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Safety Bubble Control for Coordination of Multiple Unmanned Aircraft Systems

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Abstract: A unified collision avoidance control and coordination model for multiple unmanned aircraft systems (UAS) operating in close proximity is proposed. The collision avoidance behavior is based on the elastic collision of gas particles. A safety bubble around each agent is created by means of a sensor fusion architecture, enabling the Sense-and-Avoid (SAA) behavior of the collision avoidance control. The dimension of the safety bubble changes dynamically based on a quantified collision risk which is calculated based on the capabilities of the UAS and the number of neighboring agents. The weather conditions of the environment or airway, as well as the mitigation of third party casualties are also considered. The ultimate goal is to ensure the safety of operations performed by coordinated and uncoordinated UAS, as these systems become more popular in the National Airspace System (NAS).

Keywords: Unmanned aircraft systems, sense and avoid, centralized control, decentralized control.

1. INTRODUCTION

The commercial application of Unmanned Aircraft Systems (UAS) is rapidly increasing worldwide. Since the United States Federal Aviation Administration (FAA) implemented the Part 107 legislation (Dorr, L. and Duquette, A. (2016)), UAS have gone beyond the research and hobby oriented perspectives. UAS can now be seen performing precision agriculture tasks, parcel deliveries, infrastructure inspection applications, among others. Unfortunately, there is still a gap into how to determine the coordination and the level of safety of multiple UAS working in close proximity through the National Airspace System (NAS). This scenario is indeed challenging since UAS could belong to different companies or institutions, with unrelated functions, and non-standarized Sense and Avoid (SAA) capabilities. Furthermore, it is unrealistic to expect UAS to operate in a coordinated flocking behavior, since different teams could have different directives and different operational protocols, as dictated by their owner, company, or institution. For this reason it is impossible to expect a standard communication channel among these individual systems or between different coordinated teams. From these facts, the collision avoidance skills of the UAS platforms will depend entirely on their inherited SAA capabilities. Unfortunately, a self-contained SAA mechanism capable of fully mitigating midair collisions is still not available. This issue is risky in an additional way since after crashing, a UAS most likely will become a free-falling projectile, which in turn, can end up injuring bystanders or damaging property.

The research presented in this paper aims at a reliable SAA strategy for multiple UAS operating inside a virtual airway cell. Our approach is inspired by, and makes use of the dynamic behavior of a gas particle bouncing away from other particles or fromt he boundaries of a closed system. The proposed bouncing mechanism is assumed to operate on UAS with omnidirectional motion capabilities. The implementation of the proposed model on UAS with different motion characteristic, e.g., fixed-wings, is out of the current research scope. Our work proposes a UAS-to-UAS safety distance model, which makes use of range sensors and acts as an *elastic bubble* around the UAS. The UAS safety bubble contracts and expands according to the airway conditions, e.g., wind speed, while at the same time it incorporates specific manufacturer safety distance recommendations as an extra layer of security. In order to mitigate critical UAS operation errors i.e., collisions, an error safety distance equation is defined. The model is also the basis for a UAS risk mitigation equation inspired also by the mechanical behavior of gas particles. The equation identifies *degrees of risk* according to different airway volume configurations. The risk parameters driving the risk mitigation equation are: (i) UAS safety distance error due to wind conditions, (ii) impact of the number of UAS contained in the airway, and (iii) maximum system failure rates per flight hour to mitigate third party casualty risk. Ultimately, our work advances knowledge towards the implementation of a safe Beyond Visual Line-of-Sight (BVLOS) coordinated UAS airway, among other closely related UAS applications.

This document is organized as follows. Section 2 describes the problem addressed here. Next, Section 3 presents our

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main result, a unified UAS SAA decentralized control strategy, complemented with a centralized control for coordination of multiple agents. In Section 4 numerical results are provided to validate the proposed system is dynamic and safe. Finally, Section 5 provides some conclusions and ideas for future work.

