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Decentralized Coordination of Constrained Fixed-wing Unmanned Aerial Vehicles: Circular Orbits

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Abstract: UAVs are promising platforms for various missions such as remote sensing of agricultural products, forest fire surveillance, search-and-rescue and border monitoring. A relevant common challenge in the above missions is that of convergence to an objective circular orbit. To address this challenge for fixed-wing UAVs, intrinsic constraints such as nonholonomic nature of the vehicle, minimum and maximum forward velocity, maximum angular velocity and limited detection range must be considered. In this paper, a decentralized coordination strategy is developed so that a number of fixed-wing UAVs converge to an objective circle, respecting the mentioned constraints. Also, a priority-based collision avoidance scheme is proposed to avoid inter-UAV collision. Convergence of the system is proved by analysis of the finite state machine associated with the coordination algorithm. Simulation results are presented to verify the feasibility of the proposed approach.

Keywords: Decentralized coordination; UAV; Circular orbit; Collision avoidance; Flight corridor

1. INTRODUCTION

In recent years, Unmanned Aerial Vehicles (UAVs) have gained increasing attention for various missions such as remote sensing of agricultural products (Costa et al. 2012), forest fire monitoring (Casbeer et al. 2006), search and rescue (Almurib et al. 2011) and border monitoring (Beard et al. 2006). Many of the current missions require the agents to converge to a closed curve (Jesus et al. 2013; Pimenta et al. 2013a; Pimenta et al. 2013b; Lawrence et al. 2008; Frew et al. 2008; Hsieh et al. 2008; Hsieh et al. 2007; Gonçalves et al. 2011). In (Lawrence et al. 2008; Frew et al. 2008) a vector field with a stable limit cycle centered on the target position was constructed. In the mentioned works, the authors employed a Lyapunov Vector Field Guidance (LVFG) law to bring the UAV to an observation "orbit" around the target. In (Hsieh et al. 2008), decentralized controllers were proposed to bring a number of robotic agents to generate desired simple planar curves, while avoiding inter-agent collision. In a different work (Hsieh et al. 2007), the controllers were designed in a manner that the robots converged to a star-shaped pattern and, once on the objective curve, circulated it. In the work (Gonçalves et al. 2011), a vector filed approach was used to bring several nonholonomic UAVs to a static curve embedded in the 3D space. In (Gonçalves et. al 2010), vector fields were determined so that a robot converged to a time-varying curve in *n*-dimensions and circulated it. Considering the family of closed curves, convergence to circular orbits and loitering above a given area is a particularly interesting mission scenario studied by various research groups (Jesus et al 2013; Hafez et al. 2013; Marasco et al. 2012; Chen et al. 2013). Yet, even for the simple case of an objective circle, there are open problems in the literature. As an example, in (Jesus et al. 2013), the authors employed an artificial vector field approach to bring a team of fixed-wing UAVs to an objective orbit. Yet, to address the problem of inter-UAV collision avoidance, it was assumed that the UAVs are initially flying at different heights. Therefore, in the first 2 phases of the methodology in (Jesus et al. 2013), the UAVs were confined to move in their horizontal plane, thus eliminating the risk of collision. In (Marasco et al. 2012), model predictive control was used to create a dynamic circular formation around a given target. By means of simulations, it was shown that the system was stable, but formal stability analysis was not provided. In (Hafez et al. 2013), the same approach was improved to address encirclement of multiple targets, without stability analysis. In (Chen et al. 2013), a so-called tangent-plus-Lyapunov Vector Field was developed to bring a UAV to an objective circle. Not surprisingly, inter-UAV collision avoidance was not addressed for a single UAV.

In this paper, a decentralized coordination strategy is developed such that a number of fixed-wing UAVs converge to an objective circle. The present work improves the previous works (e.g. Jesus et al. 2013) in that it does not need the UAVs to be initially at different heights. Also, it improves other works (e.g. Gonçalves et al. 2011; Pimenta et al. 2013a) in the sense that it considers the intrinsic constraints of fixed-wing UAVs, i.e. nonholonomic nature of the vehicle, minimum and maximum forward velocity and maximum angular velocity. Also, in the previous works (e.g. Jesus et al. 2013), a given UAV was required to estimate the state of the neighbouring UAVs, regardless of the distance between them. Yet, in the present work, a limited detection range is assumed. In order to assure safety of the system, based on the concept of flight-corridor, a priority-based collision avoidance scheme is proposed.

