Cooperation between Aerial and Ground vehicle groups for Reconnaissance missions

H. G. Tanner and D. K. Christodoulakis

***Abstract*— In this paper we focus on the interaction between a group of ground vehicles and a group of aerial vehicles. The ground agents interact through time-invariant rules, synchronize their velocities using a TDMA-based communication protocol, and maintain cohesion and separation by means of interagent potential forces. Ground vehicles estimate their formation's centroid using delayed information and transmit their estimates to the aerial group which circles the ground formation's centroid while avoiding midair collisions. Stability of the ground group motion is established in a Lyapunov framework, exploiting the properties of the non-negative matrices involved. A Lyapunov analysis is also used to ensure that UAVs track the ground group's centroid.**

I. Introduction

Imagine a scenario where a group of Unmanned Ground Vehicles (UGVs) needs to perform reconnaissance along a corridor within hostile territory. To protect the group from ambush, another group of Unmanned Aerial Vehicles (UAVs), surveils the surrounding area and provides early warning. This scenario could be realized if the UGVs move in unison, interagent distances among communicating UGVs is regulated, and the UAV group circles the UGV group centroid while avoiding collisions.

Several groups have developed working UGV prototypes [1]–[6] among them, the Intelligent Systems and Robotics Center of the Sandia National Laboratories [7]. Cohesion, separation and velocity alignment among the UGVs needs to be achieved with exchange of local information only. When communication delays affect nearest neighbor interaction (c.f. [8]–[11]) performance is expected to suffer [12], [13]. In our previous work [14], however, we showed that for a particular model of discrete time nearest-neighbor interaction with delayed information, synchronization of velocities to a common vector is still possible. Parallel efforts such as [15], [16], and [17] were in agreement with our results. Cohesion and separation control action is generally analyzed within a Lyapunov framework [9]. In these cases information is assumed to be exchanged and processed instantaneously.

Gyroscopic forces have been used for collision avoidance between UAVs [18], [19]. In [18] agents react only to the nearest potential obstacle in front of them. In [19] there is formal proof that collision avoidance can be achieved when only two agents are involved. Most of the work in UAV coordination focuses on the control objectives of single UAV missions or cooperation within formations of multiple UAVs. Visual servoing has been proposed in [20], [21] involving remote guidance and collision avoidance respectively. Obstacle avoidance techniques for agents equipped with infrared and visual sensors have been proposed in [22]. Laser range finders are used in [23] for static and dynamic obstacle avoidance aided by geometric algorithms, while object recognition is suggested in [24].

Intelligence Surveillance and Reconnaissance (ISR) missions, require cooperation between teams of mobile agents of different modalities, linked through a common objective. Reported work, however, on the interaction of heterogeneous teams of multiple agents typically addresses the problem of cooperation between one UGV and one UAV [1], [20]. This paper extends our earlier work of [14], enabling the UGV group to exhibit flocking-like behavior by including potential forces. It is shown in a Lyapunov framework that, these forces do not affect the convergence of velocity vectors, while offering regulation of distances between interconnected agents. We connect the UAV and UGV groups while preserving the local nature of data exchange. We develop an algorithm where each UGVs estimates the ground group's centroid using only local and delayed information. The UGVs broadcast to the UAVs the same local information they transmit to their group neighbors. The UAVs follow circular paths over the UGV formation's centroid.

II. Decentralized UGV control

The ground formation is thought of as a network of mobile agents represented as double integrators, exchange information in turns, and complete their transmission within one time step. This sequential transmission forces them to use outdated information about the fixed subset of their group mates they communicate with. The index set of the vehicles that a vehicle i communicates with is denoted $\mathcal{N}_i$.