2. PROBLEM STATEMENT

Consider a group of UAS navigating inside a virtual airway or flight corridor, see Figure 1. The UASs could be individual agents, or coordinated teams working cooperatively to accomplish a specific task. It is considered that each UAS is equipped with a combination of range sensors, which enables a sensing bubble around it. The dimensions of the flight corridor could be dictated, for example, by means of FAA restrictions on UAS operational conditions.

The main objective consists on implementing a control strategy to coordinate multiple UASs into keeping a safe distance from each other while navigating autonomously within the flight corridor, and ultimately within the NAS. The proposed methodology must meet UAS safe distance considerations, velocity of the agents, number of agents inside the flight corridor, as well as environmental conditions. Ultimately, a novel safe Unmanned Traffic Management (UTM) network will be developed to accomplish these goals.

2.1 Control Objectives and Concept of Operation

The proposed UTM formulates the interaction of multiple UASs by means of virtual elastic collisions emulating a gas particle-like behavior, in which an immediate repulsion exist upon contact. In fact, the collision occurs between the sensing systems surrounding each UAS, defined as the UAS Sense and Avoid Safety Bubble (UAS-SSB). The control strategy relies on how each agent senses UAS-SSBs, and how these expand or contract according to critical safety conditions.The model has been adapted to emulate or mimic UAS with omnidirectional motion capabilities such as multicopter drones. Future work based on results will address UAS with different dynamics.

An additional control process involves the enhancement of the environment in which the agents interact with each other. The UTM is divided into multiple UAS Coordinated Airway (UAS-CA) cells, each one with specific boundaries and safety rules for navigation. By counting the number of UASs leaving and entering a UAS-CA cell, it is possible to control the number of UASs permitted inside its limits.

The Concept of Operation shown in Figure 1 exemplifies the proposed UTM system. The safety inside the cell relies on how the UAS-CA perceives the conditions that can cause a collision. As the risk of collision increases, the UAS-SSBs should cover a wider volume of detection. The ultimate goal is to develop reliable control mechanisms to maintain a safety distance among agents (Rangel, P. (2017)).

Rather than comparing the proposed model with other swarm-based collision avoidance models for UASs, the research proposed in this paper focuses on the implementation of a multisensor detection technique capable of allowing a proper avoidance routine. The detection capabilities, which enables an adaptive sensing range, is considered as the foundation of the UAS-SSB system. For that purpose, safe distance detection among vehicles were studied and used as a reference to develop the proposed model. Examples of models that inspire the implementation of the UAS-SSB are found in (Qu, D. et al. (2014)), (Yanmaz, E. et al. (2013)), (Chiaramonte, R. B. et al. (2013)), (Bouachir, O. et al. (2014)), and (Ramasamy, S. et al. (2016)) and the references therein.

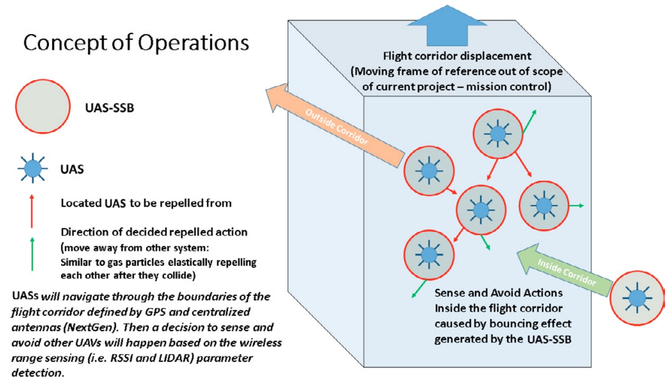

Fig. 1. A UAS Coordinated Airway cell, containing multiple UASs. Each agent is enhanced with a UAS Sense and Avoid Safety Bubble which is modeled based on gas particle behavior during head-on elastic collisions.

3. MAIN RESULT: CONTROL MODELS FOR SAFETY DISTANCE E AND RISK FACTOR RF

The proposed anti-collision and coordination system relies on the combination of *centralized* and *decentralized* behaviors, aiming at overcoming the limitations encountered under each approach. Specifically, we propose a method where the robot itself has a self-contained intelligence and autonomy (decentralized approach), which is further enhanced by an intelligent and automated environment (centralized approach).

