# Formation Control of a Group of Micro Aerial Vehicles (MAVs)

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***Abstract*—Coordinated motion of Unmanned Aerial Vehicles (UAVs) has been a growing research interest in the last decade. In this paper we propose a coordination model that makes use of virtual springs and dampers to generate reference trajectories for a group of quadrotors. Virtual forces exerted on each vehicle are produced by using projected distances between the quadrotors. Several coordinated task scenarios are presented and the performance of the proposed method is verified by simulations.**

***Index Terms*—UAV, Quadrotor, Formation Control**

## I. Introduction

Quadrotor helicopters have become very popular in the last decade. Nowadays these vehicles are used for both civil and military applications which are dull, dirty and dangerous for humans. Some civil and military applications of quadrotors are traffic and millitary surveillance, search and rescue in disasters, law enforcement and border patrol [1]–[6]. On the other hand, these applications require several robots to achieve tasks in a coordinated fashion because individual vehicles can sense changes in the environment, exchange information with each other and may go into action together. This problem has received significant attention over the last years.

In the literature there are several approaches to the group coordination problem such as behavior based, leader follower, graph theory and virtual structure [7], [8]. Convenience of these approaches are highly application specific. In behavior based approach, behavioral control is decomposed into sub-problems which are behaviors or tasks. In [9], authors propose Null-Space based behavioral control which aggregate the outputs of single behavior to compose a complex behavior. Using this approach different tasks such as obstacle and collision avoidance, and group centering have been performed. In leader follower based control some of the agents are designated as leaders. These leaders can transmit location and orientation information to other agents. However, leader does not receive any information from other agents. On the other hand, some of the agents which are designed as followers can transmit and receive information [7]. In [6], authors propose leader follower formation method for quadrotors. This method based on spherical coordinates and desired position of the follower quadrotor is designed using desired seperation, angle of incidence and bearing. Another approach to the coordination problem is the graph theory. In [10] authors assume that each robot is a node of a graph. Their aim is to achieve development of information exchange strategies that has direct role on improvement of performance and stability and robustness to variation in communication topology. In [11], the framework which is developed in [10] is applied with robust controller to the formation flight of quadrotors. The last approach is virtual structure which is a formation type that behave like single rigid entity. Each agent in the swarm moves in a certain direction and orientation by keeping rigid geometric relationship among the swarm [12]. In [13], coordinated motion of non-holonomic mobile robots are designed based on virtual structure consisting of virtual springs and dampers. Authors proposed adaptable springs for achieving coordinated tasks. In a later work [14], movement of a group of robots is achieved by virtual springs and dampers which adapt to the change in the shape of the environment.

In this paper, we propose to use a virtual reference model which is composed of point masses connected with springs and dampers to generate reference trajectories for each aerial vehicle in the group. Thus, we extend some of our earlier work ( [13], [15], [16]) to the formation control of quadrotor type UAVs. In the proposed method, we utilize orthogonally projected distances on a virtual plane to define virtual spring and damping forces that quadrotors exert on each other. As a result, coordination of the aerial vehicles is achieved on a plane while altitude reference generation for each vehicle is designed independently from this projected coordination.

The rest of this paper is organized as follows: Problem formulation is given in Section II. Modeling and control of a single quadrotor is detailed in Section III. Virtual reference model to generate reference trajectories for each quadrotor in formation is developed in Section IV. Simulation results and discussions are provided in Section V. Concluding remarks and planned future works are given in Section VI.

## II. Problem Formulation

Let $Q_1, Q_2, \ldots, Q_{n-1}$ and $Q_n$, denote the swarm of $n$ quadrotors. $T$ represents the target object for the group. We assume that quadrotors know the position of the target, before they start their task and perceive the environment using their onboard sensors. Conditions that must be satisfied for a successful coordinated task scenario are as follows

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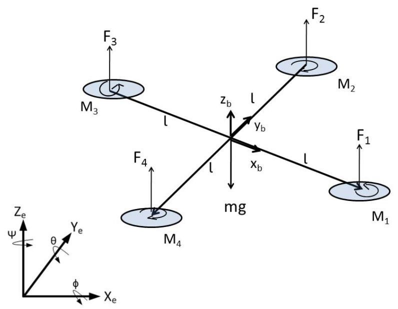


Fig. 1. Coordinate systems and forces/moments acting on a quadrotor frame

- $Q_1, Q_2, \ldots, Q_{n-1}, Q_n$ should form a circle of radius $d_{target}$ with $T$ at the center.
- The quadrotors should be uniformly distributed on the final formation.
- Each $Q_i$ should locate itself towards $T$ once it keeps a desired distance $d_{coord}$ from its closest neighbors and $d_{target}$ from $T$.

