ARUCO-BASED GLOBAL MAP INITIALIZATION FOR MULTI-ROBOT EXPLORATION

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ABSTRACT

Several approaches exist to tackle the problem of autonomous exploration and mapping of unknown environments using robots or Unmanned Ground Vehicles (UGVs), however, few use multiple robots. The implementation of several UGVs in such a task results in a significant decrease in exploration time, which may be critical in scenarios such as search and rescue. A multi-robot exploration and mapping algorithm that uses a K-Means clustering approach was developed in recent years by Goodwin and Nokleby (2022). This approach works efficiently to ensure that the robots explore different areas of the environment rather than overlapping paths, however, it has a weak point. The method requires the starting poses of the robots relative to one another to be entered manually in order to merge their LiDAR scans into a map and begin the exploration task. The work presented in this paper builds upon this approach by using a quadcopter Unmanned Aerial Vehicle (UAV) to find the UGVs' starting coordinates, leading to a significant increase in the autonomy of the system. This is achieved with the use of ArUco markers that are placed on the UGVs and are detected by the UAV's downward-facing camera. With this, the UAV can determine the pose of all of the exploration UGVs at the start of the task in order to build the global map. Both simulation and experimental results are presented that verify the effectiveness of the developed approach.

Keywords: exploration; robot collaboration; mobile robotics; UGV; UAV.

INITIALISATION DE LA CARTE GLOBALE BASÉE SUR ARUCO POUR L'EXPLORATION MULTI-ROBOTS

RÉSUMÉ

Plusieurs approches existent pour résoudre le problème de l'exploration et de la cartographie autonomes d'environnements inconnus à l'aide de robots ou de véhicules terrestres sans pilote (UGV), cependant, peu utilisent plusieurs robots. La mise en œuvre de plusieurs UGV dans une telle tâche entraîne une diminution significative du temps d'exploration, ce qui peut être critique dans des scénarios tels que la recherche et le sauvetage. Un algorithme d'exploration et de cartographie multi-robots utilisant une approche de clustering K-Means a été développé ces dernières années par Goodwin et Nokleby (2018). Cette approche fonctionne efficacement pour garantir que les robots explorent différentes zones de l'environnement plutôt que des chemins qui se chevauchent, cependant, elle a un point faible. Le procédé nécessite la saisie manuelle des positions de départ des robots les uns par rapport aux autres afin de fusionner leurs cartes et de commencer la tâche d'exploration. Le travail présenté dans cet article s'appuie sur cette approche en utilisant un véhicule aérien sans pilote (UAV) quadricoptère pour trouver les coordonnées de départ des UGV, ce qui conduit à une augmentation significative de l'autonomie du système. Ceci est réalisé grâce à l'utilisation de marqueurs ArUco placés sur les UGV et détectés par la caméra orientée vers le bas de l'UAV. Grâce à cela, le drone peut déterminer la position de tous les UGV d'exploration au début de la tâche afin de construire la carte globale. Des résultats de simulation et expérimentaux sont présentés qui vérifient l'efficacité de l'approche développée..

Mots-clés : exploration ; collaboration robotique ; robotique mobile ; UGV ; UAV.

1. INTRODUCTION

Autonomous robots are used in environments that are hazardous to humans in order to mitigate potential risks, such as in search and rescue scenarios. Other times, they are used to explore an area and gather data before humans enter it. Unmanned Ground Vehicles (UGVs) are commonly used to perform exploration and mapping tasks of unknown environments using Simultaneous Localization and Mapping (SLAM) algorithms. The use of multiple UGVs in such a task is attractive because it can greatly speed up the process of exploring a larger area. However, coordination between multiple robots is complicated because first, the robots must merge their maps, and second, path planning should be done in an efficient manner, where robots explore different segments of the area rather than overlapping routes.

A good candidate for a multi-robot exploration and mapping algorithm is one that uses K-Means clustering to delegate segments of the environment for the various robots to visit [1, 2]. One drawback of this approach, and other methods, is that knowledge of the relative starting coordinates of the robots needs to be specified in advance. In practice, this involves careful measurements of the placements of the robots in the environment. This need for human intervention drastically decreases the autonomy of the multi-robot system.