The main result consists on the development of a mathematical model for combining all the identified risks in order to define an maintain a safe distance between UASs, with an additional consideration of mitigating third party injuries. The multi-agent system (MAS) interaction model is inspired by the results in (Wilensky, U. and Resnick, M. (1999)) and (Tisue, S. and Wilensky, U. (1999)), where each agent is represented as a gas particle, and the analysis of interactions among agents make use of the Maxwell-Boltzmann distribution.

3.1 The risk factor model RF.

As stated previously, each UAS-SSB must emulate the dynamic behavior of gas particles in order for the repulsion/distance control to happen. Towards this goal, consider the following ideal gas law equation

$$P = \frac{nRT}{V} \tag{1}$$

where n represents the number of particles, V is the volume, T is the temperature, and R is the ideal gas constant. The parameters in equation (1) can be mapped into a risk mitigation equation involving UASs as follows

$$RF = \frac{n_U F_{TLS} E}{V_A} \quad (2)$$

where the particles n subjected to temperature and pressure are mapped into the number of UASs n_U. The volume V is mapped into the UAS airway volume V_A. The temperature T is mapped into the error in UAS safety distance planning E, which varies according to changing wind speed conditions and manufacturer recommendations. The ideal gas constant R is mapped into the new equation as F_{TLS} using the possible number of causalities in the ground and safety considerations values calculated in (Melnyk, R. et al. (2014)) and (Melnyk, R. (2013)). Specifically, this value describes the impact, due to weight and penetration, that can be inflicted by falling drones into diverse population densities. Finally, the pressure P is mapped as the risk value RF of a potential damage in a UAS collision. We can think of RF as a measure of how much pressure is being exerted inside a UAS-CA. Ultimately, such pressure affects also the safe distance among UASs inside the cell. Equation (2) is a risk mitigation model that specifies a inversely proportional relationship between risk of a collision and safe operation distance between multiagents. Specifically, it computes a relationship in which the parameters n_U, F_{TLS}, and E are used to adaptively control the size of the safety bubble. Therefore. when the safe distance among UAS increases, then the risk for collision will decrease, and vice versa.

3.2 The safety distance model E.

The safety distance value should be constantly updated by the UAS-CA and transmitted to the UAS-SSB. This parameter will be regulated by the UAS-CA system observations in terms of changing airway conditions such as number of drones entering the cell, current wind speed conditions within the cell boundaries, as well as the span (diameter) of the UASs, and the UAS manufacturer recommendations for maintaining a safe flight.

The safety distance E is composed by two terms: D_o representing the minimum required diameter of a safety bubble, i.e., the length of a UAS, and D_s which is recommended by the manufacturer of the UAS as a safety factor mainly based on wind conditions

$$E = \left(1 + k_w \frac{W_{\text{airwayspeed}}}{U_s}\right) D_o + D_s \quad (3)$$

where $W_{\text{airwayspeed}}$ is the dynamic wind speed value of the airway. This model allows increasing the number UAS operating in an airway by appropriately calculating the safety distance required among agents, and ultimately reducing the risk of collision impacts.

E can be improved using the number of UAS in a UAS-CA cell since for higher number the risk of collision should increase, and vice versa. The same can be assumed by the apparition of sudden high speed wind gusts that put at risk the safe operation of UAS.

3.3 UAS-SSB Sensor Fusion Implementation

The proposed sensor fusion architecture for the UAS-SSB involves the interconnection of multiple sensors, each one with a specific capability, sensitivity, and sensing range. The combination of multiple sensors, which could be for example ultrasonic, radio frequency, and optical range finders, is expected to create a multi-sensing layer around the UAS. Since each sensor will have different limitations, each layer within the UAS-SSB must be accommodated based on the sensor reaction time and the sensing priority.