The task scenario mentioned above can be a basis for the coordinated simple tasks. For instance, for a fire extinguishment scenario, $T$ represents the fireplace where quadrotors can be used to extinguish the fire in coordination. Due to higher water load capacity, such a coordinated system would enable us to suppress fire more quickly. Another application of coordinated UAV control is search and rescue of injured people in earthquake territories. In this case, $T$ can be damaged buildings and quadrotors need to decrease $d_{coord}$ and $d_{target}$ to achieve desired formation. Before continuing to next stage of the task, $Q_i$ might check if other quadrotors have succeeded the current stage of the task.

## III. Quadrotor Modeling and Control

Before modeling quadrotor dynamics we should first introduce appropriate coordinate systems. The Earth frame is the inertial coordinate system defined by coordinate axes $x_e$, $y_e$ and $z_e$. The body frame is attached to quadrotor's center of gravity and is defined by coordinate axes $x_b$, $y_b$ and $z_b$ (Fig. 1). The rotors $1-4$ are mounted to the body on +$x_b$, +$y_b$, -$x_b$ and -$y_b$ axes, respectively.

The orientation of the body frame with respect to the world frame is expressed by the rotation matrix [17]:

$$R = \begin{bmatrix} c\psi c\theta & c\psi s\phi s\theta - c\phi s\psi & c\phi c\psi s\theta + s\phi s\psi \\ c\theta s\psi & c\phi c\psi + s\phi s\psi s\theta & c\phi s\psi s\theta - c\psi s\phi \\ -s\theta & c\theta s\phi & c\phi c\theta \end{bmatrix} \quad (1)$$

where c$\alpha$ and s$\alpha$ denotes cos($\alpha$) and sin($\alpha$), respectively. The relation between the angular velocity of the vehicle and time derivative of the Euler angles is given by the following transformation:

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & s\phi c\theta \\ 0 & -s\phi & c\phi c\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (2)$$

The gravitational force is in the -$z_e$ direction and the motor thrust forces, $F_i$, are in the $z_b$ direction. Dynamics of the quadrotor can be written as

$$\begin{aligned} F_t &= m\dot{V}_e \\ M_t &= I\dot{\omega} + \omega \times I\omega \end{aligned} \quad (3)$$

where $m$ denotes the mass and $I$ denotes the inertia matrix of the quadrotor. The total external forces acting on the quadrotor are motor thrusts $F_i$, aerodynamic forces $F_{aero}$ and gravity force $F_g$. Note that position dynamics is expressed in the world frame whereas attitude dynamics in the body fixed frame. Forces in the body frame can be transformed as follows:

$$F_t = R(F_m + F_{aero} + F_g) \quad (4)$$

where

$$F_m = \begin{bmatrix} 0 \\ 0 \\ \sum F_i \end{bmatrix} \quad , \quad F_g = \begin{bmatrix} mgs\theta \\ -mgc\theta s\phi \\ -mgc\phi c\theta \end{bmatrix} \quad (5)$$

Propeller thrusts $F_{(1,2,3,4)}$ are modeled as

$$F_i = k\omega_i^2 \quad (6)$$

where $\omega_i$ is the motor rotational speed.

Moreover, total moment acting on a quadrotor are motor moments $M_i$, aerodynamic moments $M_{aero}$ and gyroscopic moments $M_g$; i.e.

$$M_t = \sum M_i + M_{aero} + M_g \quad (7)$$

Finally, the equation of motion derived from the dynamic model is given as [17]:

$$\ddot{x} = (cos\phi sin\theta cos\psi + sin\phi sin\psi)\frac{1}{m}U_1 \quad (8)$$

$$\ddot{y} = (cos\phi sin\theta sin\psi - sin\phi cos\psi)\frac{1}{m}U_1 \quad (9)$$

$$\ddot{z} = (cos\phi cos\theta)\frac{1}{m}U_1 - g \quad (10)$$

$$\dot{p} = \frac{I_{yy} - I_{zz}}{I_{xx}}qr + \frac{J_p}{I_{xx}}q\Omega + \frac{U_2}{I_{xx}} \quad (11)$$

