# Heterogeneous Multi-Robot Localization in Unknown 3D Space

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***Abstract*— This paper presents a self-localization strategy for a team of heterogenous mobile robots, including ground mobile robots of various sizes and wall-climbing robots. These robots are equipped with various visual sensors, such as miniature webcams, omndirectional cameras, and PTZ cameras. As the core of this work, a formation of four-robot team is constructed to operate in a 3D space, e.g., moving on ground, climbing on walls and clinging to ceilings. The four robots could dynamically localize themselves in an asynchronous way by using cooperative vision techniques. Three of them on the ground mutually view each other and determine their relative poses with 6 degrees of freedom (DOFs). A wall-climbing robot, which significantly extends the work space of the robot team to 3D, is at a vantage point (e.g., on the ceiling) that it can see all the three teammates, thus determining its own location and orientation. The four-robot formation theory and algorithms are presented, and experimental results with both simulated and real image data are provided to demonstrate the feasibility of this formation. Two 3D localization and control strategies are designed for applications such as search and rescue, and surveillance in 3D urban environments where robots must be deployed in a full 3D space.**

Index terms: Multi-robot system, climbing robot, localization

## I. Introduction

### A. Motivation

The focus of robotics research has evolved significantly over the last several decades – the researchers' attention has turned from the traditional industry manipulators toward mobile robots, and more recently from the control of individual robot to the coordination of multiple robots. A great amount of research on mobile robots has been published in literature. However, most of these robots works in a 2D space or strictly restricted 3D space. In [1] [2] [3], a new generation of wall climbing robot is presented and several real robot prototypes are implemented, which transform the present 2D world of mobile rovers into a new 3D universe.

On the other hand, multi-robot cooperation has become another focus of research, which aims at realizing tasks that cannot be fulfilled by a single robot. In this case, multiple robots need to be deployed, and the localization among them becomes an important issue.

A variety of sensors and technologies have been developed for robot localization, however, most of these localization methods are only applicable to robots in a 2D work space. In robotic applications, especially in urban scenarios, more and more tasks require robots to work in a 3D work space and to achieve the same level of localization ability as in 2D space. Therefore, in this paper, we introduce a robot team formation that is composed of ground robots and wall-climbing robots, working in a 3D space. The robots could localize themselves and among each other using cooperative vision strategies proposed in this paper.

### B. Related Work

There is a large body of literature in camera post estimation using N-point algorithms. In [4], the authors tracked the history of camera pose estimation problem using 3 points. A more complete survey of arbitrary N-point algorithms can be found in [5]. It should be noticed that these algorithms work well in ideal case only, which would require obvious feature points in the environment and need either point tracking or points correspondences matching.

One class of the major approaches in robot localization, the absolute localization, aims at localizing the robot in an known or sensed environment. A good survey can be found in [6], which also introduced the Monte Carlo localization method. The other class of approaches, the relative localization, is burgeoning to be a hot topic in the past few years. Researchers in this area aim at making robots work in unknown and hostile environments, without requiring the robots to obtain maps by long time learning. These works are mostly implemented among multiple robots. In [7], the authors have proposed a system that dynamically localize two robots with omnidirectional cameras by tracking the cylindrical bodies of each other to calibrate between them when moving on a 2D plane. A thorough error analysis in 3D moving target tracking is also carried out by the authors. In [8], the authors proposed a solution of self-localization among three robots which requires mutual visibility. These works partially solved the problem of mutual localization of multiple robots. However, the work space of the robots is still restricted in 2D because of the limitations of vertical view angles of the catadioptric cameras used.

### C. Overview of Our Work

This paper presents strategies for a formation of heterogeneous mobile robots that coordinate actions via self-localization in a four-robot configuration. The configuration includes 3 ground-traversing robots and one climbing robot. The system is ideally planned for tasks in urban environments, where the overhead view of the wall-climbing robot can be exploited. The wall-climbing robot expands the localization to three-dimensional unknown space because the robot is at a vantage point where it has a direct line of sight to the other three team members on the ground. It is noted that the configuration is a rather general one in that the three ground robots do not need to traverse on the same planar surface; neither do they need to see the overhead wall-climbing robot (Fig. 1).