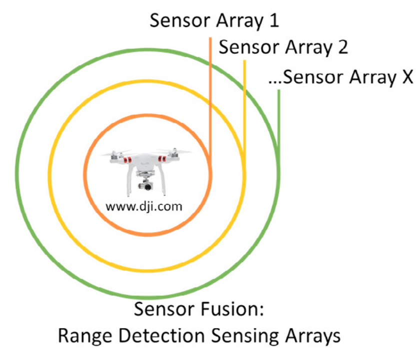

Fig. 2. UAS-SSB Sensor Fusion Layers.

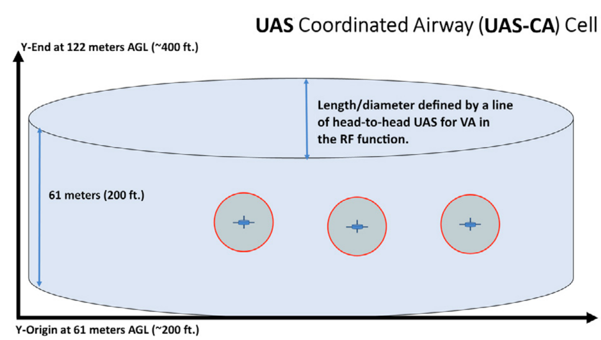

Fig. 3. Individual UAS-CA Boundary Conditions.

Figure 2 shows the proposed safety bubble for UAS, based on the multi-sensing layer approach. With this functionality, each UAS would be able to sense different levels of proximity from nearby UASs, and will be able to react accordingly. The number of sensor layers, their priority, coordination, and sensitivity need to be defined through experimentation. The power consumption and mission capabilities of the aircraft should also be considered.

3.4 UAS-CA and UAS-SSB Coordination

The detection of UAS inside the UAS-CA cell could be enabled by means of well known technologies such as Global Positioning System (GPS) and Automatic Dependent Surveillance Broadcast (ADSB) transponders. Then, it is possible to define individual cells using the FAA recommendations for aircraft navigation through the NAS. Figure 3 summarizes the FAA safety considerations based on *Part 107* legislation adopted for defining individual cells. Figure 4 shows a 2 dimensional perspective of multiple UAS enabled with the UAS-SSB and UAS-CA cell information for safely interacting with each other.

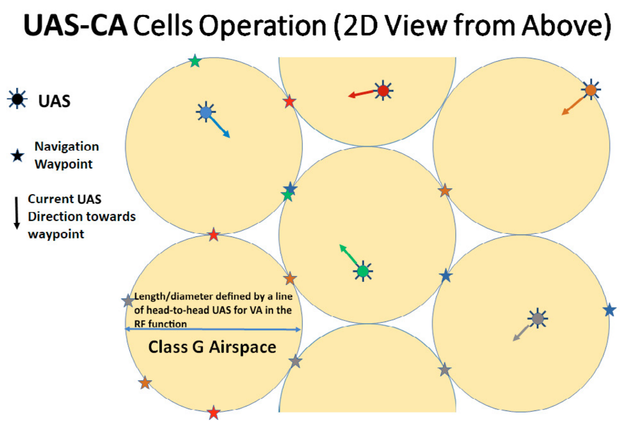

Fig. 4. UAS-CA Cluster planar (upper) view: a 2 dimensional perspective of multiple UAS making use of the UAS-CA cells for interacting with each other.

4. ANALYSIS AND COMPARISON OF THE R AND E EQUATIONS VARIABLE IMPACT

The interaction between the UAS-CA and the UAS-SSBs were adapted to a MAS control strategy. Each UAS-SSB is defined as an agent with programmed behaviors that ensure its safe navigation through the environment controlled by the UAS-CA. The behavior of the agents within the airway cell is described by similar behaviors to the gas particles behaviors in a box (Wilensky, U. (1999)). The GasLab Circular Particles MAS NetLogo simulation program (Wilensky, U. (2005)) was adopted and modified with the purpose of evaluating the implementation of the safety distance model.