$$\dot{q} = \frac{I_{zz} - I_{xx}}{I_{yy}}pr + \frac{J_p}{I_{yy}}p\Omega + \frac{U_3}{I_{yy}} \quad (12)$$

$$\dot{r} = \frac{I_{xx} - I_{yy}}{I_{zz}}pq + \frac{U_4}{I_{zz}} \quad (13)$$

where $U_1$, $U_2$, $U_3$, $U_4$ are control inputs of the quadrotor and $J_p$ is the polar moment of inertia of the propellers around the rotation axis. The control inputs are given as follows

$$\begin{cases} U_1 = k(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \\ U_2 = kl(\omega_2^2 - \omega_4^2) \\ U_3 = kl(\omega_3^2 - \omega_1^2) \\ U_4 = d(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \\ \Omega = -\omega_1 + \omega_2 - \omega_3 + \omega_4 \end{cases}$$

where $k$ is the thrust coefficient and $d$ is the drag coefficient. The transformation matrix defined by Eq. (2) is the identity

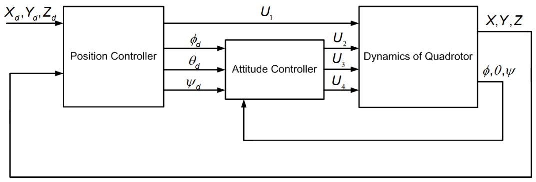


Fig. 2. Attitude and Position Control of Quadrotor

matrix at hover conditions, i.e. $\phi = \theta = 0$. It follows that around hover conditions, we have $\dot{p} \approx \ddot{\phi}$, $\dot{q} \approx \ddot{\theta}$ and $\dot{r} \approx \ddot{\psi}$. As a result, attitude dynamics can be rewritten as

$$\ddot{\phi} = \frac{I_{yy} - I_{zz}}{I_{xx}}\dot{\theta}\dot{\psi} + \frac{J_p}{I_{xx}}\dot{\theta}\Omega + \frac{U_2}{I_{xx}} \tag{14}$$

$$\ddot{\theta} = \frac{I_{zz} - I_{xx}}{I_{yy}}\dot{\phi}\dot{\psi} + \frac{J_p}{I_{yy}}\dot{\phi}\Omega + \frac{U_3}{I_{yy}} \tag{15}$$

$$\ddot{\psi} = \frac{I_{xx} - I_{yy}}{I_{zz}}\dot{\phi}\dot{\theta} + \frac{U_4}{I_{zz}} \tag{16}$$

Flight controllers are divided into two parts which are attitude and position controllers (Fig. 2). Attitude control is the heart of the quadrotor control system, because it keeps quadrotor at desired orientations in three dimensions. Attitude dynamics of the quadrotor is faster than the position dynamics, so position controller is used to generate reference angles for attitude controller.

Position controller ensures to keep the quadrotor at a desired position. Vertical motion is provided by motor thrusts, but horizontal motion is provided by changing the thrust vector direction into the desired motion direction. The motion along X and Y axes can be achieved by pitching and rolling the quadrotor, respectively. The outputs of the position controller are reference roll angle, $\phi_d$, reference pitch, $\theta_d$ and the total thrust, $U_1$. Since both vertical and horizontal motion depend on the total thrust, virtual control inputs are introduced and they are designed as PID controllers, i.e. [17], [18]

$$\mu_1 = \ddot{X}_d + K_{p_x}e_x + K_{i_x}\int_0^t e_x dt + K_{d_x}\dot{e}_x \tag{17}$$

$$\mu_2 = \ddot{Y}_d + K_{p_y}e_y + K_{i_y}\int_0^t e_y dt + K_{d_y}\dot{e}_y \tag{18}$$

$$\mu_3 = \ddot{Z}_d + K_{p_z}e_z + K_{i_z}\int_0^t e_z dt + K_{d_z}\dot{e}_z \tag{19}$$

where position tracking errors are defined as $e_q = q_d - q$ for $q$ = $X$, $Y$, $Z$. In order to compute the total thrust, reference roll and pitch angles, Eqns. (17)-(19) are utilized to solve dynamic inversion approach. The total thrust, reference roll and pitch angles can be computed as

$$U_1 = m\sqrt{\mu_x^2 + \mu_y^2 + (\mu_z + g)^2} \tag{20}$$

$$\phi_d = \left(\frac{m(\mu_x sin\psi_d - \mu_y cos\psi_d)}{U_1}\right) \tag{21}$$

$$\theta_d = \left(\frac{\mu_x cos\psi_d + \mu_y sin\psi_d}{\mu_z + g}\right) \tag{22}$$

Reference roll and pitch angles found by Eqns. (21)-(22), are inputs to the attitude control system. Furthermore, reference yaw angle can be set to any desired value.

