Coordinated Motion of UGVs and a UAV

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***Abstract*—Coordination of autonomous mobile robots has received significant attention during the last two decades. Coordinated motion of heterogenous robot groups are more appealing due to the fact that unique advantages of different robots might be combined to increase the overall efficiency of the system. In this paper, a heterogeneous robot group composed of multiple Unmanned Ground Vehicles (UGVs) and an Unmanned Aerial Vehicle (UAV) collaborate in order to accomplish a predefined goal. UGVs follow a virtual leader which is defined as the projection of UAV's position onto the horizontal plane. The UAV broadcasts its position at certain frequency. The position of the virtual leader and distances from the two closest neighbors are used to create linear and angular velocity references for each UGV. Several coordinated tasks have been presented and the results are verified by simulations where certain amount of communication delay between the vehicles is also considered. Results are quite promising.**

I. Introduction

The importance of unmanned vehicles have increased dramatically through the last two decades [1], [2], [3], [4], [5], [6]. Instead of using a sophisticated, expensive robot which may require trained expert to operate, people are attracted to the idea of using cheaper and simpler robot groups that can accomplish same tasks on their own [4]. These robot groups can compose of identical robots or heterogeneous robots, and can be used for tasks that are dull, dirty or dangerous for humans. Applications for robot groups may vary from military operations such as searching mines [7], to civil activities such as fire detection, search and rescue of a survivor [8]. Also the industrial applications are not limited to carrying products inside a factory, structural analysis and fault detection of bridges, pipelines, dams and so on.

There are several examples of UAV and UGV collaboration. Chaimowicz et al. showed that UGVs and UAVs can be employed in urban environments together where UAVs provide information for UGVs in a fast manner [9]. Tanner showed that UAVs and UGVs can be used as teams, in order to detect a moving target in a given area while combining obstacle avoidance algorithms with decentralized algorithms for flocking [10]. Luo et al. used a team composed of a UAV and UGVs that collaborate in order to find a solution to a chemical (poisonous gas) accident. In their scenario UAV searched through a hazardous environment in a pre-defined path given by a user and located the target, a broken point on the pipeline for example, then sent information to the UGV team to carry out the rescue mission [6].

In this work, we develop a novel coordination scheme for a group of UGVs and an UAV to accomplish a predefined goal, four our case surrounding a target in a coordinated manner. UGVs are guided to the vicinity of the goal position by following a virtual leader, which is obtained as the projection of UAV's 3D (x, y, z) position onto the horizontal plane, i.e. (x, y). UAV broadcasts its position information to the UGVs at certain frequency. Moreover, coordination between UGVs are achieved by defining appropriate linear and angular velocities using suitable kinematic relations. Results are successfully verified in simulation environment by a group of 3 and 5 UGVs, respectively. In these simulations, communication delays between robots are also considered.

The organization of this paper is as follows. In section II the formulation of the problem is detailed. In section III the coordination algorithm and the collision-free references are developed for UGVs. Section IV is on modeling and feedback control of nonholonomic robots, UGVs. Section V is the modeling and feedback control of a quadrotor, UAV. In section VI, the simulation results are presented to verify the proposed framework. In section VII, the paper is concluded with some remarks and some future directions are indicated.

II. Problem Definition

A group of UGVs, n nonholonomic mobile robots, namely $R_1, R_2, \ldots, R_{n-1}, R_n$, and a quadrotor type aerial vehicle, UAV, are considered to accomplish a coordinated task of navigating from some initial configuration to a target location denoted by T. The target and all of the mobile robots are assumed to be on the same plane.

Similar to a previous work [11], we consider a scenario where the success of the coordinated task is determined by accomplishing several objectives. These objectives are:

- UAV is able to locate T from a distance and can hover on the target T after reaching it.
- $R_1, R_2, \ldots, R_{n-1}, R_n$ should surround the target, T, and form a circle with radius d_{targ} where T is located at the center.
- The UGVs should be evenly spaced on the circle.
- The orientation of each R_i should be towards T once the previous three objectives are successfully accomplished.