The basic steps of the algorithm are the following. First, the formation of three ground robots is calculated using the algorithm in [8], up to a translation scale. The overhead camera on a wall-climbing robot can see them; hence correspondences of their 2D images in the view of the overhead camera and their 3D locations are built. Second, the overhead camera track the motion of the three-robot formation, therefore its own pose is determined by solving a linear equation system after obtaining 6 correspondences of 2D-3D points. As a bonus, the motion information of the ground robots provides a good estimation of the translational scale. In this way the 6 DOF poses of all the four robots are determined without assuming any 3D structure in the space. The robots self-localization is performed without referring to any landmarks in the environment except the robots themselves. A wall-climbing robot [1] [2] [3] is included in the robot team to explore the 3D work space for various tasks such as object tracking, environmental monitoring, etc.

This paper is organized as follows. In Section II, the problem formation of four-robot localization is introduced. In section III, the two localization strategies are discussed for localizing the wall-climbing robot, with robot motion planning methods that give the overhead camera (on the wall-climbing robot) sufficient number of points for self-localization. In section IV, simulation and real experimental results are presented. Finally, conclusions and future research works are discussed in Section V.

## II. Problem Formation

### A. System Composition

Our system is composed of four robots, each mounted with a camera; an illustration is shown in Fig. 1. The three robots mounted with the cameras $C_1, C_2, C_3$ are on the ground, which does not have to be on the same plane. The robot equipped with the camera $C$ is a wall-climbing robot which can move around or stay on the ceiling. The cameras $C_2$ and $C_3$ are catadioptric omnidirectional cameras, which could view 360 degrees horizontally and $-12$ to 32 degrees vertically, therefore they can see each other under most of their formations. The camera $C_1$ is a Pan-Tilt-Zoom (PTZ) camera, whose view angle could vary from 85 degrees to 15 degrees by its optical zooming. These three cameras are mounted on ground robots. The PTZ camera is used to monitor the two robots in front of it with both flexibility in Fields of View (FOVs) and image resolutions by panning, tilting and zooming. The camera $C$ is a small wireless perspective camera with a view angle of 52 degrees . It could be mounted on the wall-climbing robot with an additional camera weight of 50g. The moving direction of the robot team is in the PTZ camera viewing direction (to the left of the figure), in which the two omni-cameras could establish stereo vision for navigation and the PTZ camera could look to the moving direction and zoom in when it is necessary to find details in observation.

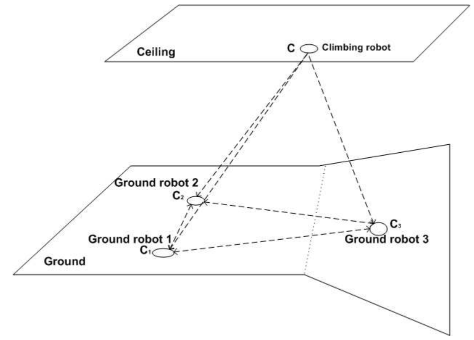


Fig. 1. Four-Robot formation in 3D circumstance

### B. Problem Formation

Because the cameras are independent to the robots, their intrinsic parameters, including their *focal lengths*, *image centers* and *aspect ratios*, are pre-calibrated. The visibility relations among cameras are as follows. The cameras $C_1, C_2$ and $C_3$ could mutually see each other, whereas the camera $C$ could see all the three cameras, $C_1, C_2$ and $C_3$. Note that we do not require any of the three ground robots to be able to see the wall-climbing robot. The problem formation model is decomposed into two parts: the localization of the three ground robots, and the pose estimation of the wall-climbing robot.

*1) Three ground robots localization:* Because the cameras $C_1, C_2$ and $C_3$ mutually view each other, we use the method proposed in [8] to estimate their relative poses (locations and orientations). The translation vector and the rotation matrix of the camera $C_j$ with respect to camera $C_i$ are defined as ${}^iT_j$ and ${}^iR_j$ ($i = 1, 2, 3$ and $j = 1, 2, 3$, $i \neq j$), respectively. Because the focal length of each camera is already known, this translation can be represented in a normalized form (i.e. image form) $\hat{u}_{ij} = (x_{ij}, y_{ij}, f_i)^T$, where $f_i$ is the focal length of the camera $C_i$, and $(x_{ij}, y_{ij})$ is the position of the camera $C_j$ in the camera $C_i$'s image coordinate system. Once we have $\hat{u}_{ij}$ with mutual visibility among the three "ground" cameras, the "relative" translations ${}^iT_j$ and rotations ${}^iR_j$ could be calculated using the method proposed in [8]. A summary of this method is provided in Section II. C for completeness.