Similarly, we design classical PID control for attitude control of the quadrotor. Since attitude dynamics are fully actuated, we do not need virtual control inputs, we can directly design control inputs $U_2$, $U_3$, $U_4$ as

$$U_2 = K_{p_\phi}e_\phi + K_{i_\phi}\int_0^t e_\phi dt + K_{d_\phi}\dot{e}_\phi \tag{23}$$

$$U_3 = K_{p_\theta}e_\theta + K_{i_\theta}\int_0^t e_\theta dt + K_{d_\theta}\dot{e}_\theta \tag{24}$$

$$U_4 = K_{p_\psi}e_\psi + K_{i_\psi}\int_0^t e_\psi dt + K_{d_\psi}\dot{e}_\psi \tag{25}$$

where position tracking errors are defined as $e_q = q_d - q$ for $q$ = $\phi$, $\theta$, $\psi$. We should again emphasize that the reference angles are computed by the position control system.

The primary goal in this work is to develop a formation control framework rather than focusing on advanced control techniques. Therefore, both position and attitude controllers are designed using simple PID controllers.

## IV. Reference Trajectory Generation

A virtual reference system is proposed where virtual masses are connected with virtual springs and dampers for generating reference trajectories for each quadrotor. Quadrotors in the group are considered as point masses denoted by $m_1$, $m_2$, $\ldots$, $m_{n-1}$, $m_n$. Coordination is defined on the basis of forces between quadrotors and the target. The reference trajectories generated by virtual model are tracked by quadrotors using onboard attitude and position controllers. At this point, virtual reference generation can be considered as a high-level controller whereas quadrotor onboard controllers (attitude and position controllers) are low-level controllers (see Fig. 3).

Coordination scheme is provided by virtual bounds which are built between each $m_i$ and its closest two neighbors. The two neighbors of $m_i$ exert forces on $m_i$ to keep the desired distance between each quadrotor. This distance can be considered as equilibrium length of the virtual springs and dampers which produce virtual forces between robots. We assume that $m_j$ is the closest neighbor and $m_k$ is the second closest neighbor of the of the $m_i$. The coordination force which is exerted on $m_i$ from $m_j$ and $m_k$ is given in [13] as

$$\begin{aligned} F_{coord} = -[&k_{coord}(d_{i2j} - d_{coord}) + \ldots \\ &c_{coord}((\dot{X}_i - \dot{X}_j) \bullet n_{i2j})]n_{i2j} - \ldots \\ &[k_{coord}(d_{i2k} - d_{coord}) + c_{coord}((\dot{X}_i - \dot{X}_k) \bullet n_{i2k})]n_{i2k} \end{aligned} \tag{26}$$

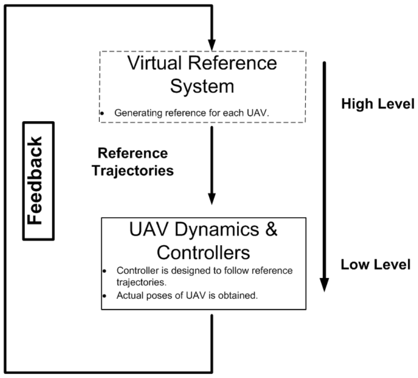


Fig. 3. Hierarchical scheme of coordinated motion

where • denotes vector dot product, $k_{coord}$ and $c_{coord}$ are the coefficients of the spring and damper. $d_{i2j}$ is the signed distance between $m_i$ and $m_j$ which is projected on to the X-Y plane, $d_{i2k}$ is the signed distance between $m_i$ and $m_k$ which is projected on to the X-Y plane. $n_{i2j}$ is the unit vector from $m_i$ to $m_j$, $\dot{X}_i = [\dot{x}_i \quad \dot{y}_i]^t$ is the velocity vector of virtual mass $m_i$. $\dot{X}_j = [\dot{x}_j \quad \dot{y}_j]^t$ is the velocity vector of virtual mass $m_j$, $n_{i2k}$ is the unit vector from $m_i$ to $m_k$. $\dot{X}_k = [\dot{x}_k \quad \dot{y}_k]^t$ is the velocity vector of virtual mass $m_k$. Moreover, $d_{coord}$ is the coordination distance to be preserved among the masses.