The nature of each task can be different from one another, but in order to accomplish these tasks together, each R_i might check if all the other UGVs have achieved the same state before starting to next phase. This objective needs to be

realized via wireless communication, after acquiring desired position and/or orientation. Collision avoidance is an essential problem in the context of coordinated motion [12]. In each phase UGVs should avoid collisions with each other or any obstacle in the environment. In this work we assume that there are no obstacles on the plane of UGVs. Also the UAV is assumed to be in a collision free environment.

In this study, we assume a stationary target, T, position of which is unknown to the UGVs but known to UAV. Detection task can be accomplished using visual features on T, with or without a priori knowledge about the target. UGVs are not allowed to park till UAV hovers on T. When UAV is on top of T, it broadcasts a signal that informs UGVs to park when they are equally spaced from target and from their closest neighbours. In the absence of this signal each R_i tries to surround the position coordinates that is currently known as the position of T. The UAV broadcasts its position on the horizontal plane as the position of T, till it reaches on top of actual T. UGVs are guided by UAV to the vicinity of actual T without being affected from the initial distance to the target.

Another assumption in our work is that each R_i, is capable of perceiving its environment by some appropriate sensor, in order to find if there is any object in their *virtual collision prediction region* [3]. Figure 1 depicts the proposed framework.

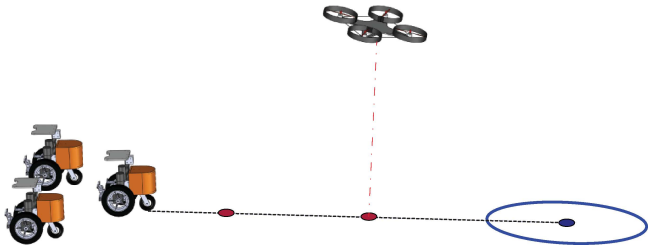

Fig. 1: Depiction of coordination scheme, where UAV, UGVs, T and UAV's projection onto horizontal plane are indicated.

III. Coordination Algorithm and Reference Generation

In this work, we are extending our previous work [11], where we have developed a coordination algorithm for a group of UGVs by properly designing the linear and angular velocities. The reference pose for each R_i is generated by a virtual reference robot. The regulation of the errors between the virtual reference robot's pose and the actual robot's pose to zero are guaranteed with a smooth time-varying feedback control law [13]. The projection of the UAV's position onto the X-Y plane is defined to be the position of the virtual leader V_L.

A. Desired Coordination Velocity

Coordination of UGVs is achieved by defining desired velocities with respect to closest neighbors of R_i and V_L.

1) Velocity due to Virtual Leader: Each R_i, has a desired velocity vector towards V_L, $\overrightarrow{v}_{i2V_L}$. $\overrightarrow{v}_{i2V_L}$ is defined to move R_i towards V_L until UAV reaches on top of T, then each R_i maintains a given distance d_{targ} between itself and T, as follows:

$$\overrightarrow{v}_{i2V_L} = k_{lin}(d_{i2V_L} - d_{targ})\overrightarrow{n}_{i2V_L} \ , \tag{1}$$

where $k_{lin} > 0$ is a constant, d_{i2V_L} is the distance from R_i to V_L, and $\overrightarrow{n}_{i2V_L}$ is the unit vector from R_i to V_L.

2) Velocity due to Neighbors: R_i interacts with only its two nearest neighbors. Each R_i is required to maintain a distance, d_{neigh} to its closest neighbors in order to move in a coordinated manner. The second closest neighbour loses its effect after reaching a predefined distance, d_{relax}, from T.

The desired velocity vector for each R_i due to closest neighbors, $\overrightarrow{v}_{neigh}$, is given by:

$$\begin{aligned} \overrightarrow{v}_{neigh} &= \overrightarrow{v}_{cl1} + \overrightarrow{v}_{cl2} \ , \\ \overrightarrow{v}_{cl1} &= k_{lin}(d_{i2cl1} - d_{neigh})\overrightarrow{n}_{i2cl1} \ , \\ \Delta d_{i2n} &= d_{i2cl2} - d_{neigh}, \\ \overrightarrow{v}_{cl2} &= \begin{cases} k_{lin}\Delta d_{i2n}\overrightarrow{n}_{i2cl2} & \text{if} \quad d_{i2T} \geq d_{relax} \\ 0 & \text{if} \quad d_{i2T} < d_{relax} \end{cases} \ , \end{aligned} \tag{2}$$

