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On the Emergence of Virtual Roundabouts from Distributed Force/Torque-based UAV Collision Avoidance Scheme

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Abstract— **This paper presents a distributed force/torque-based UAV(Unmanned Aerial Vehicle) collision avoidance scheme. This scheme is designed to deal in a distributed way with the problem of collisions among rotor craft UAVs, that are sharing the space and flying to different destinations. The proposed scheme has a modular architecture, so that it can be easily included into UAVs with a waypoint controller, GPS and communication module. The scheme is though to be simple, in order to make it scalable. It uses a combination of force and torque models for avoiding collisions, while keeping a minimum safety distance. The force model helps to keep a minimum distance among UAVs. The torque model is intended for creating virtual roundabouts, when two or more UAVs simultaneously want to fly over an intersection point. The functionality of the proposed scheme is tested by simulation. The evaluation parameters are overall mission time and the minimum distance keeping to others UAVs while avoiding collision. Scalability, the impact of different maximum speeds and the impact of different values of the parameter "avoidance coefficient" are analyzed. We show that the proposed scheme avoids collisions by the emergence of virtual roundabouts. The roundabout size is self-adaptable according to the number of UAVs. Regarding to the minimum distance among UAVs, we show that the scheme behaves similarly when the number of UAVs increases. However, the mission time increases when more UAVs are involved.**

I. INTRODUCTION

Different research fields are employing UAVs as a part of their solution for many problems. Sooner or later UAVs will fly over the cities carrying out different tasks. Here, some examples are given. In the delivery sector, UAVs are not only intended to deliver packets[1], but cooperative algorithms are under investigation in order to transport heavy or big payloads [2]. In the communication field, there are investigations in order to put GSM [3] and LTE [4] base stations on UAVs. The goal is to provide an adaptively reliable communication link. Moreover, UAVs can act as a data ferries to provide communication in disconnected Delay Tolerant Networks (DTNs)[5][6]. In the monitoring field, there are works that combine UAVs and Internet of Things (IoT). Authors in [7] proposed a combination of wireless sensor networks and a UAV for monitoring animals, that are free in large scale wild-life areas. An analysis of optimal mobility trajectories and the deployment of UAVs for collecting information from IoT devices is presented in [8]. The topic of smart cities is also related to UAVs. For example, [9] deals with the problem of gathering real time data about the traffic in cities by using UAVs. Rotor craft UAVs are usually considered for this kind of applications. They can take off vertically, hover and change the direction in a flexible way comparing with other type of aircrafts.

Existing applications consider that UAVs are able to fly autonomously over long distances. So, the probability of having collisions increases, specially when many rotor craft UAVs from different companies fly in a shared space and execute different tasks. Since the UAVs may fly autonomously, they need to be able to identify a collision risk and avoid the collision. Due to the variable UAV traffic, strategies for collision avoidance need to be scalable. In the literature there are works for collision avoidance among UAVs, when they are flying in flocks [10][11]. There are also solutions for collision avoidance between UAVs and other obstacles [12]. However, the collision problem among UAVs with different missions is still open for scalable and feasible solutions.

In order to deal with the collision problem, this paper proposes a force/torque-based UAV collision avoidance scheme. The scheme is implemented by the so called UCAM (UAVs collision Avoidance Module). UCAM is a module that contains and runs the proposed force/torque-based scheme. It can be integrated in UAVs with a waypoint controller, GSP and a communication device. By using the communication device, the UAV shares its position and velocity, while getting position and velocity information from surrounding UAVs. With this information the UCAM estimates the collision risk and runs the force/torque-based UAV collision avoidance scheme, in order to avoid the collision among UAVs. The proposed scheme uses a force model and a torque model. The force model is intended to keep the distance among UAVs. Meanwhile, the torque model deals with block situations, when UAVs fly to each others. In this case, the force model will make the UAVs to go back to avoid the collision. The UAVs will avoid the collision, but none of them will reach the destination. By using the proposed torque model, UAVs flying in opposite directions will cooperatively create roundabouts, in order to avoid collisions and to go to their destinations. Simplicity and scalability are considered in the design, in order to apply it in real UAVs.