*2) Wall-climbing robot localization:* Now that we could calculate the formation among the robots with the camera $C_1, C_2, C_3$ in real-time, we hope to find the pose (including the translation vector and the rotation matrix) of the camera

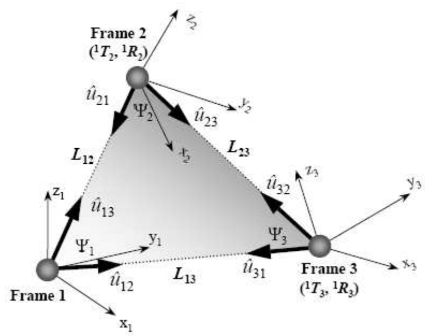



Fig. 2. Three-robot localization (Courtesy [8])

$C$ with respect to one of the three ground cameras. Suppose the image coordinate vector of the camera $C_i$ viewed by the camera $C$ is $(x_i, y_i)$, and the focal length of the camera $C$ is $f$, our task is to find the translation vector $T_i$ and the rotation matrix $R_i$ in the camera coordinate system of the camera $C$, where $i = 1, 2, 3$ can be any of the three camera. Our approach to this 3D localization is discussed in detail in section III.

### C. Prerequisite localization component

In this sub-section, we will briefly review the solution proposed in [8] in solving the localization problem among the three camera $C_1, C_2$ and $C_3$ as a basis for 3D localization strategies.

As shown in Fig. 3, because all the solutions for translational vectors are up to a scale, we assume the absolute length between cameras $C_i$ and $C_j$ is known as $L_{ij}$. For calculation, we assume that the angle between ${}^iT_j$ and ${}^iT_k$ is $\psi_i$. By the Cosine Theorem, we have

$$\begin{cases} {}^1T_2 = L_{12}\hat{u}_{12} = \frac{\sin(\cos^{-1}(\hat{u}_{21}\cdot\hat{u}_{23}))}{\sin(\cos^{-1}(\hat{u}_{13}\cdot\hat{u}_{12}))}\hat{u}_{12} \\ {}^1T_3 = L_{13}\hat{u}_{13} = \frac{\sin(\cos^{-1}(\hat{u}_{32}\cdot\hat{u}_{31}))}{\sin(\cos^{-1}(\hat{u}_{13}\cdot\hat{u}_{12}))}\hat{u}_{13} \end{cases} \tag{1}$$

Note that the vectors ${}^iT_j$ and ${}^jT_i$ are of the same length but of opposite directions, Therefore we have the following equation set

$$\begin{cases} -{}^1T_2 = {}^1R_2 \cdot {}^2T_1 \quad {}^1T_3 - {}^1T_2 = {}^1R_2 \cdot {}^2T_3 \\ -{}^1T_3 = {}^1R_3 \cdot {}^3T_1 \quad {}^1T_2 - {}^1T_3 = {}^1R_2 \cdot {}^3T_2 \end{cases} \tag{2}$$

Now that all the vectors ${}^iT_j$ are up to the same scale, each rotation matrix $\mathbf{R}$ could be normalized to the form of

$$\mathbf{R}a_i = b_i \quad i \in [1, 2] \tag{3}$$

whose solution is

$$\min_{\mathbf{R}} \sum_i \parallel \mathbf{R}a_i - b_i \parallel \tag{4}$$

which can be analytically solved by

$$\mathbf{R} = (M^TM)^{-\frac{1}{2}}M^t \quad \text{where } M = \textstyle\sum_i a_i \cdot (b_i^T) \tag{5}$$

By using this algorithm the relative poses of the cameras $C_1, C_2$ and $C_3$ could be calculated up to the same scale in real-time, if they could mutually view each other.

## III. 3D Localization Strategies

Now that we have the relative poses of cameras $C_1, C_2$ and $C_3$ at any time, the next task is to estimate the pose of camera $C$.

### A. Definition and Analysis

We define the intrinsic parameters of camera $C$ as the following: $f$ is the effective focal length; $(x_i, y_i)$ is the position of the camera $C_i (i = 1, 2, 3;$ same below) in the camera $C$'s image coordinate system. $(X_W^i, Y_W^i, Z_W^i)^T$ is the world coordinates of the camera $C_i$, all of which are determined (Section II. C) in a relative coordinate system defined with the three ground robots (up to a scale). To clarify our equations, we define $(X_W^1, Y_W^1, Z_W^1)^T$ as the origin of the world coordinate system, *i.e.*, it is $(0, 0, 0)^T$. We also define $R = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$ as the rotation matrix of the camera $C$, and $T = (T_x, T_y, T_z)^T$ as its position, both with respect to the camera $C_1$. Now our task is to find the pose of the camera $C$, *i.e.*, finding $R$ and $T$.