where d_{i2cl1} and d_{i2cl2} are the distances, $\overrightarrow{n}_{i2cl1}$ and $\overrightarrow{n}_{i2cl2}$ are unit vectors, from each R_i to its two closest neighbors. $\overrightarrow{v}_{cl1}$ and $\overrightarrow{v}_{cl2}$ are velocities due to two closest neighbors. d_{i2T} is the distance of each R_i to T and k_{lin} is a positive constant.

3) Desired Velocity Combination: The desired velocity vector, $\overrightarrow{v}_{coord}$, of R_i is defined as a convex combination of previously calculated velocities $\overrightarrow{v}_{i2V_L}$ and $\overrightarrow{v}_{neigh}$ namely:

$$\overrightarrow{v}_{coord} = k_{V_L}\overrightarrow{v}_{i2V_L} + k_{neigh}\overrightarrow{v}_{neigh} \ , \tag{3}$$

where k_{V_L} is the coefficient of velocity due to V_L, and k_{neigh} is the coefficient of the velocity due to the closest neighbors of R_i. Since these coefficients have a major role on the coordination algorithm it is beneficial to define them as adaptive parameters in order to add extra degree of freedom to the system [11].

IV. Modeling and Control of Nonholonomic Mobile Robot

For this work we have used two-wheeled nonholonomic mobile robot. Kinematic model is given as [14]:

$$\dot{x} = u_1 \cos\psi_{ref} \ , \quad \dot{y} = u_1 \sin\psi_{ref} \ , \quad \dot{\psi}_{ref} = u_2, \tag{4}$$

where x and y are the center of mass of the UGV, and ψ_{ref} is its orientation with respect to the horizontal axis. u_1 and u_2 are liner and angular velocities of the UGV. A nonholonomic mobile robot is shown in Figure 2.

In [13] it is shown that the following control law regulates error to zero under the assumption that the given trajectory, in our case trajectory created from via-points, is time varying.

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} -k_1 e_1 + u_{1r}\cos e_3 \\ -u_{1r}\dfrac{\sin e_3}{e_3} - k_2 e_3 + u_{2r} \end{bmatrix} \ , \tag{5}$$

where k_1 and k_2 are positive control gains. e_1, e_2 and e_3 are

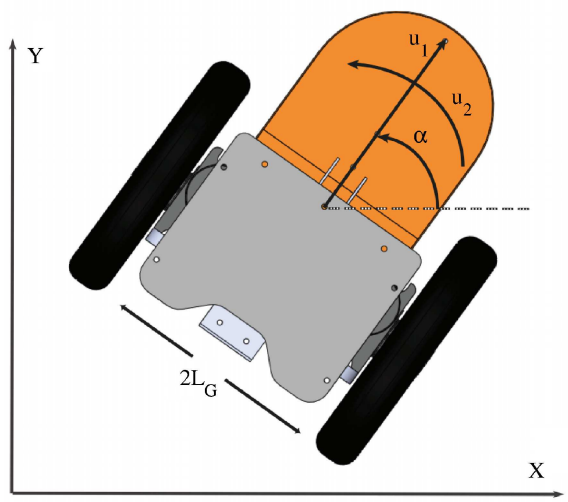

Fig. 2: A unicycle robot and its variables of interest.

transformed errors in terms of tracking errors $\tilde{x} = x - x_{ref}$, $\tilde{y} = y - y_{ref}$ and $\tilde{\psi} = \psi - \psi_{ref}$. The control inputs for the virtual robot are u_{1_r} and u_{2_r}.

For time invariant trajectories, or to park the robot at a fixed point the following controls are proposed [13]:

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} -k_3 e_1 \\ -k_4 e_3 + e_2^2 \sin(t) \end{bmatrix}, \tag{6}$$

where k_3 and k_4 are positive control gains.