Furthermore, target force that is exerted on each mass is modeled as the sum of spring and damper forces. The target force is defined as

$$F_{targ} = [k_{targ}(d_{i2T} - d_{targ}) + c_{targ}(\dot{X}_i \bullet n_{i2T})]n_{i2T} \quad (27)$$

where • denotes vector dot product, $k_{targ}$ and $c_{targ}$ are the coefficients of the spring and damper. $d_{i2T}$ is the signed distance between $m_i$ and target, $\dot{X}_i = [\dot{x}_i \quad \dot{y}_i]^t$ is the velocity vector of virtual mass $m_i$ and $n_{i2T}$ is the unit vector from $m_i$ to target. $d_{targ}$ is the distance to be preserved among the $m_i$ and target.

The total force exerted on $m_i$ is given as

$$m_i \begin{bmatrix} \ddot{x}_i \\ \ddot{y}_i \end{bmatrix} = F_{coord} + F_{targ} \quad (28)$$

The reference position for $Q_i$ can be computed by double integrating the desired acceleration in Eq. (28). On the other hand, we may need to change the parameters which are given above to perform the coordinated tasks. In our scenario we divide coordinated motion into two stages:

i) Getting closer to $T$ from the initial point.
ii) Forming circular distribution around $T$ with radius $d_{target}$.

In the first stage, coordinated motion of quadrotors is the most important issue. Until the end of first stage, $F_{coord}$ is dominant for moving robots together. However, target force, $F_{target}$, is also important to move the robots toward $T$. When any robot in the group, $Q_i$, is close to $T$ at a certain distance, $d_{break}$, the importance of target force increases. In other words, $k_{coord}$ is decreased to $k_{near}$, which is smaller than $k_{targ}$ for achieving the final formation. Moreover, the equilibrium length of the spring between the robots is changed from $d_{coord}$ to $d_{near}$. It follows from *Law of Cosines* that, $d_{near}$ is given as (29) for uniform distribution of n robot around a circle with radius $d_{target}$ [13]:

$$d_{near} = d_{target}\sqrt{2(1 - cos(2\pi/n))}. \quad (29)$$

Spring coefficient, $k_{coord}$, is changed as a continuous function of $d_{i2T}$ as in [13]:

$$k_{coord} = k_{near} + \frac{k_{far} - k_{near}}{1 + exp(\alpha(d_{break} - d_i 2T + \gamma))} \quad (30)$$

where $\alpha > 0$ and $\gamma > 0$ are constants, $0 \leq k_{coord} \leq 1$, $d_{i2T}$ is the signed distance between $m_i$ and the target, $k_{far}$ and $k_{near}$ are spring coefficients that are used in stage 1 and 2.

## V. Simulation Results

The proposed formation scheme for a group of quadrotors was simulated for a coordinated task defined by a circular formation around the target.

### A. Coordinated motion of three quadrotors

In the first scenario, quadrotors were placed at different corners of a room on the ground while $T$ was placed at center of the room. The trajectories of quadrotors are shown in Figs. 4 and 5. It can be observed that they approach each other and move towards $T$ in a coordinated manner. When they are close to $T$, they keep a mutual distance of $d_{near}$, then they spread around the circle. Finally, the group reach desired formation at 5 meters above the target indicated as star in figures. Moreover, attitude angles and positions of quadrotors are shown in Fig. 6. In light of these graphs, it is clear that quadrotors track the references with very small tracking errors. More precisely, PID controllers provide attitude and position tracking RMS errors values less than 0.01 rad and 0.02 m, respectively.