Using the well-known perspective camera model, we have

$$\begin{cases} \frac{x_i}{f}(r_{31}X_W^i + r_{32}Y_W^i + r_{33}Z_W^i + T_z) = \\ (r_{11}X_W^i + r_{12}Y_W^i + r_{13}Z_W^i + T_x) \\ \frac{y_i}{f}(r_{31}X_W^i + r_{32}Y_W^i + r_{33}Z_W^i + T_z) = \\ (r_{21}X_W^i + r_{22}Y_W^i + r_{23}Z_W^i + T_y) \end{cases} \tag{6}$$

where $i = 1, 2, 3$. This will provide 6 independent linear equations for 12 unknown variables of the rotation and translation components. Note that the rotation matrix only has three degrees of freedom, even with 9 elements. Therefore, there should be a solution using three known points seen by the camera $C$ (*i.e.*, the three robot locations) given that the rotation and translation parameters only have six degrees of freedom. However, there could be up to 4 valid solutions in this system [4]; in addition, the localization is up to a scale. This leads us to find out an alternative solution by considering the mobility of the mobile robot team and further determine the scale of the translations. If we make more observation on these three-robot-formations, *i.e.*, more equations are introduced, the linear system can be solved. As a result, two strategies of solving the localization problem by moving the ground robots are proposed.

### B. Concurrent Moving Strategy

As is shown in Fig. 3, the behavior of the *dynamic* three-ground-robot formation is composed of three steps by two movings in one localization cycle of the four-robot formation. In each localization cycle, the wall-climbing robot with the camera $C$ finishes one self-localization.

Within each localization cycle, the camera $C$ will keep itself stationary on the ceiling. Meanwhile, the other three (ground) robots with the camera $C_1, C_2$ and $C_3$ go through

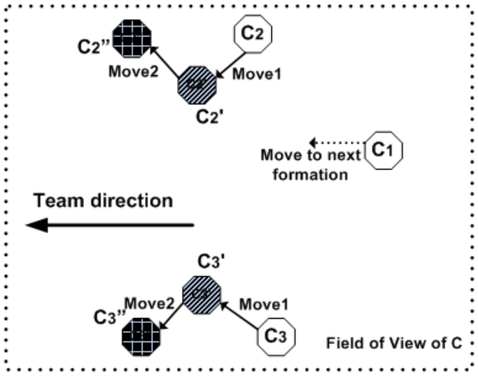



Fig. 3. Concurrent moving strategy: Camera $C_1$ keep stationary, camera $C_2$ and $C_3$ are at the initial position, a localization is made. These two cameras move twice (move1 and move 2) to repeat the calibration (at the slash shaded position, $C_2'$ and $C_3'$, and the grid shaded position, $C_2''$ and $C_3''$).

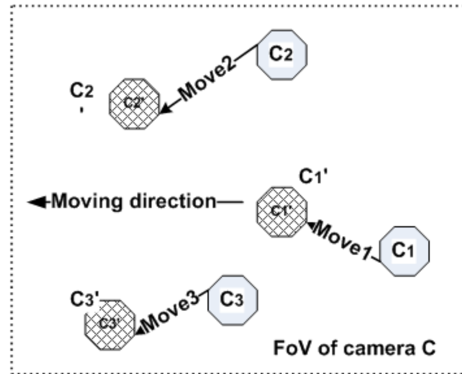



Fig. 4. Sequential moving strategy: Three robots are in their initial positions. Step 1: $C_2$ moves to $C_2'$ while $C_1$ and $C_3$ keep stationary; self-localization is performed with respective to $C_3$. Step 2: $C_3$ moves to $C_3'$ while $C_1$ and $C_2$ keep stationary; self-localization is performed with respective to $C_1$ Step 3: $C_1$ moves to $C_1'$ while $C_2$ and $C_3$ keep stationary; self-localization is performed with respective to $C_2$.

the localization in three steps. Throughout the cycle, the first camera $C_1$ remains in its initial position. When the camera $C_2$ and $C_3$ are in their initial positions, the three ground robots finish one self-localization in the reference coordinate system of the stationary camera $C_1$. During this step, the overhead camera $C$ records and identifies the image coordinates of all the three robots (cameras). Then we move the cameras $C_2$ and $C_3$ together twice (move1 and move2, consequently step2 and step3), with the feedback of the camera $C$ to make sure they are within its field of view (FOV). Each time the three cameras are in a new three-robot formation, a self-localization with respect to $C_1$ is performed again. This is repeated in steps 2 and 3.