V. Modeling and Control of a Quadrotor

The UAV used in this work is a quadrotor, the coordinate axes, moments and torques exerted on the quadrotor can be seen in Figure 3. The reason that we have chosen a quadrotor is its hovering capability and high maneuverability. The dynamic model of the quadrotors are well studied. The details of the following Newton-Euler equations can be found in [15]:

$$\begin{aligned} \ddot{X} &= (cos\phi sin\theta cos\psi + sin\phi sin\psi)\frac{U_1}{m}, \\ \ddot{Y} &= (cos\phi sin\theta sin\psi - sin\phi cos\psi)\frac{U_1}{m}, \\ \ddot{Z} &= (cos\phi cos\theta)\frac{U_1}{m} - g, \end{aligned} \tag{7}$$

$$\begin{aligned} \ddot{\phi} &= \frac{I_{YY} - I_{ZZ}}{I_{XX}}\dot{\theta}\dot{\psi} + \frac{J_P}{I_{XX}}\Omega + \frac{U_2}{I_{XX}}, \\ \ddot{\theta} &= \frac{I_{ZZ} - I_{XX}}{I_{YY}}\dot{\phi}\dot{\psi} + \frac{J_P}{I_{YY}}\Omega + \frac{U_3}{I_{YY}}, \\ \ddot{\psi} &= \frac{I_{XX} - I_{YY}}{I_{ZZ}}\dot{\phi}\dot{\theta} + \frac{U_4}{I_{ZZ}} \end{aligned} \tag{8}$$

In the equations above I_{XX}, I_{YY} and I_{ZZ} are the moments of inertia about X, Y, and Z axes, respectively. m_A is the mass of the quadrotor, J_P is the polar moment of inertia of the propellers around the rotation axis. The control inputs of the UAV, are defined as:

$$\begin{aligned} U_1 &= b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2), \\ U_2 &= L_A b(\omega_2^2 - \omega_4^2), \\ U_3 &= L_A b(\omega_3^2 - \omega_1^2), \\ U_4 &= d_f(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2), \\ \Omega &= -\omega_1 + \omega_2 - \omega_3 + \omega_4 \end{aligned} \tag{9}$$

The coefficients b is thrust factor, d_f is the drag factor and L_A is the distance from the center of the quadrotor to the center of the rotation axis of the propellers.

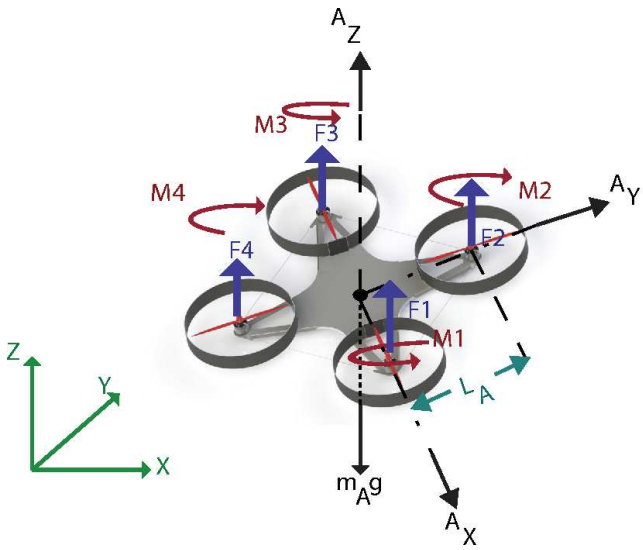

Fig. 3: A quadrotor with exerted moments and forces.

In order to control the UAV we are using a cascaded control scheme. The inner controller stabilizes the orientation angles in order to achieve a stable flight while the outer controller is responsible for the control of the position of UAV. A linearized version of the orientation angles in the equation group (8) can be seen below:

$$\ddot{\phi} = \frac{U_2}{I_{XX}}, \quad \ddot{\theta} = \frac{U_3}{I_{YY}}, \quad \ddot{\psi} = \frac{U_4}{I_{ZZ}} \tag{10}$$