This paper is organized as follows. Section II presents related work. Section III describes the proposed force/torque-based scheme. In section IV, the evaluation scenarios are described and the results are presented and analyzed. Finally, the conclusion and future work is presented in Section V.

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II. STATE OF THE ART

The problem of organizing the traffic of autonomous UAVs and avoiding collisions among them is emerging. Recent researches addressed this by defining the space within UAVs should be allowed to fly. For instance, [13] presents an algorithm that defines safe UAV routes in urban areas. Using satellite images and geographical information of roads and buildings, a route is computed in such a way that the UAV flies mostly over buildings and avoids areas with pedestrians or moving cars. However, [13] does not deal with the problem of collision among UAVs. Other proposal for organizing the future UAV traffic was presented in [14]. In this paper, the authors proposed the use of a pre-established network of routes, that considers obstacles, restricted airspace and altitudes limitations. Collisions among UAVs are avoided by using a scheduling algorithm. UAVs are scheduled by a central entity, so that they fly through a collision free route. Other similar approach was discussed in [15]. The authors proposed to construct virtual air highways for UAVs and presented a method for their deployment. The method models the desired highway placement by using a cost function. Once the air highways are placed, UAVs are supposed to fly in platoons, keeping relative fixed positions.

The works presented above deal with UAVs traffic organization, but they left open the issue of collisions among UAVs. Some strategies address this issue. For example, authors in [16] considered the collision problem between only two UAVs. Then, an optimal path for each UAV is found according to some control constrains. The computation time of a new collision free path takes 430 seconds for each UAV. Another strategy for two UAVs was presented in [17], with practical implementation. Both UAVs use cameras to identify each other and the possibility of a collision. Applying the game theory, UAVs decide in a cooperative way which UAV flies over and which one flies under the other one.

A strategy for collision avoidance among more than two UAVs was presented in [18]. For that, the authors used a Hamilton-Jacobi Reachability method. In the proposed algorithm, UAVs work in pairs. In each pair each UAV analyses the "danger zones" and cooperatively estimates a region where it can fly. The complexity of Hamilton-Jacobi Reachability methods increases with the number of UAVs. Therefore, [18] proposed Mixed Integer Program (MIP) for harmonizing the collision avoidance solutions of the different UAV pairs. The collision avoidance maneuver is executed by the pairs of UAVs according to an objective function and to a priority matrix. Although the previous methods addressed the collision avoidance problem, their algorithms are complex and time consuming. Therefore, they may do not scale. Collision avoidance algorithms need to be as simple as possible, reliable and scalable.

III. FORCE/TOQUE-BASED UAV COLLISION AVOIDANCE SCHEME

The proposed force/toque-based UAV collision avoidance scheme is implemented by the UCAM module, that was previously described in the introduction. The scheme runs in a UAV, that is executing the flow diagram presented in figure 1. First, a target position for the UAV is set and the mission is to fly there. While the UAV is flying to its target, it receives information about its own position and neighbors velocity and position. This information is delivered to the UCAM module, which evaluates the collision risk with surrounding UAVs. In case that the collision risk is higher than zero, the function "avoid_collision" is called. This function runs the force/torque-based UAV collision avoidance scheme to estimate a temporary target position. The trajectory changes due to the new target position. While the UAV is flying to the temporary destination, UCAM continues estimating the collision risk. If the collision risk decreases, the UAV continues flying to the new temporary position. Once the collision risk reaches to zero, the UAV sets the original target destination again. In case that the change on the trajectory does not reduce the collision risk, UCAM runs the force/torque-based UAV collision avoidance scheme again. Thus, a new temporary target position is estimated.