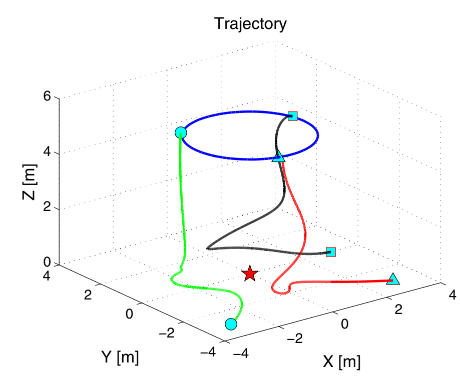


Fig. 4. Trajectories of UAV in 3-D view

### B. Coordinated motion of five quadrotors

In the second scenario, five quadrotors are placed at different corners of a room while $T$ is placed at center of the room. The trajectories of quadrotor are shown in Figs. 7 and 8. As seen from these figures, five quadrotors move in a coordinated

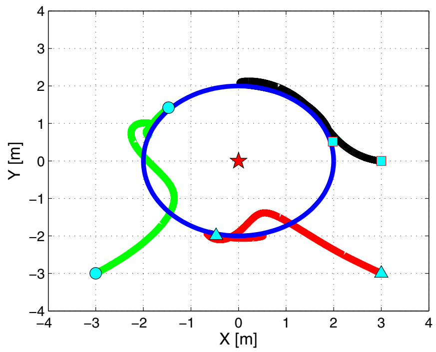


Fig. 5. Trajectories of UAV on X-Y plane

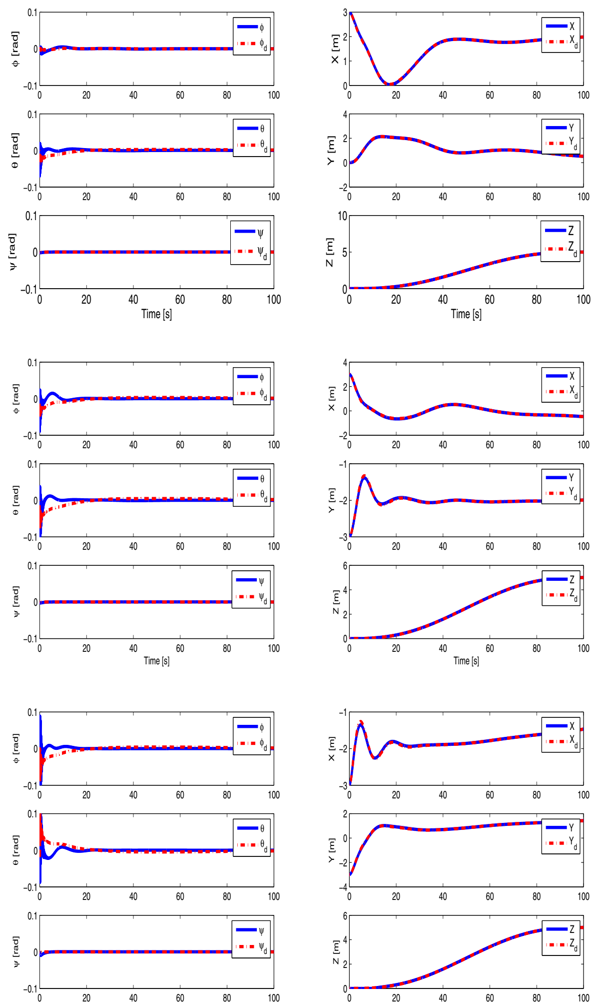


Fig. 6. Each row in the figure depicts attitude angles and positions of quadrotors.

manner until they come close to $T$ where they start to separate to form en evenly spaced distribution around the circle at 5 m altitude. Attitude angles and positions of each quadrotor are shown in Fig. 9. It is clear from these figures that quadrotors' low level PID controllers are quite successful to track the desired trajectories. Moreover, these controllers are able to keep attitude and position tracking RMS error values around 0.012 rad and 0.03 m, respectively.

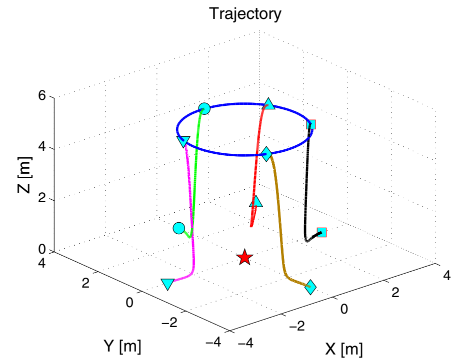


Fig. 7. Trajectories of UAVs in 3-D view

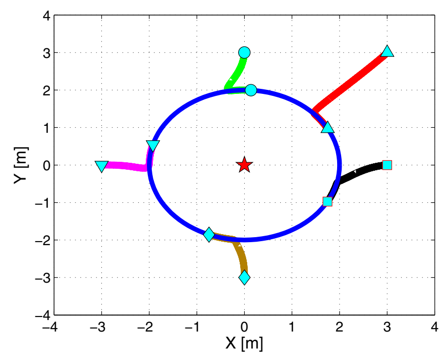


Fig. 8. Trajectories of UAVs on X-Y plane

## VI. Conclusion

We have presented a decentralized formation control approach for a group of UAVs by introducing a virtual reference model that consists of virtual springs and dampers between quadrotors. Coordination and target forces are defined in terms of spring and damping forces where springs have adaptable parameters.