The control inputs U_2, U_3 and U_4 are designed by using a PID controller. The position controller is designed by using (7). In these equations the second derivatives of X, Y and Z are the virtual controls inputs for the position controller and are defined as:

$$\begin{aligned} \mu_x &= (cos\phi sin\theta cos\psi + sin\phi sin\psi)\frac{U_1}{m_A}, \\ \mu_y &= (cos\phi sin\theta sin\psi - sin\phi cos\psi)\frac{U_1}{m_A}, \\ \mu_z &= (cos\phi cos\theta)\frac{U_1}{m_A} - g \end{aligned} \tag{11}$$

We have designed PID controllers with additional feedforward term to control the position of UAV. Assuming the yaw angle,ψ_d as constant during the flight [16] the virtual control

inputs μ_x, μ_y, μ_z can be used to compute U_1, ϕ_d, θ_d as:

$$U_1 = m_A\sqrt{\mu_x^2 + \mu_y^2 + (\mu_z + g)^2},$$
$$\phi_d = sin^{-1}\left(\frac{m_A(\mu_x sin\psi_d - \mu_y cos\psi_d)}{U_1}\right), \quad (12)$$
$$\theta_d = tan^{-1}\left(\frac{\mu_x cos\psi_d + \mu_y sin\psi_d}{\mu_z + g}\right)$$

Calculated ϕ_d and θ_d and the constant and ψ_d are the reference inputs for the orientation controller.

VI. Simulation Results

To verify our proposed method we have used both simulations and animations in MATLAB/Simulink. In simulations maximum angular speed for each UGV was set to $\frac{\pi}{3}$ rad/s while maximum linear speed was 1 m/s. UGVs are assumed to be motionless and UAV is assumed to be in hover at the beginning of simulations. UAV broadcasts its position information to the UGVs at 1 Hz and a 500 ms communication delay is assumed. We also added 100 ms communication delay between the UGVs. We have simulations for groups of three and five UGVs to collaborate with UAV in order to find and surround the T.

A. UAV and 3 UGVs

In the initial setting, the UGVs are placed at the corner of a rectangular area while T is at the center. It was observed that they approach each other and move towards T in a coordinated manner, under the guidance of UAV. The UAV waits over T while broadcasting the position of the V_L. After that, when the UGVs are close enough to T they start to spread, in order to achieve neighboring distances of d_{near}. During this spreading motion each R_i prevents collision while they are still trying to stay on the circle due to $\overrightarrow{v}_{i2V_L}$; hence perform circular motion. The 3-D trajectories for UGVs and UAV can be seen in the Figure 4. The trajectories of UGVs and UAV are depicted on the horizontal plane in Figure 5. As it can be seen from Figure 6(d) the group achieves the desired formation in the final configuration. The flight information and given reference values of the quadrotor can seen in Figure 7 and Figure 8, orientation and position respectively.

The distances between each robot from the target and the distances between each robot are tabulated in Table I

TABLE I: Final Distance Errors for Three UGVs

Dist. from	Desired Dist.	Actual Dist.	Error
R_1 to T	2	2	0
R_2 to T	2	2	0
R_3 to T	2	2	0
R_1 to R_2	3.46	3.23	6.64%
R_1 to R_3	3.46	3.72	7.51%
R_2 to R_3	3.46	3.26	5.78%

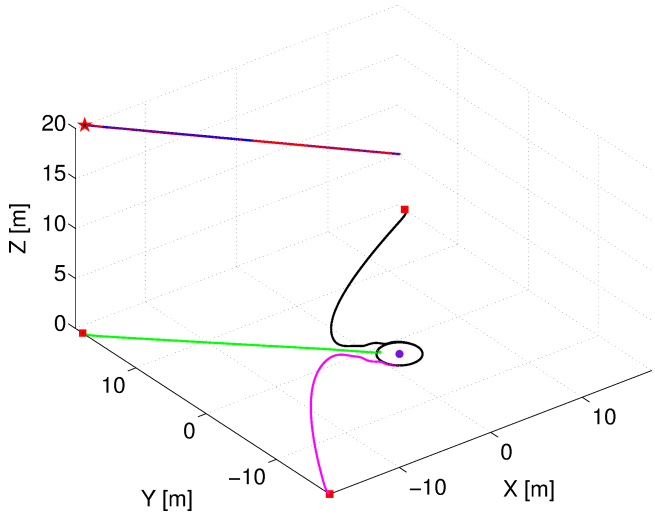

Fig. 4: Trajectories of UAV and three UGVs in 3D view.