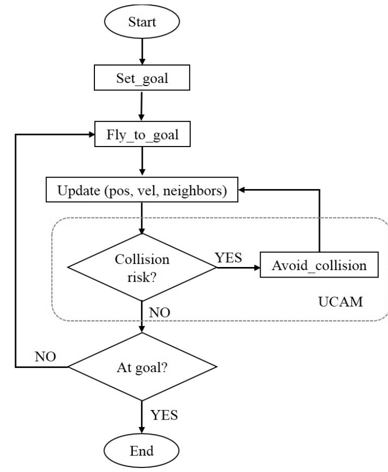


Fig. 1. Flow diagram of the behavior controller

As Figure 1 shows, UCAM executes two tasks: estimate collision risk and call the function, that runs the proposed collision avoidance scheme. In the following subsections these tasks are explained.

A. Collision risk estimation

UCAM assumes that the UAVs are equipped with a communication module. Thus the UAV can receive position and velocity updates from UAVs within the transmission range of the communication module. The UCAM risk estimator divides the UAV's surrounding area as it is shown in Figure 2. UCAM defines three boundaries. The first boundary is the minimum safety distance to the UAV that should always be kept. No UAV is allowed to come closer than this distance. The second boundary defines the reaction zone. Any UAV within this zone is considered as a risk. When a UAV enters into the reaction zone of the UAV, it will change its trajectory in order to avoid a possible collision. The third boundary is just the communication range of UAV. The UAV is not aware of other UAVs flying beyond this boundary.

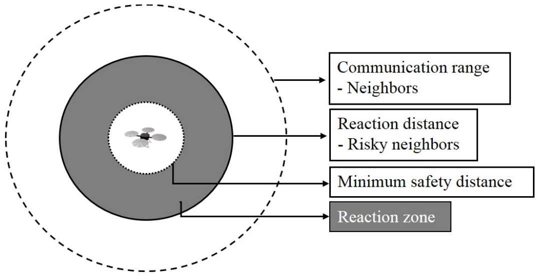


Fig. 2. UAV safety, reaction and communication zones

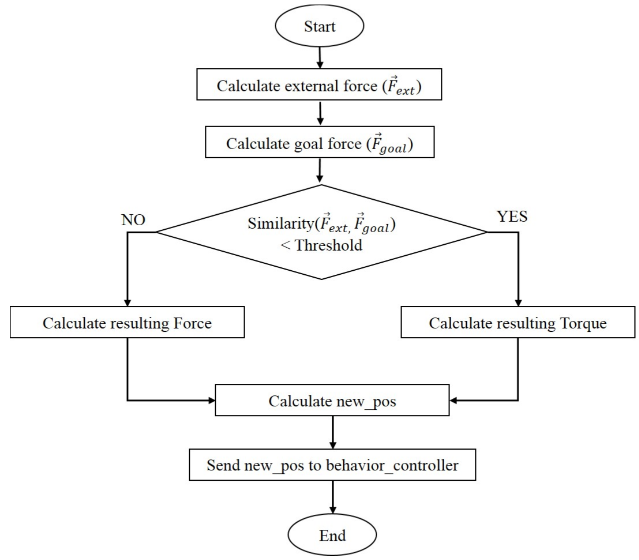


Fig. 3. Force/torque-based UAV collision avoidance scheme

UCAM differentiates neighbors without any risk from risky neighbors. Neighbors are all the UAVs flying within the communication range and risky neighbors are the UAVs flying within the reaction zone. UCAM estimates collision risk value only for risky neighbors. The risk value is defined between [0,1] and estimated using the following equation:

$$f_{risk}(x) = 1 - x \tag{1}$$

In the equation 1 $f_{risk}(x)$ determines how fast the collision risk increases, when a risky neighbors is coming close to the UAV. x represents the relative normalized distance from the UAV to a risky neighbor. UCAM estimates a collision risk value for each UAV within the reaction zone. The decision about if the new trajectory avoids the collision or not is taken based on the highest risk value after each position and velocity update. UCAM updates the collision risk every time that new information about the position and velocity of surrounding UAVs is received.