After the three localization stages, we obtain 7 (=3+2+2) known 3D locations of the moving robots. In addition, the translation scale can be roughly determined by using the motion information of the two ground robots. This leads to a linear equation system in the form of Eq. 6 but with 14 equations. By using the least square method, we can determine the pose of the camera $C$ in a linear manner, with absolute scales, and in real-time.

After one localization cycle is finished, the wall-climbing robot with the camera $C$ can move again, only with a constraints to make sure the three ground robots are within its FOV.

### C. Sequential Moving Strategy

Theoretically, concurrent moving strategy can perfectly finish self-localization of the robot team. However, we also notice that with such a moving strategy, the robot team has to move in a peristalsis fashion, which looks not very fluid. Consequently, we design another moving strategy for such localization called the sequential moving strategy that moves robots in turn.

Once again, our localization strategy will be composed of global localization cycles. In each cycle, as shown in Fig. 4, the three robots are in their original positions $C_1, C_2$ and $C_3$, and a mutual localization is conducted among them. Then, in the second step, instead of moving two robots, we only move $C_2$ to a new position $C_2'$ within $C$'s FOV. Another mutual localization among the three robot is done again and camera $C$ will record all these positions. Alternatively in the next two steps, we will move one robot each time ($C_3$ then $C_1$), and do self-calibration among three ground robots with respect to the camera coordinate of the robot which was moved the earliest. By utilizing the perspective camera model, these relative positions represented in different camera coordinate systems (due to motion) could be easily transformed to the relative position with respect to the initial pose of the camera $C_1$. Furthermore, as in the concurrent moving strategies, the translation scale can be estimated by using the motion information of the ground robots. As such, camera $C$ is able to localize itself by obtaining 6 known 3D points and establish 12 equations in the form of Eq. 6 for 12 unknowns.

Compared with concurrent moving strategy, there are two advantages in this sequential moving strategy. (1) The localization cycle could start from any stage of the movements without having to start from the first stage. (2) The sequential moving strategy is more efficient since only one movement per robot is needed. Since this moving strategy only moves one camera with two reference points fixed each time, more robust and accurate results could be obtained than from the concurrent moving strategy with only one fixed reference point. Experimental results will be shown in the next section.

The two localization strategies seem to restrict free movement of mobile robots at the first look. However, it is quite practical and could be implemented in near-realtime. In the concurrent moving strategy, the only requirement is that both the wall-climbing robot and one of the ground mobile robot (i.e. the reference robot) move to suitable locations, and pause for a while, while the other two ground robots keep on moving. Three synchronized snapshots of all of the four cameras will be sufficient to determine their relative poses. Similar observation can be made in the sequential moving strategy.

## IV. Experimental Results

### A. Simulations

The objective of our simulation is to verify the correctness, feasibility and robustness of our algorithms/strategies. We built a virtual environment using matlab for simulation purpose. The simulation is conducted in the following two steps.

Step 1. Constructing the models of a perspective camera $C$, two catadioptric cameras $C_2, C_3$, and a PTZ camera $C_1$ (at wide angle end), by defining their intrinsic parameters, *i.e.*, effective focal lengths, aspect ratios, image centers (which is extremely important for catadioptric cameras), and image resolutions (an important issue for robustness test). The parameters used are the nominal values from the real camera manuals.