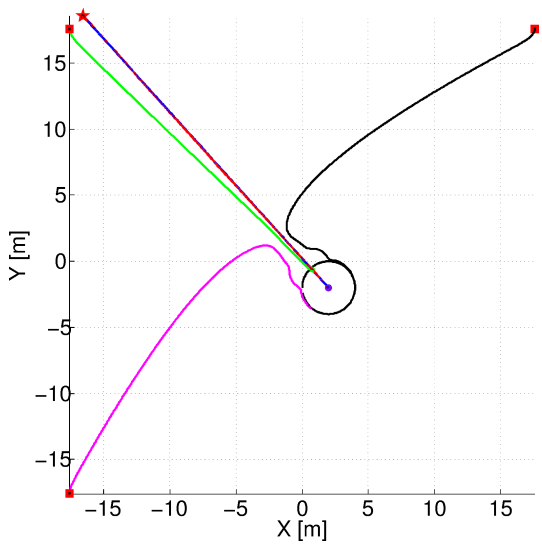

Fig. 5: Trajectories of UAV and three UGVs on X-Y plane.

B. UAV and 5 UGVs

The 3-D trajectories for UGVs and UAV can be seen in the Figure 9. The trajectories of UGVs and UAV are depicted on the horizontal plane in Figure 10. The initial setting can be seen in Figure 11(a). Since there are five UGVs, the risk of collision increases for the same value of d_{targ}; some collisions were predicted around the formation circle, but they were successfully avoided. After UAV reaches on top of the T, the UGVs received a signal that allowed them to park. Since UAV is much faster than the UGVs, UAV hovers on. The final formation is successfully achieved with a uniform distribution of UGVs as shown in Figure 11(d).

The distances between each robot and the target, and the distances between the robots are tabulated in Table II.

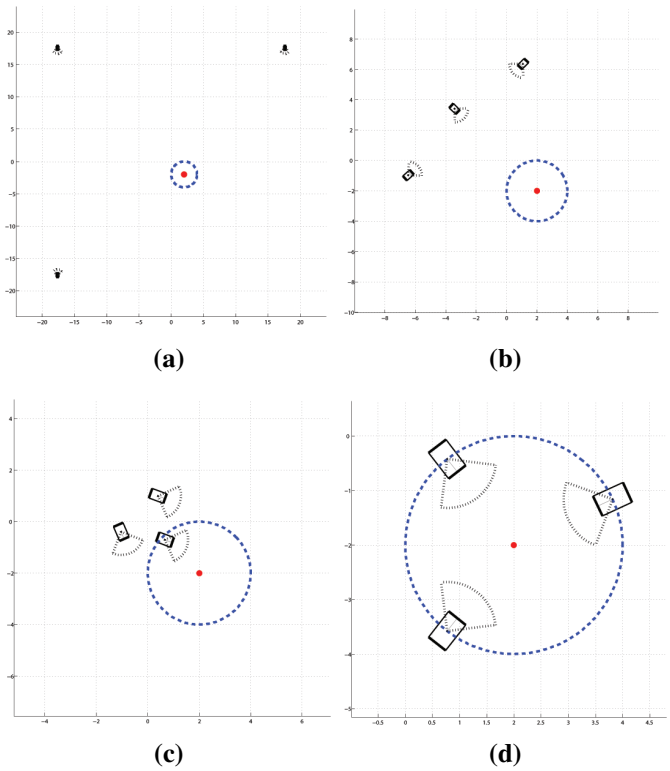

Fig. 6: Three Robots :(a) Initial configuration, (b) Zoomed version of coordinated motion, (c) Zoomed version of starting to surround T, (d) Zoomed version of desired formation.