The relative normalized distance from the UAV to a neighbor x is calculated by the equation 2. In this equation, $\parallel \overrightarrow{D_{RNi}} \parallel$ is the magnitude of distance between the UAV and the risky neighbor RNi. The $safety\_D$ is minimum safety distance and the $reaction\_D$ is the distance that defines the reaction zone boundary.

$$x = \frac{\parallel \overrightarrow{D_{RNi}} \parallel - safety\_D}{reaction\_D - safety\_D} \tag{2}$$

UCAM does not consider only the distance to UAVs for the calculation of the collision risk. It also takes into account risky neighbors direction and relative position to the UAV. Thus, a UAV within the reaction zone represents no collision risk, if it flies away from the UAV.

B. Collision avoidance

The collision avoidance function uses the force/torque-based UAV collision avoidance scheme. When function is called, the priority is to avoid the collision instead flying to the target destination. Figure 3 presents the way the proposed scheme calculates a new temporary destination to avoid the collision. First, it takes the position of all UAVs that are considered as risky neighbors and calculates the relative distance to each one. A virtual force is estimated for each risky UAV based on the following equation:

$$\overrightarrow{F_{RNi}} = \widehat{D_{RNi}} * f(x) \tag{3}$$

$\overrightarrow{F_{RNi}}$ is the vector force, that a risky neighbor(RN) i applies over the UAV. The force direction is defined by $\widehat{D_{RNi}}$, which is the unitary vector of the distance vector from the risky neighbor to the UAV. The force magnitude is defined by a function $f_{force}(x)$ and it is a value between 0 and 1. The force magnitude is calculated using one of the functions, that are shown in equation 4. x is the normalized distance to the risky neighbor (RN) i that was estimated using equation 2.

$$f_{force}(x) = \begin{cases} 1 - x \\ (1-x)^2 \\ -x^2 + 1 \end{cases} \tag{4}$$

The resultant force for all risky neighbors is calculated as equation 5 shows.

$$\overrightarrow{F_{ext}} = \sum_{i=0}^{\#RN} \overrightarrow{F_{RNi}} \tag{5}$$

The force model considers also and attractive force $\overrightarrow{F_{goal}}$ towards the goal destination. The magnitude of $\overrightarrow{F_{goal}}$ is defined by default to be 1.

Once the risky neighbor resultant force vector and the goal force vector have been calculated, the next step is to identify if UAVs are flying in opposite directions. If this is the case, we have the block described in the introduction. For that purpose, this paper proposes to use cosine similarity, which is a value between -1 and 1, that indicates how similar the direction of two vectors are. The output will be 1 if the vectors have the same direction, -1 if the directions are opposite and 0 if the vectors are orthogonal. The cosine similarity expression is given by equation 6. Here, $\overrightarrow{F_{ext}}$ is the resultant force of all risky neighbor forces and $\overrightarrow{F_{goal}}$ is and the attraction force. If the similarity value is between -0.7 and -1, it is considered that UAVs are in a block situation.

$$Similarity = \frac{\overrightarrow{F_{ext}}.\overrightarrow{F_{goal}}}{\| \overrightarrow{F_{ext}} \| \| \overrightarrow{F_{goal}} \|} \tag{6}$$

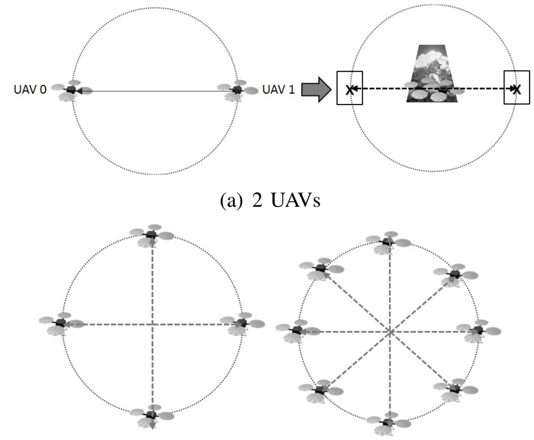
Once the UAV detects the block situation, the proposed scheme uses a torque model instead a force model. Thus, the collision will be avoided and the block situation will be solved. The torque goal is to make UAVs to rotate around the possible collision point. Thus, UAVs create a roundabout. Due to the torque model effect, the UAV turns to the right of its current flying direction. If another UAV is using the same principle for avoiding the collision, it will also turn to its right. If many UAVs identify the block situation, all of them will turn to their right. As a result, UAVs will spontaneously create a virtual roundabout in a cooperative and self-organized way.