A. Velocity alignment

The discrete time dynamics of UGVs are

$$r_i(k+1) = r_i(k) + u_i(k)T, \tag{1}$$

$$u_i(k+1) = u_i(k) + \alpha_i(k)T. \tag{2}$$

In [25] agent i updates its velocity u_i by means of instant communication as follows:

$$\alpha_i(k) = \left\{ \frac{1}{1+|\mathcal{N}_i|} \left(u_i(k) + \sum_{j\in\mathcal{N}_i} u_j(k) \right) \right\} \frac{1}{T},$$

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where T is the sampling period and $i = 1, \dots, N$ is the index of the particular UGV. We show that the choice of T has no effect on stability. However, the larger the sampling period, the larger the associated delay, and thus the slower convergence is. In state-space form, the UGV group updates its velocity as

$$u(k+1) = \{[(I+D)^{-1}(A+I)] \otimes I\}u(k), \tag{3}$$

where the Kronecker product describes compactly the dynamics along every component of r, $u(k)$ is the stack vector of $u_i(k)$ for $i = 1, \dots, N$ and A, D are the adjacency and valency matrices of $\mathcal{G}$, respectively, [26]. To keep track of ordered transmissions we use a binary matrix S, with rows indexed by the agents and columns indexed by time steps: $s_{ij} = 1$ indicates that agent i transmits at cycle step j. As time evolves, the columns of S shift from left to right, with the rightmost column being recycled to the left. At two consequtive time steps, we can have for example

$$S(k) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad S(k+1) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}.$$

To describe the dynamics when delays are introduced in the update rule, we augment the velocity vector with the delayed information:

$$U(k+1) \triangleq \underbrace{\begin{bmatrix} \{[(D+I)^{-1}(I+A)]\otimes I\}[S_i \otimes S_i^T] \\ \begin{matrix} I & 0 & \dots & \dots & 0 & 0 \\ 0 & I & \dots & \dots & 0 & 0 \\ 0 & 0 & I & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 & 0 \\ 0 & 0 & 0 & \dots & I & 0 \end{matrix} \end{bmatrix}}_{H(k)} U(k), \tag{4}$$

where $U(k)$ is the stack vector of $u(k)$ through $u(k-N+1)$ and S_i is the ith column of S. We order the transmissions according to the indexing of the agents. After the Nth agent terminates its broadcast at the Nth time-step, the first *communication cycle* will be complete. The state transition matrix between communication cycles is:

$$M \triangleq H(N)H(N-1)\cdots H(1). \tag{5}$$

The matrix M is not ergodic due to existence of zero columns. In [14] we showed the zero columns in M represent delayed states that are not necessary to update the system's dynamics. We remove these columns and corresponding rows from M, obtaining reduced state transition matrix $\bar{M}$. We give formal proof in [14] that: $\lim_{k\to\infty} \bar{M}^k = \mathbf{1}c^T$, which establishes the convergence of the reduced state vector to $\xi\mathbf{1}$, for some $\xi \in \mathbb{R}$. If current and (bounded) delayed states of all agents converge to a common value, all current states will also converge.

B. Group cohesion and collision avoidance

Assume that agents communicate their position along with their velocity. We build upon the velocity synchronization controller by adding potential field forces, f. The velocity dynamics of the model are represented by:

$$U(k+1) = H(k)U(k) + \begin{bmatrix} f(k) \\ 0_{n(N-1)\times 1} \end{bmatrix}. \tag{6}$$

We study differences $\Delta f(x) = f(x)\Big|_k - f(x)\Big|_{k-1}$ between consecutive time steps. Using Taylor expansion, we express the total difference as

$$\Delta f(x) \;=\; \frac{\partial f}{\partial x}\delta x + \frac{\partial^2 f}{\partial x^2}\delta x^2 + \cdots + \frac{\partial^n f}{\partial x^n}\delta x^n \dots,$$

where we set $\delta g(x(k)) = \frac{\partial g(x)}{\partial x}\Big|_{k-1}\delta x(k)$.