Simulation results provided for three and five quadrotors are quite promising. Quadrotors performed the coordinated tasks without any problem. The number of quadrotors can be increased without any significant difficulty since the proposed method is highly scalable. However, performance of the proposed formation control scheme was demonstrated with 3 and 5 quadrotors just to show the potential of our method.

As a future work, we plan working on the physical implementation of the proposed coordination scheme. Moreover, we plan designing quadrotor individual position and attitude controllers using advanced control techniques that are robust to external disturbances such as wind.

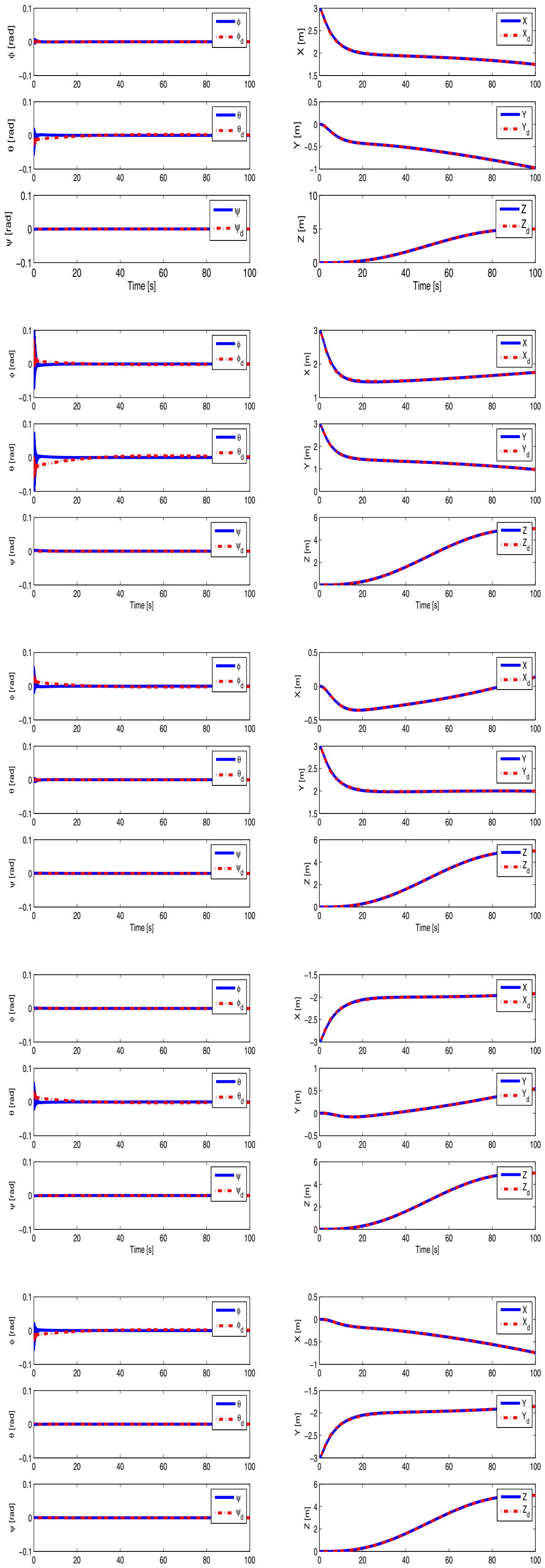


Fig. 9. Each row depicts attitude angles and positions of one quadrotor in the formation

## REFERENCES

[1] S. Gupte, P. Mohandas, and J. Conrad, "A survey of quadrotor unmanned aerial vehicles," in *Southeastcon, 2012 Proceedings of IEEE*, 2012, pp. 1–6.