The proposed solution to tackle this major drawback of multi-robot exploration is to employ an Unmanned Aerial Vehicle (UAV) that can detect the locations of the UGVs at the start of a mission. The UAV is to perform a sweep of the area and detect the positions and orientations of all UGVs using a downward-facing camera. To ensure detection and improve accuracy, ArUco markers are placed on all UGVs to be seen by the camera. The poses of the UGVs, as seen by the UAV, are then used as inputs to the multi-robot exploration and mapping algorithm.

The detection of the UGV poses relative to one another by the UAV creates a global map, where all robots know where the others are located. This enables map merging, which is necessary for the exploration and mapping task, taken care of by the K-Means clustering algorithm.

Once exploration begins, both UGV wheel odometry and scan-matching are used to track their poses, updating the global map. The shared map enables further possibilities for UAV/UGV collaboration, such as obstacle detection. This is especially useful for ground vehicles equipped with a 2D LiDAR that may not be able to detect elevation changes, such as drop-off points, or obstacles that are below the plane of their 2D LiDAR sensors. Undetected obstacles can prevent UGVs from gathering important data, or worse, can make them at risk of getting stuck or facing harm, rendering them unable to complete their task.

The main contribution of this paper is a novel approach for the autonomous initialization of global mapping methods that uses UAVs and UGVs. The implementation of this approach increases the autonomy of existing approaches to multi-robot exploration and mapping. The outline of the remainder of this paper is as follows. Section 2 provides background on the current state-of-the art. Section 3 presents the method for localization of the UGVs using a UAV. Section 4 presents the experimental and simulation results. Section 5 presents the conclusions and Section 6 presents the planned future work.

2. BACKGROUND

2.1. Mixed UAV/UGV Collaboration

Collaboration between heterogeneous robots has been a growing field of research over the past two decades. It allows for the robots' strengths to be combined, surpassing their individual capabilities. The combination of aerial and ground vehicles is particularly strong because of their complementary strengths and weaknesses. While UGVs can carry high payloads and have long battery lives, their ability to traverse an area is limited by environmental obstacles. In comparison, UAVs are able to travel through areas more freely and have a higher vantage point, but they cannot carry high payloads and fly for long durations. Mixed UAV/UGV systems have seen use in several industries, such as agriculture [3], manufacturing [4], and construction [5].

In this research work, the UAV can assist the UGVs with their exploration and mapping task by determining their starting poses and establishing a shared map between the robots. This improves the exploration task by increasing the level of autonomy. This particular scenario of UAV/UGV collaboration can be classified as both robot types having the same functional role (mobile sensor), a coupled goal (exploration), and decentralized decision making, as per the three-axis taxonomy proposed by Chen et al. [6].

In existing mixed UAV/UGV systems, the aerial vehicle is most commonly used as a flying sensor, leveraging its elevated field of view. Some implementations use the UAV and UGV simultaneously, so that the UAV can provide the UGV information in real-time [5, 7, 8]. In other cases, the UAV surveys an area and then brings back the information to a ground station to be processed prior to the deployment of the UGV. In the case of this project, the former method is used because the UAV can publish the poses of the UGVs in real-time, without the need for additional processing. Additionally, the use of the UAV simultaneous to the UGV exploration task is important for a future phase of this project, where real-time obstacle detection will be used. Although many existing systems use the UAV to do all the path planning for the UGV, as in [8] and [9], this project only requires the UAV to provide the locations of obstacles. This is because there is already an effective frontier exploration algorithm for UGVs [1, 2], so it is not necessary to do full path planning.

Relative localization is a prerequisite for many robot collaboration scenarios so that actions can be coordinated. One approach found in the literature employed a UAV with a camera that can detect UGVs that have a simple visual marker; a white rectangle with a black dot inside [10]. This approach resulted in a position error of 12 cm and an angular error of 10°. Another method to find relative poses between aerial and ground robots sees the UGV equipped with a laser pointer that projects a pattern onto the ceiling, which a UAV spots with its camera and calculates their relative poses [11].

