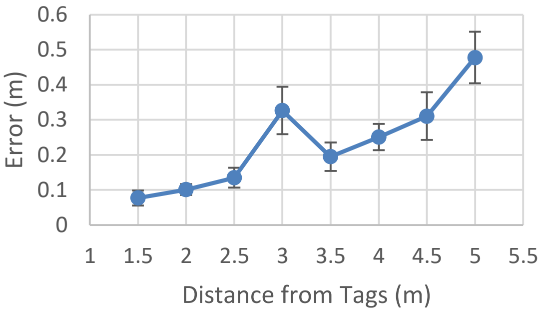

Figure 7: Localization error at different distances from tags. The on-board UAV's camera is facing perpendicular to tag's plane.

As seen in Figure 7, localization accuracy decreases as the UAV gets further from the AprilTag. The discrepancy at 3 m distance is due to the take-off position. Although, a tag is visible even before taking off, the localization is not sufficiently accurate and robust while the UAV is moving. It is expected that the graph monotonically increases if the data associated with take-off is filtered out from the results. Another observation is that the standard deviation increases as the UAV gets further from the AprilTag. This implies that the localization is more robust at closer distances.

Finally, the yaw angle of the UAV at a fixed distance (2 m) from an AprilTag is investigated to quantify the localization accuracy at various view angles. An automated flight plan (depicted in Figure 8) is implemented and the localization error is reported (in Figure 9) at various yaw angles (ψ).

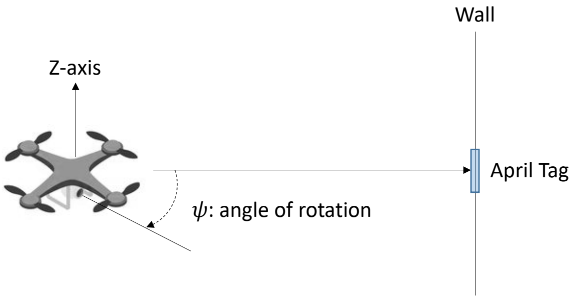

Figure 8: Automated flight plan to quantify the effect of yaw angle (ψ) on the localization accuracy

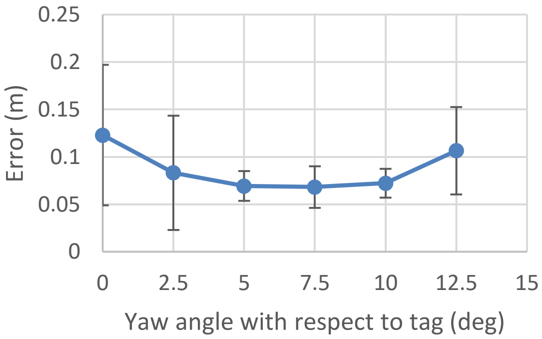

Figure 9: Localization error at different yaw angles. The UAV is flying *2 m* away from the tag and the yaw is variable.

As seen in Figure 9, the localization is robust and the accuracy is very stable for the yaw angles investigated. The large discrepancy at $\psi = 0$ is due to the take-off position, and if the data associated with the take-off is eliminated, the graph becomes even more stable and robust. Comparatively, the standard deviation is expected to be as low as the same values reported for $\psi = (5, 7.5, 10)$; however, the take-off localization inaccuracy is affecting the standard deviations as well. It should be noted, that the further the UAV is from an AprilTag, the lower the expected maximum yaw angle because of the line of sight and angle of view.

6 Conclusions

An indoor localization system using fiducial markers was developed in this study. AprilTags were used to globally localize flying UAVs in indoor construction environments. UAVs will then be used to capture some critical information about building components under-construction. Such information is then linked with a global system like BIM in order to measure the actual construction performance metrics with designed values to update plans accordingly. Progress of construction components can, for example, be measured at different locations in order to update the schedule accordingly. A robust indoor localization framework will provide an opportunity to fly autonomously and perform the whole process automatically. In order to verify and validate the performance of the proposed framework, an experimental study was designed. Some key findings are summarized as follows:

- Localization error decreases as the angle of view to horizontally placed tags on the grounds aligns with the on-board camera orientation. As the angle of view becomes steeper with respect to the camera orientation, the error increases.
- As expected, localization error increases as flying vehicles get further from AprilTags. The localization error will be higher than 30 cm if the UAV is flying further than 3.5 m from an AprilTag.
- Localization accuracy is very robust and stable for the yaw angles at which an AprilTag is visible by the UAV's camera.

For all cases, localization during take-off and landing is not sufficiently accurate to be reliable. Hence, the data associated with those situations must be filtered out for more accurate analyses. Future work includes incorporating the findings with automated flight plans on real construction sites. Threshold values are going to be extracted as constraints for distance and view angles to optimally place the tags on a construction site to be monitored.

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