Step 2. After having these camera models, we build an 3D experimental environment. The ground is modeled as a hyperboloid surface (to simulate 3D orientations of the three ground robots) and the ceiling as a sinusoid curvature (for the same reason for the wall-climbing robot). The radius of the curvature of the hyperboloid ground is 8 meters. The period of the sinusoid ceiling is 10 meters with a magnitude of 0.25 meters. The purpose of designing such surface is to provide a "general" 3D environment. The distance between the ceiling and the ground is 3.5 meters. Both moving strategies are applied to the robot team of four. The distance of each movement of the robots obeys a isotropic *Gaussian* distribution of $N(0.8, 0.2)$ meters. The initial formation of the three robot is a triangle with baseline length of 2 meters and other two edges of 1.5 meters. The overhead camera (on the wall-climbing robot) is right above the middle of the base line. The orientation of each camera parallelly embeds in the tangent plane at their attaching point of the surface. Gaussian noises are added to test the robustness of our approach. The position of the camera $C_i$ in the camera $C_j$'s image coordinate system is added by an error of $N(0, 2)$ in units of pixels and it uniformly distributes in isotropic directions. Simulation results are shown in Table I. The measurements of errors in locations are the *Euclidian* distances between localized positions and real positions (in cm), and the errors in angles (degrees) are the mean of errors of the yaw, pitch and tilt angles of each camera. In the table, the final locations ($T$) and orientations ($R$) of each localization cycle are shown for both the concurrent and the sequential moving strategies. Simulation results indicate that the two strategies produce the same level of accuracy in localization. The sequential strategy has more stable performance than the concurrent strategy.

TABLE I
Simulation Results

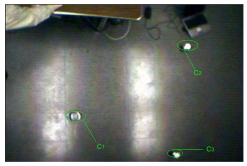
| **Concurrent** | | | |
|---|---|---|---|
| **Camera #** | **Real T.** | **Estimated T** | **Error** |
| $C$ | (111.80,0,357.73) | (110.89,0.87,360.28) | 2.85 |
| $C_1$ (ref) | (0, 0, 0) | (0, 0, 0) | 0 |
| $C_2$ (final T) | (-127.54,191.39,3.11) | (-124.52,190.13,1.23) | 3.77 |
| $C_3$ (final T) | (96.73,174.22,2.56) | (96.01,173.21,1.20) | 1.84 |
| **Camera #** | **Real R** | **Estimated R** | **Error** |
| $C$ | (90, 0, 0) | (88.65,1.07,-1.55) | 1.31 |
| $C_1$ (ref) | (0, 0, 0) | (0, 0, 0) | 0 |
| $C_2$ (final R) | (0.22,-0.39,0.20) | (2.24,-3.07,2.46) | 2.58 |
| $C_3$ (final R) | (0.21,0.47,-0.50) | (-1.29,-0.37,1.42) | 0.97 |
| **Sequential** | | | |
| **Camera #** | **Real T.** | **Estimated T** | **Error** |
| $C$ | (111.80,0,357.73) | (112.73,1.22,356.85) | 1.77 |
| $C_1$ (final T) | (82.66,7.17,1.25) | (82.87,7.33,1.51) | 0.37 |
| $C_2$ (final T) | (79.71,126.30,4.98) | (80.42,126.37,4.40) | 0.92 |
| $C_3$ (final T) | (-85.33,141.05,4.94) | (-84.70, 142.34, 4.72) | 1.46 |
| **Camera #** | **Real R** | **Estimated R** | **Error** |
| $C$ | (90, 0, 0) | (89.07,0.62,-0.94) | 0.83 |
| $C_1$ (final R) | (1.33,0.37,2.71) | (1.46,0.22,1.40) | 0.56 |
| $C_2$ (final R) | (1.21,-0.97,2.44) | (1.67,-0.06,1.43) | 0.86 |
| $C_3$ (final R) | (1.33,0.87,3.44) | (2.60,0.45,1.98) | 1.05 |

### B. Real Experiments

Our experiments are conducted using the following devices (Fig. 5(a))): *(1)Three ground robots: One ActivMedia Pioneer II robot and two ActivMedia Pioneer III robots; (2) A climbing robot: City-Climber as reported in [1] and [3]. (3) A perspective camera: SPUD 975T wireless camera by Videocomm Tech.(4) Two catadioptric cameras: Optical part – D40 by RemoteReality Sensor – Dragonfly by PointGrey research; and (5) A PTZ camera: C50i by Canon Inc.* These cameras are calibrated using the calibration tool box in [9]. The intrinsic parameters of these cameras are very close to those in their respective product manuals (used in simulation).