Many collaborative missions wherein a UAV provides environmental information to UGVs have been presented. Of note was research work that involved the use of a UAV to capture the environment in a short window in front of a moving ground vehicle [12]. The focus of the research was to create a coverage plan for the UAV to scan the necessary area and determine the optimal path to be followed. The goal of another mission was to use a UAV-UGV pair to explore and map a large outdoor area [13]. The ground robot's navigation was aided by visual feedback from the aerial robot and obstacles were mapped by combining sensor information from both robots. Elevation data was gathered by a UAV-generated pointcloud and then used to execute path planning for a UGV in the work of [14]. The UAV even went on to aid the UGV in climbing a cliff with the use of a tether.

2.2. Multi-Robot Exploration and Mapping

To achieve multi-robot exploration, a method that uses a K-Means clustering approach was chosen [1, 2]. This method builds on existing frontier exploration algorithms by using clustering to partition frontier data points into clusters. From there, an assigner node instructs each robot to travel to the centroid of the frontier cluster nearest it. For easy assignment, the number of clusters is chosen to equal the number of robots. The algorithm is terminated once all frontiers have been explored and the task can be considered complete. Although this algorithm is very efficient for multi-robot exploration and mapping, it is important to note that it requires the starting position of the UGVs to be entered manually. This reduces the autonomy of the real-world system as a human must make the measurements of the robots' starting coordinates and enter them in. The work done in this project allows for the locations of the UGVs to be determined by the UAV, thus removing the human operator from possible dangerous environments, reducing the possibility of errors in setting the UGVs' starting positions, and increasing the overall autonomy of the system.

3. GLOBAL MAP INITIALIZATION

3.1. Robot Hardware and Software

The robots used for the experiments of this work include a custom-built quadcopter UAV and several Turtlebot3 Burger UGVs, shown in Figure 1. The quadcopter is equipped with a Intel RealSense D435i camera capable of capturing RGB and depth images. It has its own computer that allows it to fly autonomously and do low-level image processing. The UGVs are equipped with 2D LiDARs and run on a Raspberry Pi microprocessor. All robots use Robot Operating System (ROS) architecture to communicate with each other.

3.2. Implementation of ArUco Markers

A prerequisite for multi-robot exploration is to first establish a shared map. The proposed method for the creation of a global map involves placing ArUco markers on the UGVs and performing a survey flight with the UAV to detect them using its downward-facing camera. This improves on the work of [10] because the use of an ArUco marker allows for more precise localization. Once the UAV locates a UGV by its ArUco marker, it publishes a transform that tells the UGV where it is relative to the reference frame, 'Map'. From there, when the UGV travels, it keeps track of its displacement using wheel odometry and by matching its LiDAR scans. In summary, this allows for the locations of all robots to be known at any given moment and enables multi-robot exploration and mapping.

ArUco markers are images composed of a 5x5 grid of black and white squares that are commonly used for localization. When spatial calibration is performed, it is possible to estimate the pose of the marker relative to the camera viewing it. Even in non-uniform light conditions, the ArUco marker library has been found to be stable and robust. Researchers have implemented ArUco markers to study displacements less than 1 mm to measure the vibrations of a structure [15]. Figure 2 shows an example of an ArUco marker being detected by the quadcopter's camera. The unique ID of the marker is detected as well as its orientation in order to properly determine the poses of individual UGVs. The ArUco markers used in this work are 10 cm wide and the camera resolution is 640 by 480 pixels.

3.3. Procedure for Global Map Initialization

Once an ArUco marker is detected by the quadcopter UAV, its pose is calculated relative to the origin of the Map frame. The ROS server then publishes a transform from the Map frame to the home frame of the UGV. This transform is published to the ROS server so that all robots are aware of each others' locations. Figure 3 shows the frames and transforms that make up this framework. Prior to the ArUco markers being found, the UGVs were not connected to the Map frame and had no information about their positions and orientations. The link shown in red represents the transform published by the quadcopter upon the detection of the UGVs. Thereafter, they are tethered to the Map frame and can be placed in the environment.