The proposed torque model uses the idea of torque in mechanics, which is an action that makes an object to rotate around a point [19]. However, here the proposed torque model is not consistent either with the way the mechanical torque is calculated or its units. The torque model calculates the angle, that the UAV has to turn to the right. This angle is a function of the distance to the closest risky neighbor. The angle may have values between 0 and 90 degrees and is calculated using the following equation:

$$f_{torque}(x) = 90 * (1 - x) \tag{7}$$

Until now, the new direction of UAV has been determined by using either the force model or the torque model. In order to define how long the UAV is going to fly in the new direction, an avoidance coefficient is proposed. Thus, a new temporary destination for the UAV is calculated using equation 8. This coefficient is given in meters, but it does not necessarily mean that the UAV should fly this amount of meters in the new direction. The UAV flies in the new direction until the risk of a collision disappears. Then, the UAV flies to its goal destination.

The avoidance coefficient seems to be useless, since it does not play any role in defining the distance that a UAV should fly in the new direction. However, in UAVs using a waypoint controller, the avoidance coefficient indirectly controls the smoothness of UAV reactions. Waypoint controllers use PID(Proportional-Integral-Derivative) controllers for reaching the new position. Setting a new position is like setting a new set point for the PID controller. If the new set point is too different from the current state, the PID controller will increase its output as much as it can, in order to reach the new set point. In the case of the UAV, the output is the speed. The avoidance coefficient defines how different is the new position compare to the current position. Thus, the UAV flies fast with a large avoidance coefficient, flies slow with a small avoidance coefficient and hovers on the current position with an avoidance coefficient equal zero.



(a) 2 UAVs

(b) 4 UAVs (c) 8 UAVs

Fig. 4. Scenarios

TABLE I
REFERENCE VALUES

Parameter	Initial value
UAV speed	9 m/s
Communication interval	10 ms
Safety distance	10 m
Reaction distance	45 m
Avoidance coefficient	5 m
Weight	2 kg

$$\overrightarrow{new\_pos} = \overrightarrow{current\_pos} + avoid\_c * \widehat{new\_dir} \tag{8}$$

This section presented the proposed force/torque-based UAV collision avoidance scheme. The next section evaluates its the performance.

IV. Simulation and results

The force/torque-based UAV collision avoidance scheme is evaluated using the Morse simulator [20]. Morse is a 3D simulator for robotics which includes some sensors, actuators and robot models. It provides also an environment, where physical constrains such as the gravity or inertia can be taken into account.

The scheme functionality was tested in the scenarios presented in Figure 4, with 2, 4 and 8 UAVs. The UAVs were homogeneously deployed on the perimeter of a circle. Each UAV must fly exactly to the opposite side of the circle, avoiding the collision situation that may take place on the middle. Table I presents the values for the different simulation parameters. These reference values were chosen so that they meet the minimum condition for keeping a safety distance of 10 meter between any two UAVs.

With the conditions mentioned above, the impact of changing the reference parameters was studied. This study was carried out modifying one by one all parameters as table II shows. For each change, the simulation was repeated ten times and the results were averaged using a T-Student distribution with 95% of confidence interval. In this paper,

TABLE II
EVALUATION INTERVAL FOR THE DIFFERENT PARAMETERS

Parameter	Initial value	End value
UAV speed	3 m/s	15 m/s
Communication interval	10 ms	50 ms
Reaction distance	50 m	20 m/s
Avoidance coefficient	5 m	20 m

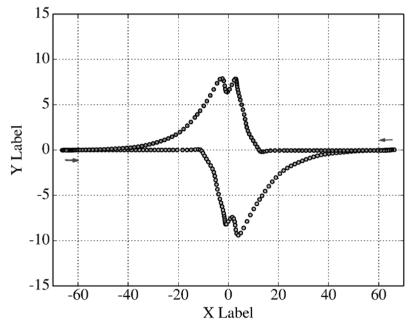
the whole experiment is resumed in four analysis. These analysis show, that the parameters with higher impact on the mission time and on the minimum distance to the closest UAV are the UAV maximum speed and the avoidance coefficient.