The rest of the paper is as follows. In Section 2, the problem statement is presented. Our methodology is described in Section 3. In Subsection 3.1, for a single UAV, the problem of convergence to the objective circle is studied. In Subsection 3.2, for a team of fixed-wing UAVs, the problem is revisited and collision avoidance scheme is proposed. System convergence is guaranteed, based on the analysis of the finite state machine representation of the proposed methodology. In order to show the feasibility of our proposed approach, simulation results are presented in Section 4. Conclusions and our directions for future research are given in Section 5 and Section 6, respectively.

2. PROBLEM STATEMENT

Consider a nonholonomic fixed-wing UAV with the following simplified kinematic model:

$$\dot{q} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} u. \qquad (1)$$

Where $q = [x \quad y \quad \theta]^T \in \Re^2 \times S^1$, in which x, y denote the Cartesian coordinates of the center of mass of the UAV and θ is its heading angle. Let $u = [v \quad \omega]^T$, where v and ω denote forward and angular velocity inputs, respectively. Also, the physical size of the UAV is represented by a circle with radius r_{UAV} . The model in (1) is a 3 Degree-of-Freedom (DoF) kinematic model, which can be readily extended to include z coordinates as well (Gonçalves et al. 2011). It is assumed that the UAV in (1) is subject to the following constraints on its inputs:

$$v_{\min} \le v \le v_{\max}, \quad (2)$$

$$-\omega_{\max} \le \omega \le \omega_{\max}, \quad (3)$$

where $v_{\min} > 0$ and $v_{\max} > v_{\min}$ are the minimum and maximum forward velocity bounds, respectively. Also, in (3), $\omega_{\max}$ is the maximum possible heading rate in the counterclockwise sense, also known as maximum Rate of Turn (RoT). In view of Dubins model (Dubins 1957), the above equations imply a non-zero minimum radius of curvature, corresponding to the vehicle maximum RoT. Without loss of generality, it is assumed that the radius of the objective circle C is R_o with $R_o \ge \frac{v_{\min}}{\omega_{\max}}$, and its center is located at $x_c = 0$ and $y_c = 0$. Now, it is possible to formally state the problem at hand:

Problem statement: Consider N UAVs, initially out of the objective circle, represented by the model given in (1), with the physical size r_{UAV} . Devise a decentralized coordination strategy such that the UAVs converge to the objective circle C and circulate it, respecting the nonholonomic constraint and those given by (2) and (3), with finite limited detection range. Also, inter-UAV collision avoidance must be guaranteed throughout the mission.

Our proposed strategy will be described in the following section.

3. METHODOLOGY

The path to bring a single UAV to the objective circle C is composed of 3 segments. The UAV is initially assumed to be out of the objective circle. In the first segment, the UAV starts loitering in a clockwise manner. Then, in the second segment, the UAV flies on a straight line toward the center of the objective circle. Finally, the UAV leaves this straight line and makes a loitering to converge to the objective circle. This methodology is discussed in detail in Subsection 3.1. The problem is extended to multi-UAV scenario in Subsection 3.2. The worst case for collision avoidance scheme is that all the UAVs are at the same height. Therefore, we will consider the motion of the UAVs in the $x-y$ plane.

3.1 Single UAV Scenario

As mentioned previously, in our proposed methodology, the path to bring a UAV to the objective circle consists of 3 segments, shown in Fig. 1.

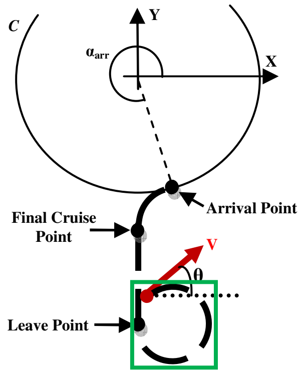

Fig. 1. Schematic view of the UAV path toward the objective circle

The green square in Fig. 1 will be later defined and employed in a manner such that initial deadlocks can be avoided. Also, α_{arr} will be later defined. An important definition is given here:

Definition 1: Loitering circle of the UAV at a given point is the loci of all points that would be occupied by the UAV if it started loitering with its maximum RoT. The loitering circle corresponding to a clockwise loitering is called the right loitering circle and the one corresponding to a counterclockwise loitering is called the left loitering circle. The radius of both loitering circles is denoted by R_l .