Our interaction force is the gradient of a quadratic potential function of the distance $\|r_{ij}\|_2$ (Figure 1), between agents i and j, calculated based on the *delayed* information the agents have about each other. The stack vector of (delayed) relative positions and velocities used, therefore, is calculated as $r_{ij} \triangleq (B \otimes I)Sr$, $u_{ij} \triangleq (B \otimes I)SU$, where B is the incidence matrix of $\mathcal{G}$. We define: $V_{ij} \triangleq a(\|r_{ij}\|_2 - r_d)^2, \quad a > 0$, where r_d is the desired distance

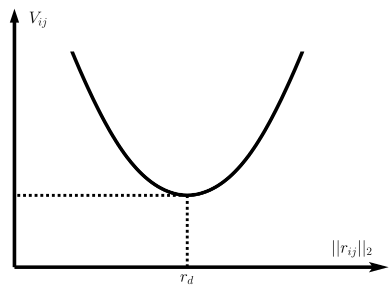

Fig. 1: The inter-agent potential function. The gradient of the function is finite at zero, and even when collision is imminent, only finite interaction forces are exerted.

which any agent should maintain from its neighbors. The difference $\Delta V_{ij}(k)$ between two time steps is:

$$\begin{aligned}\Delta V_{ij}(k) =& 2a\Big[\|r_{ij}(k-1)\| - r_d + \hat{r}_{ij}(k-1)\delta r_{ij}(k)\Big] \\ & \cdot \hat{r}_{ij}(k-1)^T \delta r_{ij}(k),\end{aligned}$$

where $\hat{r}_{ij}$ is the unit vector in the direction of r_{ij}. Our assumption that agents do not use their own state before they broadcast it to their neighbors, ensures that $\Delta V_{ij} = -\Delta V_{ji}$. Let us set

$$f_{ij} \triangleq 2a\Big[\|r_{ij}\| - r_d + \hat{r}_{ij}^T \Delta u_{ij} T\Big]_{k-1} \hat{r}_{ij}(k-1)^T.$$

We define the swarm's total potential as the sum of all interconnected agent potentials: $\sum_{i\sim j} \Delta V_{ij}(k) = \frac{1}{2}\sum_{i=1}^n \sum_{i\sim j} f_{ij}^T \; \delta r_{ij}(k)$, vector $\mathrm{sign}(U) \triangleq \big(\mathrm{sign}(U_1) \;\; \cdots \;\; \mathrm{sign}(U_n)\big)^T$, and the input force f as ($\circ$ denotes Hadamard multiplication)

$$f(k-1) \triangleq -\mathrm{sign}(U) \circ T \sum_{i=1}^{n} \sum_{i\sim j} f_{ij} \circ u_{ij}, \tag{7}$$

where all quantities in the right hand side are calculated at step $k-1$. By (7) and because it is $u_{ij}(k-1)T = \delta r_{ij}(k)$, we have $\mathrm{sign}(U(k-1))^T f(k-1) = -\sum_{i=1}^n \sum_{i\sim j} \left(\frac{\partial V_{ij}}{\partial \|r_{ij}\|}\hat{r}_{ij}\right)\Big|_{k-1} \delta r_{ij}(k)$.

Theorem II.1 *The discrete time system* (6) (1)*, where f is defined in* (7)*, converges asymptotically to the set where $U(k-1) = \mathbf{1}c$ and $f = \mathbf{1}c'$ with $c, c' \in \mathbb{R}$.*

Proof: Consider the Lyapunov function candidate:

$$W(k) = \sum_{i=1}^{n} \sum_{i \sim j} V_{ij}(k) + \|U(k)\|_1.$$

we use the fact that $\Delta||U(k)||_1 = \frac{\partial ||U||_1}{\partial U}\Big|_{k-1} \delta U(k)$, then the total difference in the velocity term will be

$$\begin{aligned}\Delta||U(k)||_1 = \operatorname{sign}\big(U(k-1)\big)^T H(k-1)U(k-1) - \\ - ||U(k-1)||_1 + \operatorname{sign}\big(U(k-1)\big)^T f(k-1).\end{aligned}$$