The first analysis focuses on the scheme functionality. The second analysis evaluates the scheme scalability and the impact of increasing the number of UAVs. The third analysis looks at the impact of changing UAVs maximum speed. Finally, the last analysis observes the impact of choosing different avoidance coefficients.

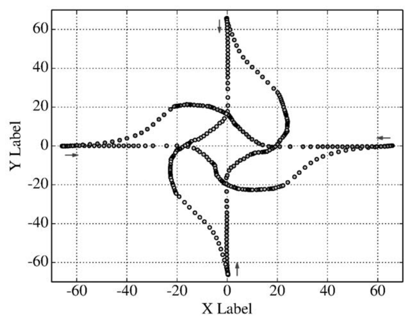
A. *Force/torque-based UAV collision avoidance scheme functionality*

This section studies the ability of the proposed scheme to avoid collisions among UAVs by constructing virtual roundabouts. Figure 5 shows the trajectories followed by UAVs when using the proposed scheme for avoiding collisions. Figure 5(a) shows the trajectories followed by 2 UAVs. The dotted lines represent the trajectory of the UAVs flying from the left to the right and vice-versa. The separation between dots shows the speed of the UAV. When the UAV flies fast, dots are more separated. Although the simulation was carried out in 3D, the force/torque-based scheme estimates trajectories in the horizontal plane. The figure 5(a) shows that each UAV turns to its right, when it realizes the collision risk and the block situation. That means that each UAV applies the torque model in order to estimate an angle between 0°and 90°. It is important to notice that, although the reaction distance is 45 meters, the trajectory change takes place when the relative distance is almost 20 meters. This effect is due to the UAV's inertia, which at the speed of 9 m/s reduces the reaction zone almost to the half. Once the block situation is avoided by the torque model, UAVs continue flying in the new direction. Thus, the collision risk decreases. When the collision risk becomes zero, the UAVs try to go to their goal destinations. The figure 5(a) shows that UAVs may enter the reaction zone of each other, when they fly to their goal destination. The UAVs change their trajectory again. This change can be seen in the middle of the trajectories and it is responsible for the "M" shape of the trajectories. Since the direction are not totally opposite, the force model and not the torque model is responsible for the new temporary destination. Both trajectories are similar, due to the symmetric placement of UAVs and same rules in the UCAM module of both UAVs.

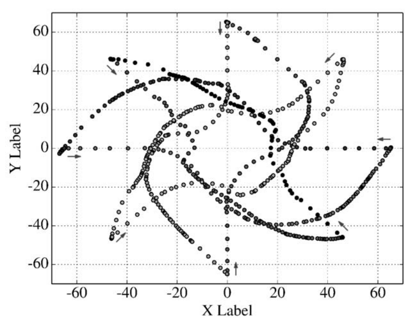
Figure 5(b) shows the scenario with 4 UAVs. It can be seen that the UAVs start reacting earlier than in Figure 5(a).



(a) 2 UAVs



(b) 4 UAVs



(c) 8 UAVs

Fig. 5. Trajectories achieved by the force/torque UAV collision avoidance scheme

The reason is that a UAVs first notice the UAVs approaching from the side, which are closer than the UAV coming from the opposite direction. The same situation can be observed in figure 5(c) with 8 UAVs. Figures 5(b) and 5(c) show better the roundabout construction, which is cooperatively achieved by the force/torque-based UAV collision avoidance scheme. Figures 5(a), (b) and (c) show that the roundabout's size depends on the number of UAVs. Since more UAVs occupy more space, the more number of UAVs, the bigger the roundabout.