The proposed strategy can be represented by means of a finite state machine. Here, four states namely, Initial Loitering, Cruise, Final Approach and "On the Objective Circle" are defined to address different segments of the UAV flight. The UAV starts in the Initial Loitering state. The following actions are executed in each state:

<u>*Loitering state:*</u> $v = v_{\min} \le v_c \le v_{\max}$ and $\omega = -\omega_{\max}$

<u>*Cruise state:*</u> $v = v_c$ and $\omega = 0$

<u>*Final Approach state:*</u> $v = v_c$ and $\omega = -\omega_{\max}$

<u>*On the Objective Circle state:*</u> $v = v_c$ and $\omega = \frac{v_c}{R_o} \le \omega_{\max}$

The transitions can be viewed in the state diagram presented in Fig. 2. In the first state, i.e. the Initial Loitering state, the UAV starts loitering with its maximum RoT ($-\omega_{\max}$) in the clockwise direction, with constant forward velocity v_c

($v_{\min} \le v_c \le v_{\max}$). The tangent line connecting the center of the objective circle to the initial loitering circle is the second part of the path toward the objective circle, i.e. the Cruise state. The point where the initial loitering circle is patched to the cruise path is called the Leave Point (see Fig. 1). In the Cruise state, forward velocity input is again v_c and $\omega_c = 0$. At the end of the cruise state, the UAV reaches a point called Final Cruise Point (FCP), at which the loitering circle of the UAV is tangent to the objective circle. At this point, the UAV starts the final part of the path, i.e. the Final Approach state. In this state, the forward velocity command remains unchanged (v_c) and the angular velocity is $-\omega_{\max}$. The Final Approach state ends when the UAV reaches the objective circle and then it starts circulating it. The point at which the Final Approach curve is patched to the objective circle is called the Arrival Point. On the objective circle, the Arrival Point corresponds to α_{arr}, i.e., the angle of polar coordinate with its origin coincident with the center of the objective circle. On the objective circle, the angular velocity command is employed to make the UAV follow a virtual leader whose position on the objective circle is given by the polar angle $\alpha(t) = \alpha_{arr} + \frac{v_c}{R_o} t$. In the final state, $\omega = \frac{v_c}{R_o} \le \omega_{\max}$.

By construction, it is clear that the constraints given in (2) and (3) are satisfied in all the 3 phases that bring the UAV from its initial state to the objective circle.

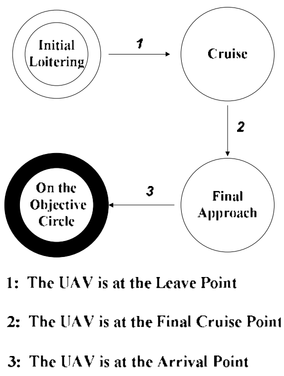

Fig. 2. Finite state machine representation of the proposed methodology for one UAV

In order to show the feasibility of the proposed approach, a definition must be made:

Definition 2: A condition $l = 0$ is nonpersistent over time if $l = 0$ at a finite time T and there exists a finite time $\hat{T} > T$ for which $l \ne 0$ (Pimenta et al. 2013a).

Proposition 1: Consider a nonholonomic fixed-wing UAV, initially out of the objective circle, represented by (1), subject to constraints (2) and (3). With the algorithm given in Subsection 3.1, the UAV converges to the objective circle C.