The total difference in the Lyapunov function candidate can be written:

$$\begin{aligned}&\Delta W(k) = 2\sum_{i \sim j} \Delta V_{ij}(k) + \Delta\|U(k)\|_1 = \\ &= \operatorname{sign}\big(U(k-1)\big)^T H(k-1)U(k-1) - ||U(k-1)||_1,\end{aligned}$$

and it is *nonpositive* since $H(k-1)U(k-1)$ has been shown in [14] to be a contraction:

$$\begin{aligned}&0 > ||H(k-1)U(k-1)||_1 - ||U(k-1)||_1 \geq \\ &\geq \operatorname{sign}\big(U(k-1)\big)H(k-1)U(k-1) - ||U(k-1)||_1,\end{aligned}$$

because $||H(k-1)U(k-1)||_1 = \Big(\sum_{i=1}^{n} |h_{1i}u_i| +, \cdots + \sum_{i=1}^{n} |h_{ni}u_i|\Big)^T \geq \operatorname{sign}\big(U(k-1)\big)H(k-1)U(k-1)$. By the discrete version of LaSalle's invariance principle, the dynamics of (r_{ij}, u_{ij}) induced by (6), and with initial conditions in any compact set defined by the level sets of W (which bound all velocities and inter-agent distances), converges to the set of fixed points of $W(k)$. Examining the difference in the Lyapunov function, this is the fixed point of $H(k-1)U(k-1)$, and therefore,

$$U(k-1) = \mathbf{1}w, \qquad (6) \Rightarrow f = \mathbf{1}w'.$$

■

Note that convergence of the elements of f to a common value does not imply that relative distances converge to r_d.

C. UGV group centroid estimation

For the UAV team to cooperate with the ground formation it has to have knowledge of the formation's general whereabouts. We will express the overall location of the UGV group using its centroid position. The centroid is calculated using information from all UGVs. Since, however, no global information processing is desirable, we design a cooperative estimation scheme that allows the UGV to obtain the group's centroid coordinates using local information.

The position of the centroid as estimated by agent i is c_i and is updated in discrete time as follows:

$$c_i(k+1) = \frac{c_i(k) + \sum_{j \in \mathcal{N}_i} c_j(k)}{1 + |\mathcal{N}_i|},$$

UGV agent i broadcasts its estimate c_i together with its individual state information (velocity, position).

The position of the group centroid is estimated in a similar decentralized way as ground agent i calculates the location and velocity of its current neighbors. Centroid estimates by all UGVs based on delayed information form the centroid position estimation vector C which is updated in discrete time by $C(k+1) = H(k)C(k) + U(k)T$, where $H(k)$ is stochastic: $H(k)\mathbf{1} = \mathbf{1}$. At steady state, we will have $U(k) = \mathbf{1}w$, $w \in \mathbb{R}$, so the dynamics of C is

$$C(k+1) = H(k)C(k) + \mathbf{1}wT, \tag{8}$$

at the next time step, $C(k+2) = H(k+1)H(k)C(k) + 2Tw\mathbf{1}$, and by induction:

$$C(N) = H(N-1)\dots H(k)C(k) + (N-k+1)\mathbf{1}wT.$$

It is shown in section II-A that $H(N-1)\dots H(k)C(k) = \mathbf{1}\lambda$ and since $\mathbf{1}wT \in \operatorname{span}\{\mathbf{1}\}$, at steady state $C(N) \in \operatorname{span}\{\mathbf{1}\}$. In this case centroid estimates converge to the same vector, which is close to the actual centroid, but lags behind due to the use of delayed position information.

III. Decentralized UAV control

The assumptions we make about the UAV team are as follows: the UAVs are considered point-mass vehicles in the vicinity of the UGV group, and fly at constant, common altitude; the UAVs can sense the location of each other within a predefined radius R_c. We assume a common fixed magnitude of linear velocity V for every UAV in order to prevent stalling and at the same time maintain lift.