A last scenario is used to test the functionality of the proposed scheme. Figure 6 shows again a scenario with 8 UAVs. 4 UAVs are initially localed at the positions A,C,E and G, which are the corners of a square. The other 4 UAVs are deployed with initial positions B,D,F and H. Notice that the UAVs at positions A,C,E and G are farer from the center

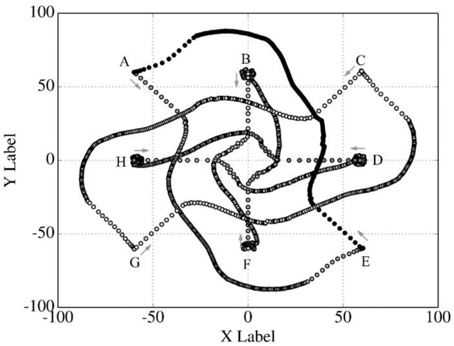


Fig. 6. Double roundabout achieved by the force/torque UAV collision avoidance scheme. Distances in meters

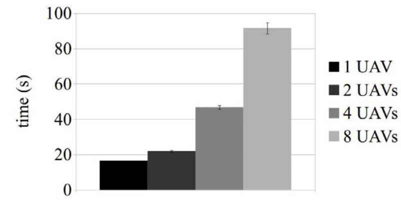
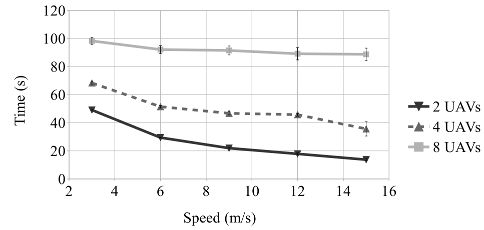
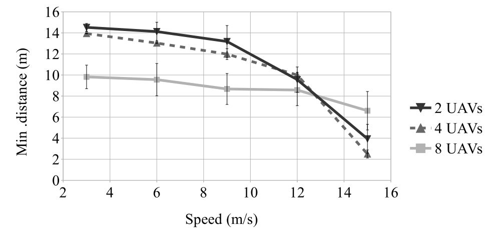


Fig. 7. Impact of the number of UAVs on the average mission time



(a) Average mission time



(b) Min. distance among UAVs

Fig. 8. Impact of different UAV maximum speeds on mission time and minimum distance in a scenario with 2, 4 and 8 UAVs.

than the UAVs at positions B,D,F and H. Again, all 8 UAVs should fly to the opposite side. For example, UAV at position A should fly to position E, UAV at position B should fly to position F, and so on.

In Figure 6, two roundabouts can be observed. The first one is a small roundabout made by UAVs starting at positions B, D, F and H. These UAVs are closer to the center and detect the collision risk earlier than the UAVs with initial positions at A,C,E and G. Then, they start doing the roundabout first. UAVs with start positions A,C,E and G arrive later. They have to avoid not only each other, but the UAVs in the small roundabout as well. Therefore, UAVs with start positions A,C,E and G make the second roundabout. Notice that UAV coming from position A flies almost parallel to the UAV flying from B to F. When the UAV coming from B reaches F, the UAV coming A surrounds position F and then it flies towards position E. Meanwhile, the UAV at position F moves around its goal position, in order to keep the minimum distance to the UAV coming from A. Each UAV in Figure 6 requires 128.42 seconds in average for traveling from the starting position to their goal position. Additionally, the shortest distance between 2 UAVs was 12,65 meters. This scenario shows that the force/torque UAV collision scheme is able to avoid collisions also in complex situations, e.g. when UAVs are surrounded by others UAVs.

B. Scalability and mission time

Concerning scalability, Figure 7 presents the required amount of time for completing a mission, when there are 1, 2, 4 and 8 UAVs approaching each others. The time needed by one UAV represents the ideal case, when there is no collision risk and the UAV can fly direct to the goal. The figure shows that when it gets crowded, the required time for completing the mission increases.