Proof: consider the state diagram shown in Fig. 2, schematically representing the proposed navigation methodology. The UAV is initially in the Initial Loitering state. Due to the finite length of the curve travelled in the Initial Loitering state, Condition #1, i.e. reaching the Leave Point is nonpersistent. Thus, once at the Leave Point, the UAV will enter the Cruise state. In the Cruise state, the distance between the UAV and the objective circle decreases monotonically. Therefore, Condition #2, i.e. reaching the Final Cruise Point is nonpersistent and the UAV will enter the Final Approach state. Finally, Condition #3 is nonpersistent, due to the finite length of the arc travelled in this state. It is concluded that the UAV will finally converge to the objective circle. ■

3.2 *Multi-UAV Scenario*

In this section, the previous strategy is extended to address multi-UAV scenarios. To ensure the safety of the system, the first issue that must be addressed is inter-UAV collision avoidance. Here, two possible collision events must be considered. In the first case, two UAVs may collide on their path toward the objective circle. In the second case, a UAV approaching the objective circle may collide with another one already moving in the objective circle. Each of these cases is addressed separately in the following subsections.

3.2.1 Collision avoidance in the Cruise state

The collision avoidance scheme presented in the following will prevent deadlocks, i.e. persistent loitering maneuvers in the Cruise state. Here, a number of definitions must be made:

Definition 3: Consider the path segment corresponding to the Cruise state of the UAV. Flight corridor is the union of all (right and left) loitering circles tangent to the cruise segment of the flight.

It is clear that if the flight corridors of two UAVs do not intersect, there is no possible collision event between those two UAVs.

Definition 4: The smallest circle that encompasses the right and left loitering circles is called the safety circle.

In Fig. 3, part of the flight corridor of a UAV and its safety circle is schematically shown. It is clear that the UAV can stay in its safety circle, without violating the constraints in (2) and (3). In other words, safety circle of the UAV can stay stationary, if required.

Definition 5: A collision avoidance maneuver is when a UAV moves into its right loitering circle and finishes one complete circle.

Once the UAV completes one full loitering circle, it is back on its original cruise path toward the objective circle. If the potential collision event is not resolved, it starts another loitering collision avoidance maneuver and keeps loitering until its flight corridor is free of a potential collision event. Then, it starts moving toward the objective circle again.

In order to avoid the potential collision events, a prioritization scheme is defined. In brief, when applicable, the UAV which is closer to the objective circle has higher priority and moves first. In the case of equal distance, higher priority is given to the UAV with greater heading angle and thus it can move first. The collision event is resolved when the UAV with higher priority leaves the detection range of the UAV with lower priority. In the following paragraphs, detailed analysis is presented.

Our proposed collision avoidance scheme modulates the movements of the UAVs so that safety circles of two UAVs do not block each others' flight corridor simultaneously. Here, an important observation is that the radius of the objective circle cannot be smaller than that of the loitering circle ($R_l \le R_o$). Therefore, if the flight corridors of two UAVs intersect, the angle between their flight corridors is smaller than $\frac{\pi}{2}$. In the worst case where the angle between the flight corridors of the two UAVs is $\frac{\pi}{2}$, with the safety circles of two given UAVs mutually tangent to their flight corridors, the UAVs should detect each other with a finite detection range of $(4\sqrt{2}+2)R_l + 2 * r_{UAV}$. The $4\sqrt{2}R_l$ term in the detection range corresponds to the distance between the centers of the safety circles of the two UAVs mutually tangent to the flight corridor of one another. Also, addition of the conservative second term i.e. $2R_l$ accounts for the fact that one of the UAVs may already be loitering to avoid a possible collision.

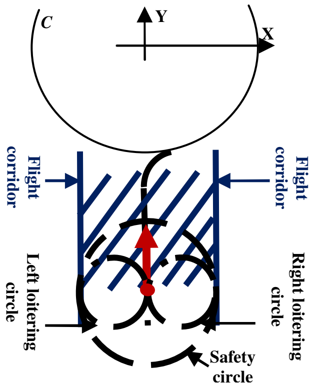

Fig. 3. A portion of UAV flight corridor

An important observation is that if the safety circle of UAV_j does not overlap the flight corridor of UAV_i at a given moment, there will be no potential risk of collision for UAV_i with UAV_j, at that configuration. Regarding the relative configuration of any two UAVs, there are 3 possible scenarios to be considered. In the first scenario shown in Fig. 4a, safety circle of UAV_j is tangent to the flight corridor of UAV_i, but safety circle of UAV_i does not intersect flight corridor of UAV_j. Here, it is clear that UAV_j should continue moving toward the objective circle while UAV_i should start a collision avoidance maneuver. Let us show the distance between UAV_i and the center of the objective circle by DOC_i. Similarly, the distance between UAV_j and the center of the objective circle is denoted by DOC_j. For the configuration shown in Fig. 4a, it is easy to verify that $DOC_i < DOC_j$.