The mission procedure established requires the quadcopter to perform a survey flight around the environment at the start of the mission while the UGVs remain stationary. Once all ground robots have been located, a global map has been established and each robot knows where it is in that map. This is a prerequisite for the coordination of autonomous exploration using the K-Means clustering approach [1, 2]. The shared map also opens up the possibility of using additional information from the UAV for obstacle detection and reconnaissance, which is planned future work for this research project.

4. EXPERIMENTAL RESULTS

4.1. Multi-Robot Exploration and Mapping

Tests were performed to confirm the functionality of the K-Means clustering approach to multi-robot exploration, both in simulation and in the laboratory. The code originally developed in [1, 2] was used in

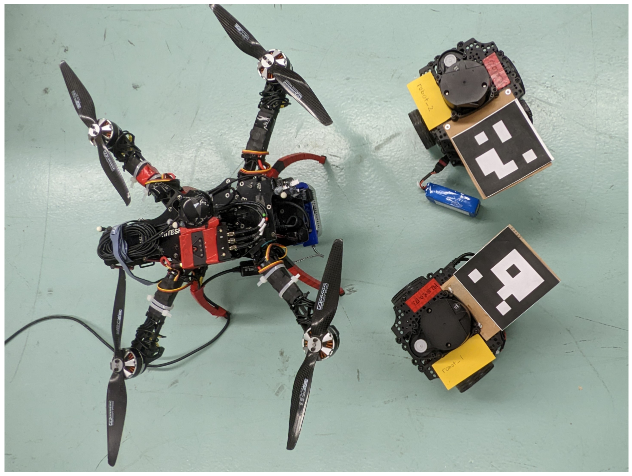


Fig. 1. Custom-built quadcopter UAV and Turtlebot3 Burger UGVs.

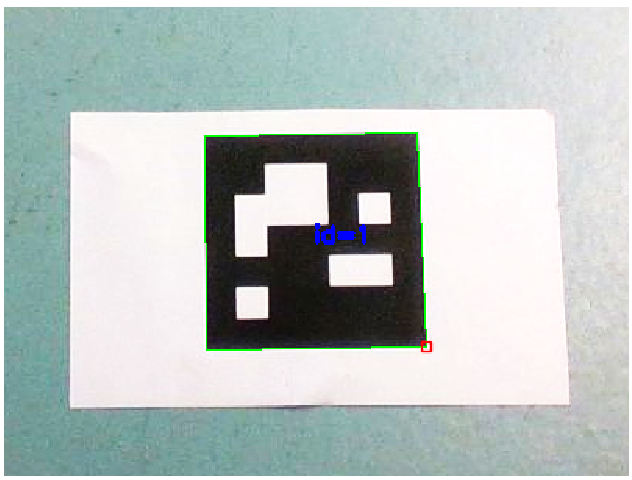


Fig. 2. Detection of ArUco marker.

this implementation, with minor modifications made, including changes to be compatible with a more recent version of ROS (ROS Noetic) and to integrate the UAV global map initialization method.

A simulation environment in ROS Gazebo was used to test the ability of three UGVs to explore and map the area, with the set-up shown in Figure 4(a). After the program was run, a merged map was created from the maps created by the individual robots, as shown in Figure 4(b). The experiment visualizes the map that was created as well as the individual paths that the robots took to map the area, with their starting positions indicated with an 'X'. These paths are a result of the K-Means clustering methodology used for the individual UGV navigation. The simulation was run ten times, with varying numbers of robots, starting positions, and environments. The algorithm was found to work successfully throughout the experiments, with resulting maps that adequately represent the environment and visible segmentation in the paths the robots took. The main purpose of this experiment was to validate that the multi-robot exploration algorithm was successfully implemented in the new version of ROS. A more detailed analysis regarding the effectiveness of the algorithm compared to other methods can be found in the original work [1]. One additional finding was that it was necessary to ensure that the experimental environment was fully enclosed, otherwise, the UGVs would try to explore beyond the desired area and never finish.