Every UAV circles over its estimate of centroid of the UGV formation at a common altitude with desired radius d_i and common fixed magnitude of linear velocity V. We use unicycle dynamics to represent the UAVs:

$$\dot{x}_i = \mathrm{V}\cos\theta_i, \qquad \dot{y}_i = \mathrm{V}\sin\theta_i, \qquad \dot{\theta}_i = \omega_i. \tag{9}$$

where $i = 1, \dots, M$ is the index of the particular UAV. At every time step the UAVs determine the center of their circular flight by averaging centroid information received by the UGVs. The control input is the angular velocity ω.

To ensure coverage of the UGV team from the air, every UAV follows circular orbits of desired radius d_i. UAVs at or closer than, the predefined distance R_c must perform collision avoidance maneuvers, until distance between them is greater than R_c. All UAVs involved in a near collision event perform collision avoidance maneuvers using saturated maximum angular velocity ω_{max}. Each aerial vehicle averages the centroid estimates it receives from broadcasting UGVs. To complete the mission objectives UAVs engage in circular orbit around the centroid estimate.

In discrete-time Equations (9) read:

$$x_i(k+1) = x_i(k) + \frac{\mathrm{V}\Big\{\sin\Big(\theta_i(k)+\omega_i(k)T\Big)-\sin\theta_i(k)\Big\}}{\omega_i(k)}$$
$$y_i(k+1) = y_i(k) + \frac{\mathrm{V}\Big\{\cos\theta_i(k)-\cos\Big(\theta_i(k)+\omega_i(k)T\Big)\Big\}}{\omega_i(k)}$$
$$\theta_i(k+1) = \theta_i(k) + \omega_i(k)T$$

where ω_i is the bounded control input for UAV i.

A. Tracking the UGV group centroid

We define

$$p_i = [x_i \; y_i]^T, \quad c_i = [c_{xi} \; c_{yi}]^T,$$
$$\delta_i = p_i - c_i, \quad \eta_i = [-\sin\theta_i \;\; \cos\theta_i]^T,$$
$$r_i = \frac{1}{2}\|\delta_i\|^2 = \frac{1}{2}\Big\{(x_i - c_{xi})^2 + (y_i - c_{yi})^2\Big\},$$

where p_i is the planar position vector of UAV i from the origin, c_i is the position vector from the origin of the centroid as estimated by UAV i, δ_i is the current planar distance between UAV i and the centroid estimation and η_i is a unit vector normal to the velocity of UAV i.

The first and second derivatives of r_i are:

$$\dot{r}_i = (c_i - p_i)^T(\dot{c}_i - \dot{p}_i)$$
$$\ddot{r}_i = \mathrm{V}^2 + \mathrm{V}\delta_i^T\eta_i\theta_i - 2\dot{p}_i^T\dot{c}_i + \dot{c}_i^2 - 2\delta_i^T\ddot{c}_i \qquad (10)$$

In equation (10) the first two terms do not depend on the derivatives of c_i, while the last three terms do. Every UAV converges to circular orbit around the centroid estimate available c_i with desired radius of d_i using the continuous-time control law, (obtained by using feedback linearization):

$$\omega_i = \frac{1}{\mathrm{V}\delta_i^T\eta_i}\Big\{-\mathrm{V}^2 - q^2(r_i - \frac{1}{2}d_i^2) - 2q\dot{r}_i\Big\}, \qquad (11)$$

where $q > 0$ is a control gain. As a result, the dynamics of the distance between the UAV and the estimated centroid is described by

$$\ddot{r}_i + 2q\dot{r}_i + q^2(r_i - \frac{1}{2}d_i^2) = g_i(r_i, \dot{c}_i, \ddot{c}_i), \qquad (12)$$

where g_i is comprised of all the terms that depend on the derivatives of c_i, and for analysis purposes are treated as a disturbance $g_i = -2\dot{p}_i^T\dot{c}_i + \dot{c}_i^2 - 2\delta_i^T\ddot{c}_i$. Equation (12) describes a critically damped, second order, linear system perturbed by g_i.