A second possible scenario is shown in Fig. 4b. In this scenario, if any of the UAVs moves, the flight corridor of the other UAV will be blocked. In this specific configuration where $DOC_i = DOC_j$, the UAV with greater heading angle will have priority over the UAV with smaller heading angle ($0 \le \theta < 360$ deg). Thus, higher priority is given to UAV_j and lower priority is given to UAV_i. Thus, UAV_j keeps moving toward the objective circle while UAV_i starts a collision avoidance maneuver.

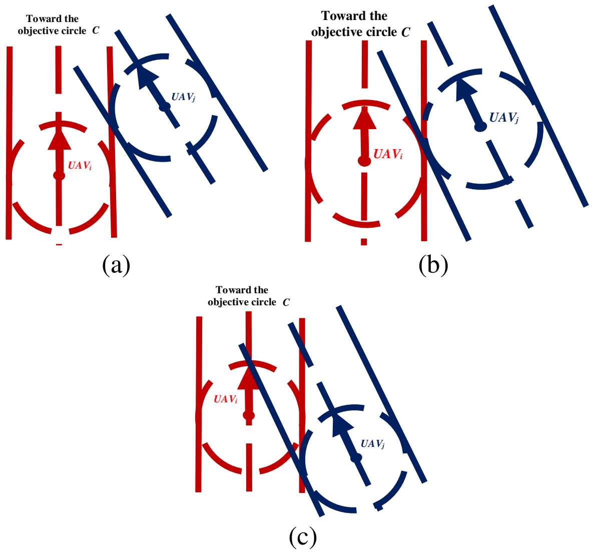

Fig. 4. Flight corridors of two UAVs and their safety circles – first scenario

Finally, the third possible scenario is shown in Fig. 4c, in which it is easy to verify that $DOC_i < DOC_j$. Here, it is clear that UAV_i should have higher priority over UAV_j. As a result, UAV_i continues moving toward the objective circle while UAV_j starts a collision avoidance maneuver. Similar reasoning can be made to come to the same conclusions where UAV_j approaches UAV_i from the left side. By construction, the above collision avoidance scheme does not allow the safety circles of two UAVs to simultaneously block each others' flight corridor. It is also important to show that deadlock situations do not occur in scenarios with more than two UAVs, i.e. chain-type deadlocks. A chain-type deadlock, for 3 UAVs, is one in which UAV_j has got priority over UAV_i and UAV_k has got priority over UAV_j, but UAV_i has got priority over UAV_k. The same definition can be easily extended to scenarios with more than 3 UAVs. In a chain-type deadlock, each UAV is blocked by another one and thus no UAV can move toward the objective circle.

Based on the previous discussion, if UAV_j has got priority over UAV_i, $DOC_j \le DOC_i$. Similarly, if UAV_k has got priority over UAV_j, $DOC_k \le DOC_j$. Thus, it is concluded that $DOC_k \le DOC_i$ and hence UAV_i cannot have priority over UAV_k. Also, in the cases where $DOC_i = DOC_j$, the value of the heading angle uniquely determines which UAV can move and therefore eliminates deadlocks. As a result, no chain-type deadlock, i.e. persistent loitering maneuvers can occur while the UAVs are in their Cruise state.

3.2.2 Collision avoidance in the Final Approach state

In the Final Approach state, possible collisions between the approaching UAVs and the ones already moving on the objective circle must be avoided. The collision avoidance scheme presented in the following will prevent deadlocks, i.e.

persistent loitering maneuvers in the Final Approach state. Here, a definition is made:

Definition 6: The Decision Point, shown in Fig. 5, is a point on the cruise segment of the flight where the minimum distance between the center of the right loitering circle and that of the objective circle is $R_o + R_l + 2r_{UAV}$.