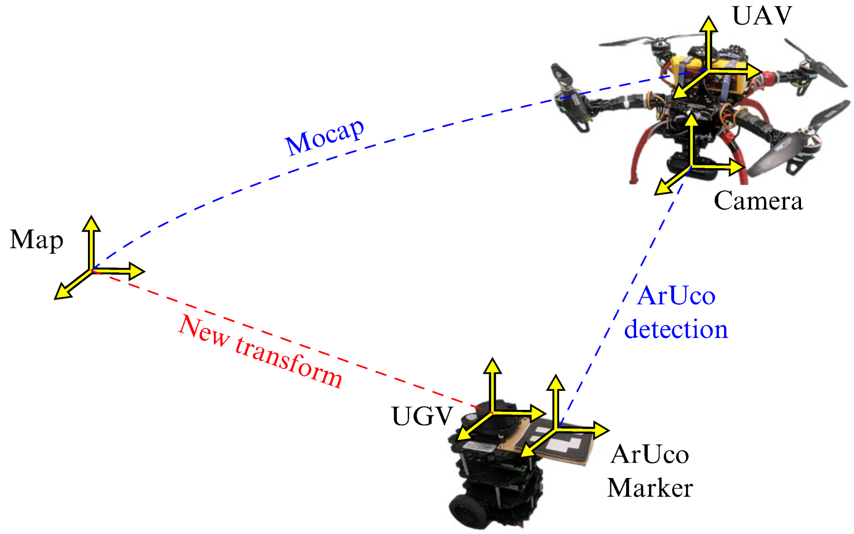


Fig. 3. Transform diagram for robot localization.

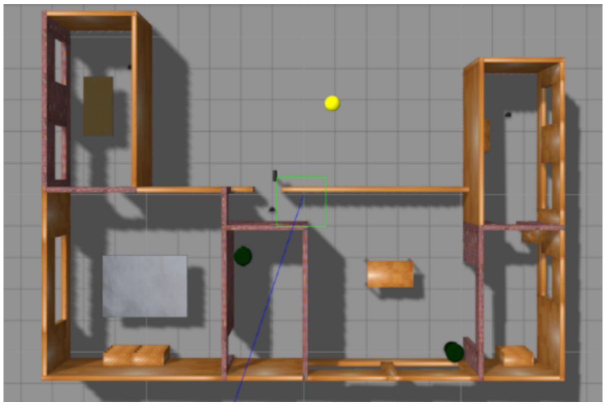
The exploration algorithm was also tested in a real-world environment. This experiment took place in a blocked-off hallway, providing an area of 25 m^2 to test the algorithm with two UGVs. The purpose of this experiment was to verify the functionality of the UGV mapping and exploration algorithm in the real-world, without the use of the UAV for global map initialization. Thus, the original method of manually measuring the relative UGV starting positions was necessary. The visualization result shown in Figure 5 demonstrates that the robots were able to create a merged map and that they segmented their exploration in opposing directions.

4.2. Initialization of the Global Map

To validate the method of determining the starting poses of the UGVs by using a UAV, testing was done using the set-up shown in Figure 6, which includes two UGVs. First, the UGVs were turned on and began scanning their environment through LiDAR. At this time, the robots were not aware of their relative positions and their scans showed a mismatch, as shown in Figure 7(a). Then, the UAV autonomously flew in a preprogrammed pattern to scan the area, in search of the UGV ArUco markers. Upon detection of a UGV, a node on the ROS server published the pose of the UGV relative to the Map frame. In reaction, the RVIZ visualization shifted the robot and its scan to the appropriate location. Once the UAV had finished its survey and both UGVs were located, it landed. The resulting visualization shown in Figure 7(b) demonstrates successful localization of the robots, with correct positions and orientations and accurate LiDAR scan overlap. This created a properly merged map from which exploration can be carried out. Note, the area in this set-up was too small to test the multi-robot exploration, this is carried out in the next sections in a larger area.