Since the UAVs can obtain velocity information from the UGVs, they can use the estimate of the velocity of the centroid $\hat{\dot{c}}_i$, and modify (11) as follows:

$$\omega_i = \frac{1}{\mathrm{V}\delta_i^T\eta_i}\Big\{-\mathrm{V}^2 - q^2(r_i - \frac{1}{2}d_i^2) - 2q\dot{r}_i - \hat{\beta}_i\Big\}, \qquad (13)$$

where $\hat{\beta}_i \triangleq -2\dot{p}_i^T\hat{\dot{c}}_i + \hat{\dot{c}}_i^2$ is the estimation of β_i. We define $\beta_i \triangleq -2\dot{p}_i^T\dot{c}_i + \dot{c}_i^2$, $\gamma_i \triangleq -2\delta_i^T\ddot{c}_i$. In discrete time, equation (13) reads

$$\Omega_i(k+1) = \frac{-\mathrm{V}^2 - q^2\Big(r_i(k) - \frac{1}{2}d_i(k)^2\Big) - 2q\frac{r_i(k)-r_i(k-1)}{T} - \hat{\beta}_i(k)}{\mathrm{V}\delta_i(k)^T\eta_i(k)}, \qquad (14)$$

where $\hat{\beta}_i(k) = -\frac{2(p_i(k)-p_i(k-1))^T(\hat{c}_i(k)-\hat{c}_i(k-1))(\hat{c}_i(k)-\hat{c}_i(k-1))^2}{T^2}$. The closed loop system equation (12), becomes

$$\ddot{r}_i + 2q\dot{r}_i + q^2(r_i - \frac{1}{2}d_i^2) + (\hat{\beta}_i - \beta_i) - \gamma_i = 0. \qquad (15)$$

System (15) is Input-to-State-Stable with respect to $(\hat{\beta}_i - \beta_i) - \gamma_i$ and note that at steady state: $\limsup_{t\to\infty} \|(\hat{\beta}_i - \beta_i) - \gamma_i\| = 0$. Thus, Lemma 4.7 [27] ensures that $r_i \to \frac{1}{2}\delta_i^2$, which means that the center of every UAV's circular orbit converges to the UGV group centroid estimation exponentially.

B. Collision Avoidance

Our approach is similar in spirit to that of [18] and [19]. If at time step k two or more UAVs are in close proximity they modify their angular velocities ω_i at the following time step $k+1$ as follows:

$$\omega_i(k+1) = \omega_{max}\mathrm{sign}\Big\{\sum_{j:\|\mu_{ij}\|<R_c} \frac{\mu_{ij}(k)}{\|\mu_{ij}(k)\|^2} \times u_i(k)\Big\}. \qquad (16)$$

The main differences of our treatment compared to [18]:

- ω_i assumes only two values $-\omega_{max}$, ω_{max} during evasive maneuvers, ensuring faster disengaging,
- Every UAV within range is taken into consideration, by summing over all agents j too close to UAV i,
- The cross product in (16) weighs each neighbor's contribution according to proximity.

It has to be noted that no formal proof for collision avoidance involving multiple agents is currently available for gyroscopic inputs.

Collision configurations can be categorized into twelve different classes according to relative angular velocity and relative positions. To avoid collision the UAVs adjust their angular velocities to

$$\omega_i(k+1) = \omega_{max}\mathrm{sign}\Big\{\frac{\mu_{ij}(k)}{\|\mu_{ij}(k)\|^2} \times u_i(k)\Big\} = -\omega_{max},$$
$$\omega_j(k+1) = \omega_{max}\mathrm{sign}\Big\{\frac{\mu_{ji}(k)}{\|\mu_{ji}(k)\|^2} \times u_j(k)\Big\} = -\omega_{max}.$$

The resulting angular velocities both have direction into the figure plane, driving the two UAVs farther apart. There are two other possible one-on-one configurations where the cross product in equation (16) is zero. In these cases the UAVs assume aligned angular velocities for the collision to be avoided. The remaining nine possible configurations, fall under the examples described above.