[2] E. Altug, J. Ostrowski, and R. Mahony, "Control of a quadrotor helicopter using visual feedback," in *Robotics and Automation, 2002. Proceedings. ICRA '02. IEEE International Conference on*, vol. 1, 2002, pp. 72–77 vol.1.

[3] T. Tomic, K. Schmid, P. Lutz, A. Domel, M. Kassecker, E. Mair, I. Grixa, F. Ruess, M. Suppa, and D. Burschka, "Toward a fully autonomous uav: Research platform for indoor and outdoor urban search and rescue," *Robotics Automation Magazine, IEEE*, vol. 19, no. 3, pp. 46–56, 2012.

[4] V. Cichella, I. Kaminer, E. Xargay, V. Dobrokhodov, N. Hovakimyan, A. Aguiar, and A. Pascoal, "A lyapunov-based approach for time-coordinated 3d path-following of multiple quadrotors," in *Decision and Control (CDC), 2012 IEEE 51st Annual Conference on*, 2012, pp. 1776–1781.

[5] Y. Wang, Q. Wu, and Y. Wang, "Containment control for multiple quadrotors with stationary leaders under directed graphs," in *Decision and Control (CDC), 2012 IEEE 51st Annual Conference on*, 2012, pp. 2781–2786.

[6] T. Dierks and S. Jagannathan, "Neural network control of quadrotor uav formations," in *American Control Conference, 2009. ACC '09.*, 2009, pp. 2990–2996.

[7] A. Davidi, N. Berman, and S. Arogeti, "Formation flight using multiple integral backstepping controllers," in *Cybernetics and Intelligent Systems (CIS), 2011 IEEE 5th International Conference on*, 2011, pp. 317–322.

[8] J. A. Guerrero and R. Lozano, "Flight formation of multiple mini rotorcraft based on nested saturations," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, 2010, pp. 634–639.

[9] F. Arrichiello, S. Chiaverini, and T. Fossen, "Formation control of marine surface vessels using the null-space-based behavioral control," in *Group Coordination and Cooperative Control*, ser. Lecture Notes in Control and Information Science, K. Pettersen, J. Gravdahl, and H. Nijmeijer, Eds. Springer Berlin Heidelberg, 2006, vol. 336, pp. 1–19.

[10] J. Fax and R. Murray, "Information flow and cooperative control of vehicle formations," *Automatic Control, IEEE Transactions on*, vol. 49, no. 9, pp. 1465–1476, 2004.

[11] U. Pilz, A. Popov, and H. Werner, "Robust controller design for formation flight of quad-rotor helicopters," in *Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009. Proceedings of the 48th IEEE Conference on*, 2009, pp. 8322–8327.

[12] W. Ren and R. Beard, "A decentralized scheme for spacecraft formation flying via the virtual structure approach," in *American Control Conference, 2003. Proceedings of the 2003*, vol. 2, 2003, pp. 1746–1751.

[13] N. Gulec and M. Unel, "A novel coordination scheme applied to nonholonomic mobile robots," in *Decision and Control, 2005 and 2005 European Control Conference. CDC-ECC '05. 44th IEEE Conference on*, 2005, pp. 5089–5094.

[14] P. Urcola, L. Riazuelo, M. Lazaro, and L. Montano, "Cooperative navigation using environment compliant robot formations," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, 2008, pp. 2789–2794.

[15] N. Gulec and M. Unel, "A novel algorithm for the coordination of multiple mobile robots," in *Computer and Information Sciences - ISCIS 2005*, ser. Lecture Notes in Computer Science, P. Yolum, T. Gungor, F. Gurgen, and C. Ozturan, Eds. Springer Berlin Heidelberg, 2005, vol. 3733, pp. 422–431.

[16] Y. H. Esin and M. Unel, "Formation control of nonholonomic mobile robots using implicit polynomials and elliptic fourier descriptors," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 18, no. 5, pp. 765–780, 2010.

[17] E. Cetinsoy, C. Dikyar, S.and Hancer, K. Oner, E. Sirimoglu, M. Unel, and A. M. F., "Design and construction of a novel quad tilt-wing uav," *Mechatronics*, vol. 22, no. 6, pp. 723–745, Sept. 2012.

[18] F. Nonami, K.and Kendoul, S. Suzuki, W. Wang, and D. Nakazawa, *Autonomous Flying Robots : Unmanned Aerial Vehicles and Micro Aerial Vehicles*. Springer Verlag, Japan, 2010.