In order to determine the accuracy with which the UAV can estimate the positions and orientations of the UGVs, its estimates were compared to ground truth measurements. The ground truth measurements were gathered from an OptiTrack motion capture system that could determine the positions of the UGVs within 1 mm. Twenty runs were performed with the UGVs positioned differently in the environment and the results between the UAV's estimate and the motion capture data were compared. The data compared included the x and y coordinate directions and the rotation, ω, about the z axis. It was not necessary to measure the z position, as all robots are of equal height and the mapping is only done in 2D space.

The results after this experiment's first trial showed that the orientation was estimated correctly within 1.7° but the x and y positions were significantly inaccurate, suggesting an offset. This was found to be due



(a)

(b)

Fig. 4. (a) Simulation environment for multi-robot navigation testing. (b) Merged LiDAR map from simulated UGVs. Robot starting positions are indicated with an 'X' and the paths taken are shown with red, green, and blue lines.

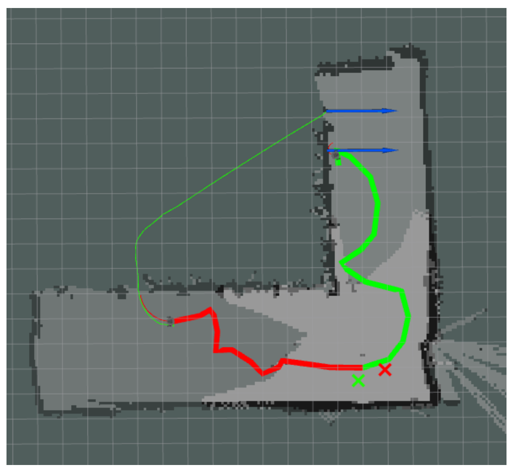


Fig. 5. Real-world exploration with two UGVs. Robot starting positions are indicated with an 'X' and the paths taken are shown with red and green lines, respectively.

to the fact that the ArUco markers are not mounted directly on top of the UGVs, but rather to one side. Additionally, factors of human error were identified and mitigated by setting a guide to ensure the robots were properly aligned to a zero position prior to the experiment. Once these changes were implemented, the experiment was repeated and it was found that the accuracy of the position estimates improved, with an average error of 4.9 cm. Further statistics regarding the experiment can be found in Table 1.

The environment that the UGV pose estimate experiment was conducted in had an area of 4.5 m^2 and, thus, the average position estimate error relative to the environment area was 1.1%. However, the position estimate error is independent of environment size, resulting in an increasingly small relative error when the environment is expanded.

Further tests with different configurations were conducted. Pose estimation was determined as correct for this process so long as the estimated angle of the UGV was within 5° of the actual orientation and the position was within a 10 cm radius of the correct location. Pose errors within this threshold were found possible to be corrected by comparing the LiDAR scans. These findings lend well to the results of the pose estimate experiment as throughout the runs, these limits were never exceeded.