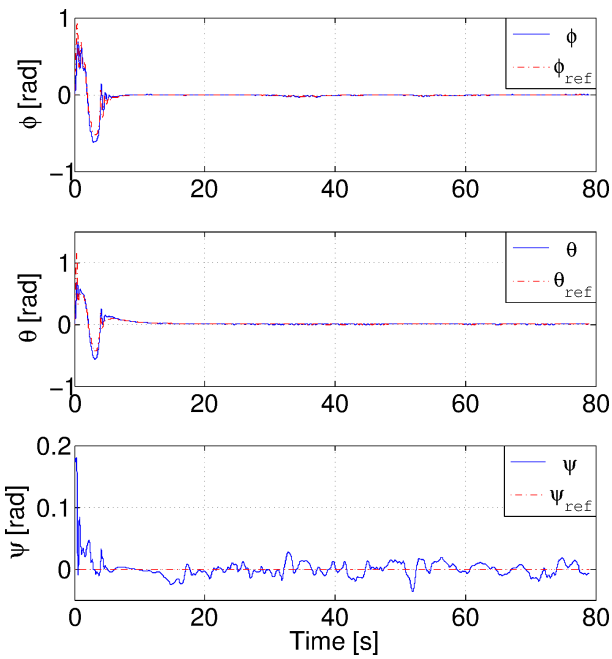

Fig. 7: ϕ, θ, ψ of UAV with calculated reference values.

VII. Conclusions

In this paper, we have used a virtual leader and a decentralized coordination algorithm in order to coordinate a group

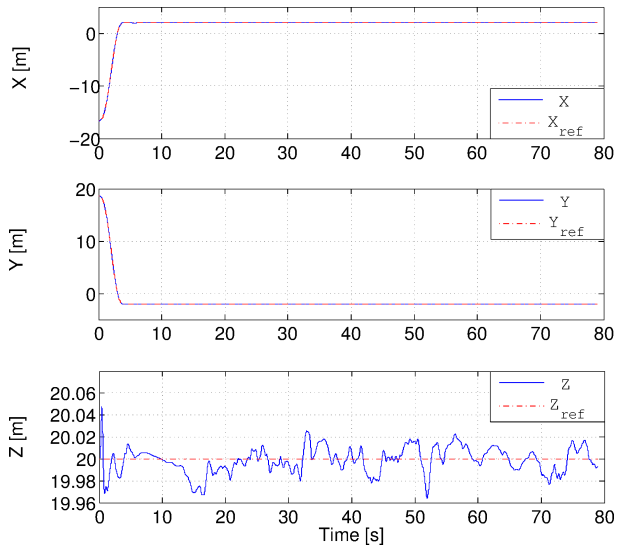

Fig. 8: X, Y, Z of UAV with reference values.

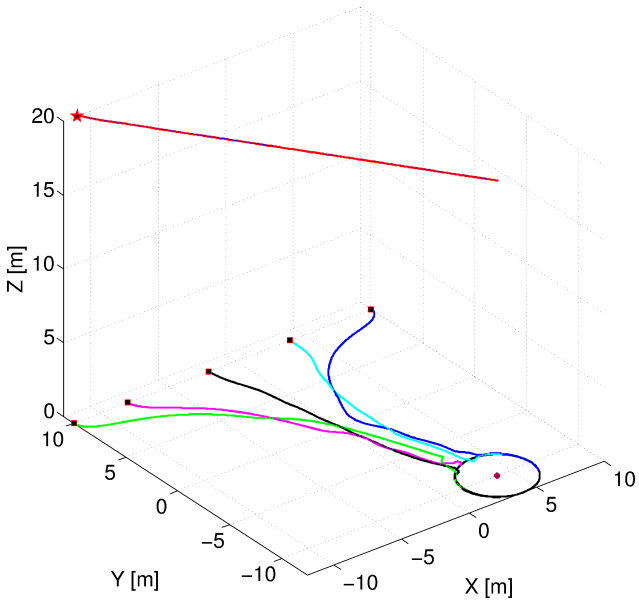

Fig. 9: Trajectories of UAV and five UGVs in 3D view.