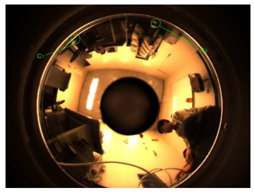
For accurate measurement purpose, we detach the cameras from the robots. The experiment is conducted with cameras only. The cameras in each image are calculated by thresholding under human guidance.
The computation of localization algorithm can be finished real timely. (Solving the transformations and the linear equation system take less than 2ms in matlab.) Image segmentation using threshold in 24 bit color and calculate the COM of robot marker space takes less 12ms on a $640 \times 480$ image under Visual C++. The computation are conducted on a personal computer. Experimental results are shown in Table II; only position accuracy information are provided for the real data since the lack of the ground truth data for orientations. However the estimated rotation parameters solved by the two strategies are very close to each other. Results of translation parameters show that the sequential strategy produces more accurate results than the concurrent strategy does. Compared with simulation, the errors in real experiment are one magnitude greater than those in simulation. These errors could result from the following factors: sizes of the calibration targets (the robots), lens distortion, and the fact

(a) Experimental Setting



(b) View from Camera C

(c) View from Camera $C_1$



(d) View from Camera $C_2$

Fig. 5. Experimental Robot Settings and Views from three different types of cameras. The robot targets are marked green in the pictures.

TABLE II
EXPERIMENT RESULTS ON REAL DATA

| **Camera #** | **Real T** | **Estimated T** | **Error** |
|---|---|---|---|
| **Concurrent** | | | |
| $C$ | (23.7,75.2,295.5) | (35.4,60.6,302.3) | 19.9 |
| $C_1$ (ref) | (-34.4,66.8,2.9) | (-34.4,66.8,2.9) | 0 |
| $C_2$ (final T) | (159.8,17.6,2.4) | (175.5,29.5,14.0) | 23.4 |
| $C_3$ (final T) | (161.1,180.4,2.4) | (173.4,168.9,7.9) | 17.7 |
| **Sequential** | | | |
| $C$ | (23.7,75.2,295.5) | (29.8,69.5,298.6) | 8.9 |
| $C_1$ (final T) | (57.2,61.3,2.9) | (62.3,57.9,4.4) | 6.3 |
| $C_2$ (final T) | (127.6,15.9,2.4) | (123.6,19.2,5.0) | 5.8 |
| $C_3$ (final T) | (130.1,174.3,2.4) | (137.0,169.2,4.4) | 8.8 |
| **Camera #** | **Real R** | **Estimated R** | **Error** |
| **Concurrent** | | | |
| $C$ | — | (10.2,-7.6,92.3) | — |
| $C_1$ (ref) | — | (8.7,-13.5,-4.6) | — |
| $C_2$ (final T) | — | (14.2,9.1,-7.0) | — |
| $C_3$ (final T) | — | (13.5,-6.2,7.9) | — |
| **Sequential** | | | |
| $C$ | — | (12.9,8.6,90.5) | — |
| $C_1$ (final T) | — | (9.6,17.7,-5.8) | — |
| $C_2$ (final T) | — | (15.4,9.3,-8.1) | — |
| $C_3$ (final T) | — | (5.1,-2.7,2.0) | — |

that the three ground robots are on a flat plane, which is the case that camera calibration usually needs to avoid.

## V. Conclusions and Discussions

In this paper, we have proposed an approach for self-localization among four robots in 3D space. Two dynamic robot-team formation strategies are presented to obtain 3D poses of all the four robots with analytical solutions and with absolute translation scales. Both of them work robustly and accurately with simulation; acceptable results are produced in experiments with real imagery data. Our experiments indicate that real-time localizationamong multiple robots is feasible through inexpensive cameras in unknown 3D space.

The main contributions of this paper lie on three points. First, multi-robot localization is realized in a 3D space, with various cameras - perspective cameras, PTZ cameras and catadioptric cameras. Second, in the four-robot team, the three ground robots do not need to see the wall-climbing robot over-looking them, thus loosening the constraints of mutual visibility as in [8]. Third, the three robot localization solution in [8] is up to a scale, but no information about absolute distances is obtained. In our work, the localization process is implemented by multiple movements, which give us enough information to calculate the absolute translations in the robot formation by using the robot movement information.

For real robotic applications, real time is always one of the key issues to guarantee the success of the missions. In our current experiments, the localization algorithm can achieve near real-time performance. However, the localization of the overhead camera needs to go through several moving stages of the three on-ground robots. To achieve better real time property, analytical algorithm to solve the problem in on step is desired. This is our ongoing research, the solution of which will result in a more efficient way for the localization among multi-robot in 3D space.


## Acknowledgment

This work was supported in part by the U.S. Army Research Office under Grant W911NF-05-1-0011 and U.S. National Science Foundation under Grant No. CNS-0424539.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