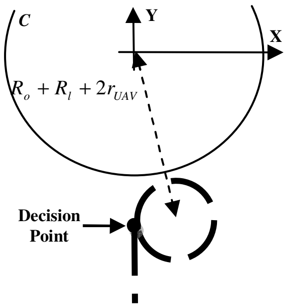

Fig. 5. The Decision Point

This is the ultimate point where the UAV can make a loitering circle without the risk of colliding with the UAVs already on the objective circle. After the Decision Point, if the approaching UAV starts a loitering maneuver, it can potentially collide with the UAVs on the objective circle. As a result, at the Decision Point, the UAV must make the decision whether it can approach the objective circle without the risk of collision. It is clear that the Final Cruise Point is closer than the Decision point to the objective circle.

For an approaching UAV, the length of the final approach curve is computed for a given set of $\{R_o, R_l, r_{UAV}\}$. Here, a conservative solution is considered. The approaching UAV starts the Final Approach state only if there is no UAV on the objective circle in the interval $[\alpha_{\min} \quad \alpha_{arr}]$. As defined before, α_{arr} corresponds to the angular position of the Arrival Point at the objective circle. If we denote the length of the approach phase by l_a, $\alpha_{\min}$ is the polar angle (behind α_{arr}, in the counterclockwise sense) whose arc distance with α_{arr} on the objective circle is equal to $c * l_a + 2r_{UAV}$, where c is a constant (greater than 1). A conservative option is to select $c = 2$. In this manner, the approaching UAV will decide to approach the target circle if there is the angular clearance corresponding to $2(l_a + r_{UAV})$ on the objective circle, thus avoiding collision with the UAVs already on the objective circle. This required angular clearance limits the number of the UAVs that can converge to the objective circle to a finite number $N_{\max}$. Still, $N_{\max}$ can be increased if the required angular clearance, i.e. the constant c is recomputed in a more rigorous manner. An important observation is that, for $c = 2$, the minimum required detection range in this state is smaller than $l_a + 2(l_a + r_{UAV})$. Noting that $l_a \le 0.25R_l$, it can be concluded that the minimum required detection range is given by $\max\{(4\sqrt{2}+2)R_l + 2 * r_{UAV},\ l_a + 2(l_a + r_{UAV})\}$, i.e., $(4\sqrt{2}+2)R_l + 2 * r_{UAV}$. Finally, a remark is made:

Remark 1: If the ratio $\frac{R_o}{R_l}$ is an integer number, there are finite possibilities for the UAV to start its Final Approach state. If the required angular clearance is not guaranteed in any of the possibilities, the UAV will be stuck in a deadlock condition and cannot enter the Final Approach state. Yet, in practice, this is not a practical concern since the ratio $\frac{R_o}{R_l}$ is not an exact integer value.

With the above remark, it is concluded that the proposed collision avoidance scheme allows no persistent collision avoidance loitering maneuvers in multi-UAV scenario.

3.2.3 Covergence to the objective circle in multi-UAV scenarios

The proposed strategy can be shown by means of the state diagram in Fig. 6.

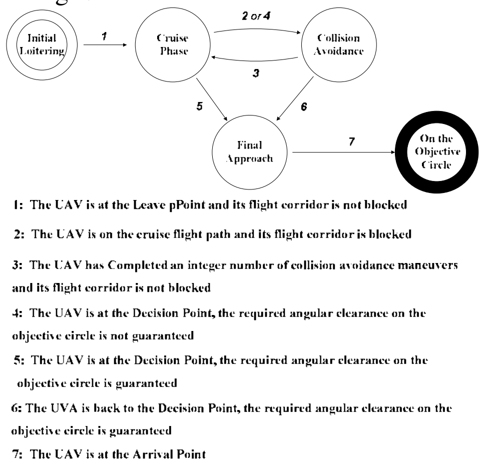

Fig. 6. Finite state machine representation of the proposed methodology for multiple UAVs

Here, the actions in the Initial Loitering, Cruise and "On the Objective Circle" states are the same as the ones in Section 3.1. In the remaining states, the following actions are made:

Collision Avoidance state: $v = v_c$ and $\omega = -\omega_{\max}$

Final Approach state:

After the Decision Point, before reaching the Final Cruise Point: $v = v_c$ and $\omega = 0$

After the Final Cruise Point: $v = v_c$ and $\omega = -\omega_{\max}$

It is important to notice that the Final Approach state, in multi-UAV scenario, consists of two steps. In the first step, the UAV keeps moving on the straight line after its Decision Point and before reaching the Final Cruise Point. Once at the Final Cruise Point, the UAV starts loitering and converges to the objective circle. Also, in the transitions, the expression "flight corridor is blocked" means that the UAV's flight corridor is already blocked by the safety circle of another UAV or it is in one of the three defined scenarios of potential collision and it has lower priority in relation to the other UAVs in its detection range.

Convergence to the objective circle, in multi-UAV scenario is discussed in the following paragraphs. First, an assumption is made such that the UAVs are not "born" in an initial deadlock configuration.

Assumption 1: Consider a square with the edge length $2(R_l + r_{UAV})$, with its center coincident with that of the initial loitering circle of the UAV and one of its edges parallel to the UAV's flight corridor (See Fig. 1). It is clear that, in the Initial Loitering state, the UAV is confined to the space encompassed by the defined square. It is assumed that the different squares corresponding to different UAVs do not initially overlap each other.

Assumption 1 is necessary to ensure that the UAVs do not inevitably collide with each other, due to inappropriate initial conditions.

Proposition 2: Consider $N \leq N_{\max}$ nonholonomic fixed-wing UAVs, initially out of the objective circle, with detection range $(4\sqrt{2}+2)R_l + 2 * r_{UAV}$, with the initial conditions not violating Assumption 1. Each UAV is represented by (1), subject to constraints (2) and (3). With the coordination strategy and collision avoidance scheme given in Subsections 3.2.1 and 3.2.2, the UAVs converge to the objective circle C, without inter-UAV collision, satisfying the constraints in (2) and (3).

Proof: The $i-th$ agent, i.e. UAV_i is initially in the Initial Loitering state. Assumption 1, combined with the fact that the curve travelled in the Initial Loitering state is of finite length, ensures that Condition #1 is nonpersistent and therefore the UAV will leave the Initial Loitering state and start the Cruise state after some finite time. Once the UAV is in the Cruise state, the distance between the UAV and the objective circle decreases monotonically. If no collision avoidance maneuver is required in the Cruise state, the UAV stays in this state until it reaches the Decision Point. Once the UAV is at the Decision Point and the required angular clearance is guaranteed on the objective circle (Condition #5), the UAV switches to the Final Approach state. It is reminded that Remark 1, along with $N \leq N_{\max}$ ensures that Condition #5 is nonpersistent. Noting that the curve travelled in the Final Approach state is of finite length, Condition #7 is nonpersistent and the UAV will finally converge to the objective circle.

In the Cruise state, there are possible configurations at which the UAV needs to start a collision avoidance maneuver (Condition #2). In that case, the UAV switches to the Collision Avoidance state and starts a loitering maneuver. Given the prioritization scheme, Condition #3 is nonpersistent and after completing an integer number of collision avoidance loitering circles, the UAV will be back to the Cruise state and continue its path toward the objective circle. Also, it is possible that the UAV reaches the Decision Point but the required angular clearance on the objective circle is not provided (Condition #4) and the UAV switches to the Collision Avoidance state. Similarly, as discussed in Subsection 3.2.2, Condition #6 is nonpersistent and the UAV, after completion of an integer number of collision avoidance loitering circles, will switch to the Final Approach state and will converge to the objective circle. ■

4. SIMULATIONS, RESULTS AND DISCUSSION

In order to show the feasibility of our proposed approach, a 10-UAV scenario is developed. An objective circle with a radius of 1 km with its center at the origin, i.e. $[0 \quad 0]^T$ is assumed. Also, the physical size of each UAV is represented by a circle of radius 1.5 m. Forward and maximum angular velocity of the UAV is assumed to be 10 m/s and 0.1 rad/s, respectively. These values correspond to a loitering circle with the radius 100 m. The initial conditions of the 10 UAVs are shown in Fig. 7.