TABLE II: Final Distance Errors for Five UGVs

Dist. from	Desired Dist.	Actual Dist.	Error
$R_1 toT$	2.5	2.5	0
$R_2 toT$	2.5	2.5	0
$R_3 toT$	2.5	2.5	0
$R_4 toT$	2.5	2.5	0
$R_5 toT$	2.5	2.5	0
$R_1 toR_2$	2.94	2.73	7.14%
$R_1 toR_3$	2.94	2.93	0.34%
$R_2 toR_3$	2.94	3.21	9.18%
$R_3 toR_4$	2.94	2.86	2.72%
$R_4 toR_5$	2.94	2.69	8.50%

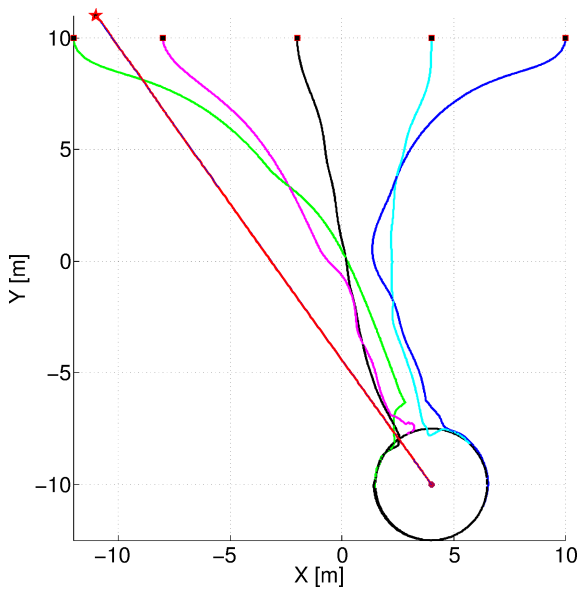

Fig. 10: Trajectories of UAV and five UGVs in 2-D view, on X-Y plane.

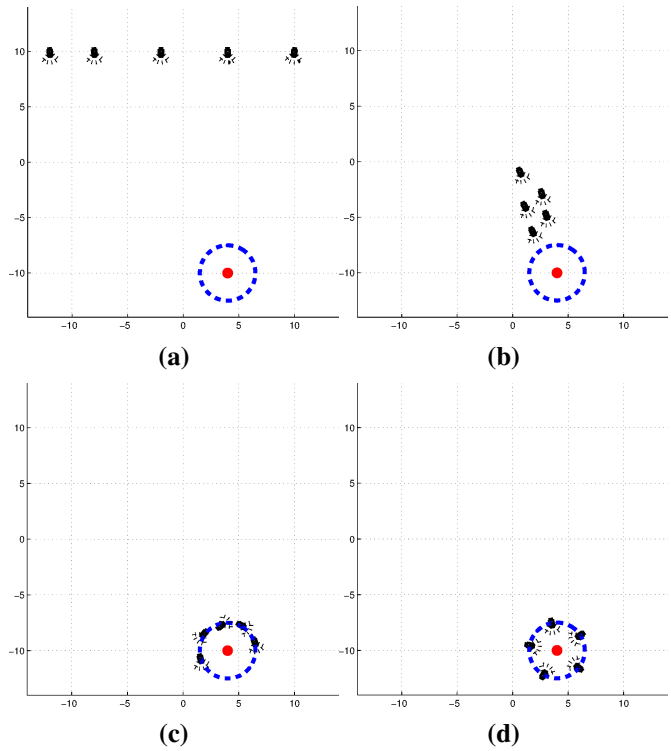

Fig. 11: 5 Robots: (a) Initial configuration, (b) Coordinated motion, (c) Circular motion around target, (d) Desired formation.

of nonholonomic mobile robots and a quadrotor. In order to satisfy nonholonomic constraints we have defined virtual reference robots that enabled us to create reference pose for each robot from the linear and angular velocities. Possible collisions are predicted and avoided by an algorithm that we have previously developed.

As it can be seen from the simulation results, we are able to guide a group of UGVs to the vicinity of T, with the help of via point trajectory provided by UAV. In our simulations we also introduced 500 ms communication delay between UGVs and UAV, and 100 ms delay between UGVs.

As future work, we are planning to work on the physical implementation of the proposed coordination scheme with nonholonomic mobile robots and a quadrotor in order to surround and manipulate an object.

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