C. Combined control law

The two distinct control laws (14) and (16) are combined into a switching control scheme that for UAV i in district time will function as follows:

- If $\|\mu_{ij}\| > R_c$, $\forall j = 1, \ldots, M$ and no collision is imminent:

$$\omega_i = \begin{cases} \max\{\Omega_i, -\omega_{max}\} & \text{if } \Omega_i \le 0 \\ \min\{\Omega_i, \omega_{max}\} & \text{if } \Omega_i > 0 \end{cases} \qquad (17)$$

- If $j : \|\mu_{ij}\| < R_c$ and a collision might occur:

$$\omega_i = \omega_{max}\text{sign}\Big[\sum_{j:\|\mu_{ij}\|<R_c} \frac{\mu_{ij}}{\|\mu_{ij}\|^2} \times u_i\Big] \qquad (18)$$

Since the application of the orbiting controller (14) can be interrupted by a finite time collision avoidance maneuver, the exponential stability results of Section III-A are reduced to uniform ultimate boundedness of tracking errors.

IV. Simulations

The UGV group consists of 7 agents, with random initial conditions in a $[-1.7, 1.7]$ m interval for the position and $[-1, 1]$ m/s for the velocity vectors. We have selected a common desired interagent distance R_d of 1 m. To improve performance and decrease the risk of collision ground agents estimate the current position of their neighbors using the delayed state, propagating it through the dynamics for the period of the delay. The UAV group consists of 4 agents that follow circular orbits over the UGV group. The UAVs have random initial conditions in a $[-4.89, 2.89]$ m interval for their position and $[-4.89, 2.89]$ m/s for the unit speed vectors. The common magnitude for speed is $V = 50$. For UAVs 1 to 4 the desired radius d is 0.2432, 0.4865, 0.7297, 0.9730 m respectively. The common sensing range is $R_c = 1.7513$ m.

Figures 2 through 6 represent a realization of the scenario described in Section I. Figure 2 shows an overhead snapshot of the initial configuration of a 7-agent UGV group communicating over a complete interconnection graph and 4 UAVs flying above them. The UAVs are not connected to each other and are not on the same plane (altitude) with the UGV group.

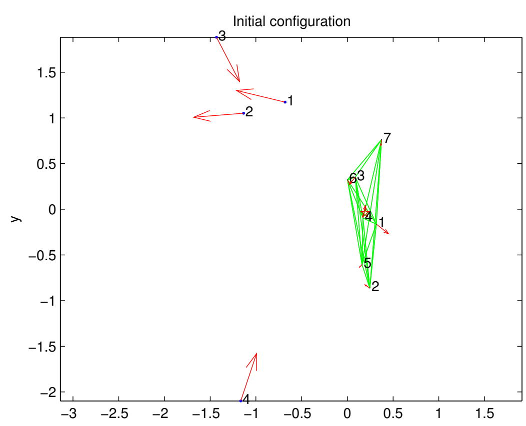

Fig. 2: Initial configurations of UAV and UGV groups. The big arrows (numbered 1 - 4) denote random initial velocities of the same magnitude for the UAVs. UGVs 1 through 7 are connected to each other by links.