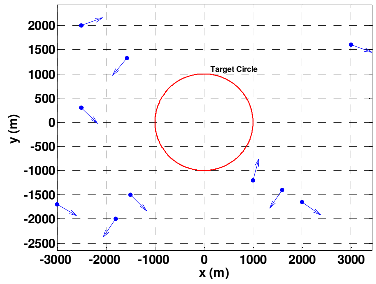

Fig. 7. Initial conditions of the 10 UAVs in the simulated scenario

For the above scenario, simulations were carried out and the snapshots of results are shown in Fig. 8-10. As it can be seen from the figures, the 10 UAVs have successfully converged to the objective circle, without colliding with each other. As an example, consider the UAV in the upper-right part of Fig. 7, whose initial position and heading is $[3000 \quad 1600]^T$ and -20 deg, respectively. As shown in Fig. 8-10, this UAV initially starts a loitering circle and then keeps moving toward the objective circle on its cruise path. Yet, as it arrives at its Decision Point, the required angular clearance on the objective circle is not provided because parts of the objective circle are already occupied by the UAVs starting from the lower-right part of Fig. 7. Thus, to avoid collision with the UAVs already on the objective circle, this UAV starts a loitering maneuver. After one complete loitering maneuver, the UAVs on the objective circle have moved ahead and thus the approaching UAV can start its Final Approach state and it converges to the objective circle. Several other collision avoidance maneuvers can be observed in the simulated scenario. As an example, the UAV departing from the lower-left part of Fig. 7 make 3 full loitering maneuvers not to collide with the UAVs on the objective circle. Yet, as discussed earlier, the conditions leading to loitering maneuvers are nonpersistent and all the UAVs converge to the objective circle in finite time. Thus, the feasibility of our proposed methodology is verified.

5. CONCLUSIONS

In this paper, a high-level decentralized coordination strategy was developed to bring a number of constrained fixed-wing UAVs to an objective circle. Our methodology takes account of inherent constraints of fixed-wing UAVs i.e., nonholonomic nature of the vehicle, minimum and maximum forward velocity, maximum angular velocity and limited communication range. Also, a priority-based scheme was proposed to avoid inter-UAV collision events. The second-order dynamics of the UAV was not considered and therefore certain margins must be considered for real-world implementation. Moreover, the proposed approach is a high-level algorithm to be followed by the UAVs. Thus, given the uncertainties, wind effects and other real-world phenomena, in order to use this approach, a low-level controller must be used. This will allow the real UAVs to perform the desired behaviour in each of the states. Finally, the transitions from a state to another are given as equality-type conditions. For real world implementation, thresholds must be defined and the equalities must be replaced by appropriate inequalities.

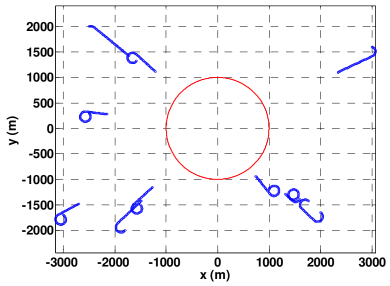

Fig. 8. Simulation results – first snapshot

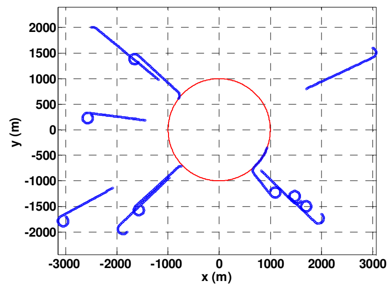

Fig. 9. Simulation results – second snapshot

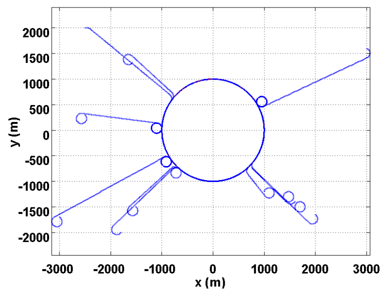

Fig. 10. Simulation results – third snapshot

6. FUTURE WORK

We intend to verify the effectiveness of the proposed methodology on real UAVs. Currently we are working on the requirements and procedures for a field test.

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