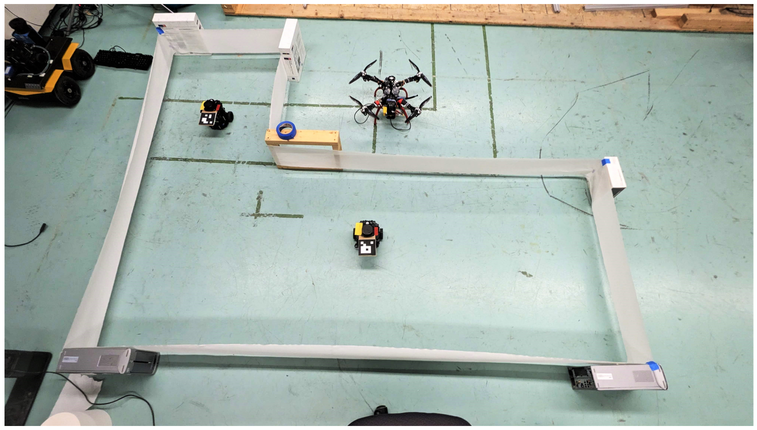
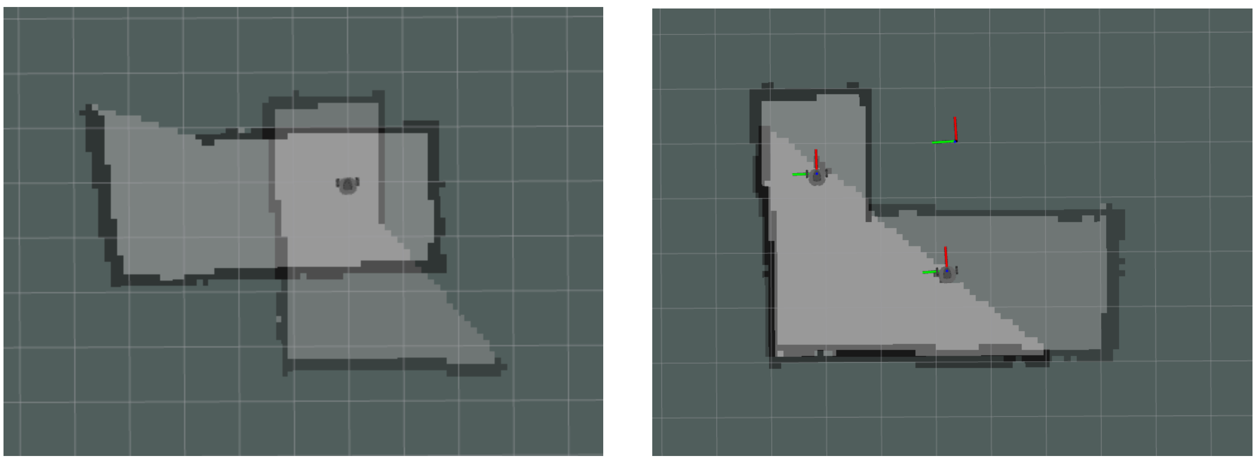


Fig. 6. Real-world test set up for global map initialization experiment.



(a) (b)

Fig. 7. (a) UGV LiDAR scans at mission start, showing mismatch. (b) UGV LiDAR scans after global map initialization using UAV and ArUco markers.

4.3. UAV Localization for Multi-Robot Mapping

Following the successful results for the creation of a global map using a UAV and the multi-robot exploration done independently of one another, it was desirable to combine these tasks to prove the functionality of the complete system. The previous test set-up in Section 4.2 was too small to allow for meaningful exploration, and thus, the set-up as shown in Figure 8(a) with an area of 8.8 m^2 was created.

For this experiment, the UAV first performed an autonomous flight to survey the area and determine the poses of the two UGVs. Once found, their coordinates were published to the ROS server and all robots were made aware of each others' locations. From this, a global map was created and the LiDAR scan data from the UGVs was merged. With the map established, the UGVs began their exploration of the area with the K-Means clustering frontier exploration algorithm, wherein the centralized ROS server assigned the robots unexplored areas.

The visualization in Figure 8(b) depicts the resulting merged map created by the UGVs at the end of their exploration and the paths they took. The resulting map which accurately represents the environment validates that the UAV was able to successfully capture the initial poses of the UGVs for the purpose of

Table 1. Error in UGV pose estimate.

	Position estimate	Orientation estimate
Average error	4.9 cm	1.7°
Maximum error	9.7 cm	0.07°
Minimum error	0.5 cm	3.9°
Standard deviation	2.7 cm	1.3°

multi-robot exploration.