V. Conclusions

In this paper we presents a methodology where two groups of UGVs and UAVs cooperate to achieve the control

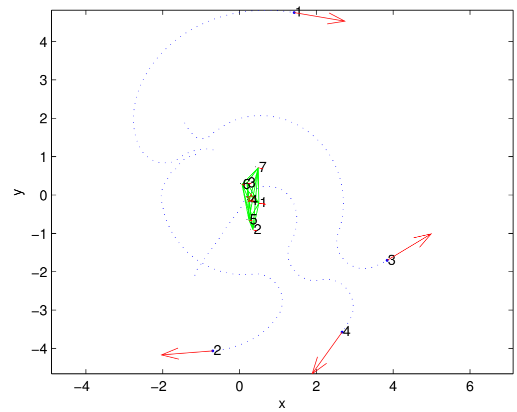

Fig. 3: Collision avoidance maneuvers by UAVs 2, 4 and 3. The dotted curves denote the UAVs' paths.

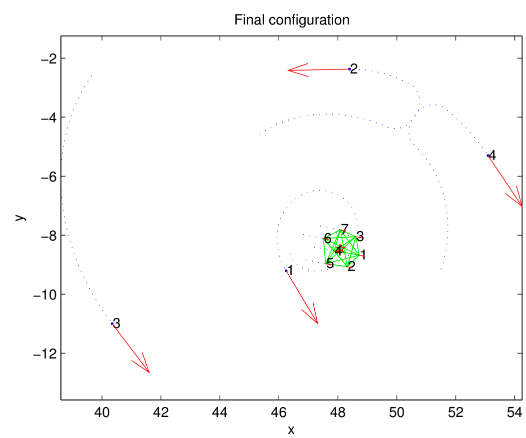

Fig. 4: Configuration for UGV and UAV groups after 3000 time steps. UAVs 2 and 4 came near collision during the final time steps.

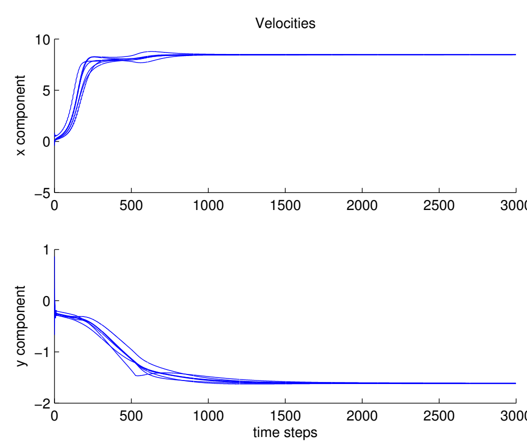

Fig. 5: Evolution of velocities for UGV group. The lines are different speeds agents assume during the simulation time. Convergence for both components is achieved after 1500th time step.

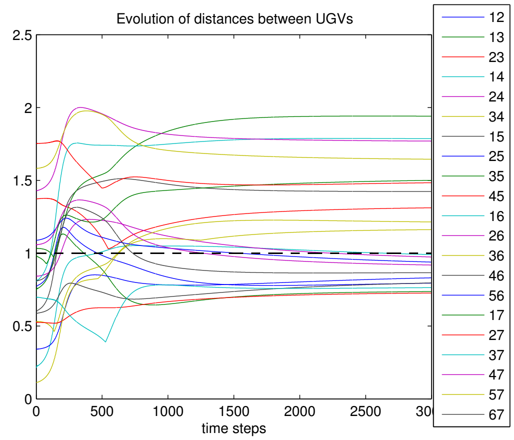

Fig. 6: Evolution of distances between UGVs. Collision avoidance is achieved since no distance among the UGVs is close to zero. The group has reached steady state formation with relative positions stabilized.

objectives that could realize a multi-agent ISR mission. Communication protocol, interagent cohesion and separation forces and a velocity synchronization scheme are combined into a control and communication strategy that is shown to yield asymptotic stability within a Lyapunov framework. Compared to our earlier work in [14] in this paper we present a cooperative control scheme between heterogeneous groups where we introduce potential-based forces. This addition ensures cohesion and separation in the UGV group, without affecting distributed velocity synchronization. In addition, we develop a distributed way of estimating the UGV group centroid, and we designed controllers that enable the UAVs to track the ground group centroid and stabilize on circular orbits around it.

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