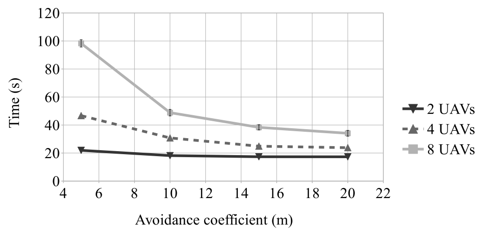
C. Impact of UAV speed

Due to inertia, speed of the UAVs is one of the most influential factors, when a UAV needs to change the trajectory. Therefore, the proposed scheme is evaluated with UAVs flying at different speeds. Figures 8 present the results for the scenarios with 2, 4 and 8 UAVs. In this case, the maximum speed was changed from 3 up to 15 m/s and the mission time and the minimum distance to the closest risky neighbor were measured.

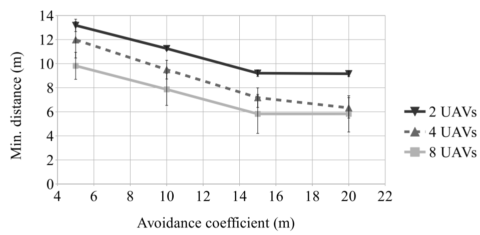
Figure 8(a) shows the average time for the UAVs to reach the target destination for each considered speed. The black line, gray line and dash line in the Figure 8(a) corresponds to the scenario with 2, 4 and 8 UAVs respectively. In the Figure 8(a) it is possible to see that the higher speed of a UAV, the shorter the mission time. On the other side, 8(b) shows that with higher speed the minimum distance among UAVs becomes smaller. Both results were expected. However, Figure 8(a) and (b) show that, the higher the number of UAVs, the less sensitive the system is to UAVs maximum speed. The gradient of the 8 UAVs line in 8(b) is smaller than the other two lines. As result, the minimum distance among UAVs is larger with 8 UAVs than with 4 or 2 UAVs at the speed of 15 m/s. This is because the more UAVs are in the vicinity, the greater is probability, that the UAV has to change the direction. This velocity change leads to a lower average velocity for each UAV.

D. Avoidance coefficient

The “avoidance coefficient” is the proposed way to simply control a UAV’s reaction when using a waypoint controller. In this paper the impact of this parameter is evaluated in the reference scenario (Table I) with 2, 4 and 8 UAVs. The value of the “avoidance coefficient” is increased from 5m



(a) Mission time



(b) Min. distance

Fig. 9. Impact of different avoidance coefficient values on mission time and minimum distance. Scenario with 2, 4 and 8 UAVs.

to 20m. Figure 9 shows that this parameter significantly affects the mission time. A small avoidance coefficient causes that a UAV to react slower and smooth during the collision avoidance period. Since the waypoint controller uses a PID controller, setting a small avoidance coefficient value is like setting a close destination, which makes the UAV to slow down. If all the temporary destination points are close, the UAV will not reach the maximum speed that it can fly at.

V. Conclusions

In this paper a distributed force/torque UAV collision avoidance scheme was presented and evaluated by simulation. The scheme was evaluated with 2, 4 and 8 in Morse simulator. We showed that UAVs using the proposed scheme are able to avoid collisions by cooperatively implementing roundabouts. The size of the roundabout emerges according to the number of UAVs that want to cross over the intersection. Simulation results show that the scheme is scalable. However, the more UAVs are involved, the more time it takes to avoid the collision and reach the target position for all of them.

The simulation also showed the impact of speed increase. Due to inertia's effect, the higher the speed, the more distance is needed for UAVs to react. Therefore, it is more difficult for UAVs to keep the minimum safety distance among them, when the speed increases. However, the more number of UAVs, the less the impact of UAVs maximum speed. The last simulation results showed also a significant impact of the avoidance coefficient on the mission time and minimum distance among UAVs. For the future work, the size of the reaction zone needs to change dynamically according to UAV speed. The avoidance coefficient should be modified on the flight, in order to optimize the mission time. A dynamical setting of these parameters will allow the proposed scheme to keep the minimum safety distance to other UAVs, regardless of UAVs maximum speed. It also will reduce the mission time for all UAVs.

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