This same experiment was run several times with changing UGV starting poses. These trials had the UGVs placed near one another for some runs and on opposite sides of the environment for others. The criteria for success are:

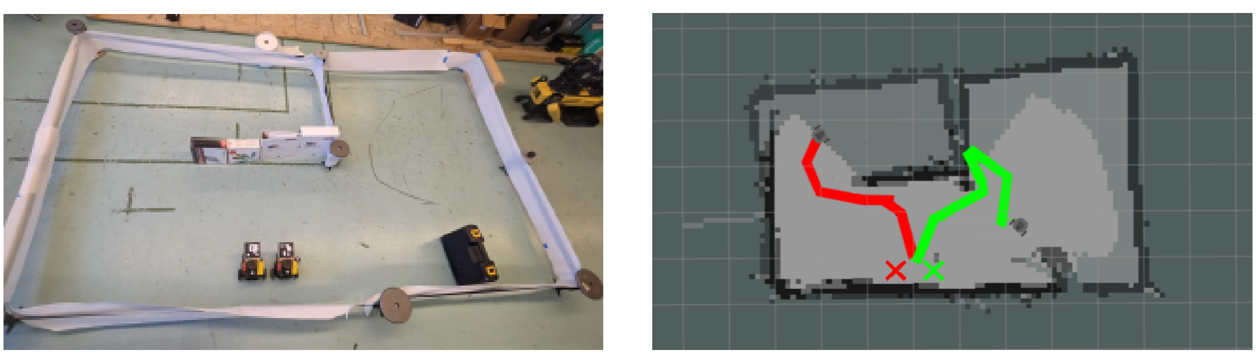
1. The UAV captured the initial poses of the UGVs with sufficient accuracy for map merging (position within 10 cm radius and orientation within 5°).
2. The multi-robot exploration generates a map that represents the environment accurately.
3. Segmentation in the robot paths during exploration is evident.

Throughout the experiments, it was found that the criteria were successfully met with repeatability. The results of the global map creation and multi-robot exploration experiments suggest that a significant foundation has been formed for future development involving the use of the UAV to aid with real-time obstacle detection.

The foremost challenge of the developed method to initialize a global map was identified to be that the accuracy of the UAV position estimate affects the UGV localization accuracy. This was not an issue in the laboratory environment as the motion capture system provides a very accurate UAV position estimate, however, it could be a potential issue when GPS is used to determine the position of the UAV.

5. CONCLUSIONS

The research presents a unique approach to global map initialization between a UAV and multiple UGVs through the use of ArUco markers. In this approach, the UAV performs an autonomous flight to survey the



(a) (b)

Fig. 8. (a) Real-world test set up. (b) Resulting map after UAV localization and exploration with two UGVs. Robot starting positions are indicated with an 'X' and the paths taken are shown with red and green lines, respectively.

area and uses its downward-facing camera to determine the poses of the UGVs by the markers mounted to them. This approach was used to create a shared map between the UGVs in order for multi-robot exploration and mapping to be possible. The use of the UAV increases the autonomy of the multi-robot system, preventing the need to manually enter each robot's starting coordinates to the program.

The development and experimentation of the framework employed a custom-built quadcopter UAV and multiple Turtlebot UGVs. Through experimentation, it was found that the UAV was able to estimate the poses of the UGVs with an average position error of 4.9 cm and an average orientation error of 1.7°. These results were found to be adequate as inputs to the multi-robot exploration algorithm. An existing multi-robot exploration and mapping algorithm which used a K-Means clustering method was chosen. Through testing in both simulation and real-world environments, the algorithm was found to build a coherent map and delegate the frontiers for the various robots to explore successfully.

6. FUTURE WORK

The research presented is considered to be a precursor for future work involving the use of the UAV for obstacle detection to aid the UGVs in their exploration. UGVs equipped with a 2D LiDAR are not able to detect drop-off points and obstacles that are below the height of their LiDAR sensors. This leaves them vulnerable to the possibility of not being able to complete their task or of facing damage. A UAV with a downwards-facing depth camera would be able to detect such obstacles and share their locations with the UGVs in real-time through the shared map.

Aside from obstacle detection, the UAV could also be used to correct errors in the UGVs' positions during the mission, which accumulate due to wheel slippage. This will involve sensor fusion between the various robots and would result in a more accurate map. Finally, more complete real-world testing will be conducted with a larger area of exploration and a greater number of UGVs.

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