The modified NetLogo model considers the particles as UAS-SSBs. Parameters such as airway size, initial UAS speed and wind speed are defined by the user. The E value is automatically calculated and transmitted to each UAS-SSB. The boundaries of the UAS-CA cell are assumed to be a geofence and the agents will bounce away from it. Also, the UAS-SSBs will bounce away from each if they collide. The simulation calculates the time in which the boundary of a UAS-SSB senses the edge of another UAS-SSB or the UAS-CA borders. If no collision is detected, the UAS continues with its current speed and direction. The exchange of kinetic energy between agents is inspired from the particles interactions as shown in (Wilensky, U. (2005)). All UAS-SSBs in the model are assumed to have the same mass for them to be elastic.

Our study consists on simulating equation (2) and equation (3) in NetLogo for evaluating the safety properties accomplished. We keep the gas particle behaviors intact in order to validate the UAS-particle analogy approach. The new rules in equation (2) and equation (3) were added to each agent in order to observe the impact of their microlevel behavior into the overall environment (macrolevel perspective). Detailed information for simulating the E model is shown in Table 1.

A squared 2-dimensional UAS-CA cell was selected for this study, chosen accordingly to heuristic UAS length/diameter specifications. The running time is defined in ticks, which are analogous to seconds in the main model, and pixels are used for describing dimensions. With this information,

Table 1. NetLogo Multiagent Simulation Parameters for the safety and dynamic analysis of the E model

NetLogo Multiagent Simulation Defined Parameters for the E model			
Key	Magnitude	Unit	Description
UAS Manufacturer Parameters			
Patch unit (pu)	4.6535	pixels	Pixel magnitude measurement for each patch unit (pu)
Do	2	pu	Maximum diameter of UAS-SSB (UAS max wheelbase)
Ds	5	pu	Manufacturer recommended safety distance
Us	10	pu/ticks	Top speed limit that can be achieved by UAS-SSB
Ws	8	pu/ticks	Max wind speed resistance capacity of UAS-SSB
Time Parameters			
ts	0.5	ticks	Intruder UAS-SSB minimum distance detection recommended time
ta	0.4	ticks	UAS-SSB reaction minimum displacement recommended time
tr	0.9	ticks	UAS-SSB total SAA reaction recommended time
Equation 4.23 (E) Parameters			
Eideal	9	pu	The ideal recommended SAA safety distance
kw	4.375	unit less	kw gain for the UAS-SSB
Elimit	14	pu	Overall consideration E value for maximum "at least" sensor range

Table 2. NetLogo Multiagent Simulation Parameters for the Safety and Dynamic analysis of the R Model and UAS-CA Capacities

NetLogo Multiagent Simulation Defined Parameters for the RF MODEL			
Key	Magnitude	Unit	Description
Equation 2 (RF) and UAS-CA Parameters			
Nmax	5	turtles	Maximum recommended UAS-SSB Capacity
n	1 to 6	turtles	Range of UAS-SSBs utilized in the simulation
dr	15	unit less	Distance relationships for plot section and collision analysis
FTLS	Table 4.8		Normalized Maximum System Failure Rates to meet ground TLS
E_2D_limit	153.94	pu^2	Circular UAS-SSB area dimension limit for Square UAS-CA airway
LA	84	pu	Airway side length required for Square UAS-CA
VA	7056.00	pu^2	Square UAS-CA area dimension
Circle Packing	0.91	%	Circle packing Coefficient for 2-D UAS-CA
Measured Elimit UAS-CA Capacity	45.84	turtles	VA/E_2D_limit UAS-CA Cell UAS-SSB Measured Capacity
Real Elimit UAS-CA Capacity	41.57	turtles	VA/E_2D_limit UAS-CA Cell UAS-SSB Circle Packing Consideration Capacity

Table 3. Evaluation Plan for equation (2) and equation (3)

Testing plan to Analyze the Dynamic and Safe Operation of Equation (2) and Equation (3) Parameters					
SAFETY / CHAOS	No UAS-SSB E=Do		Fixed UAS-SSB E=Ds		Variable UAS-SSB E=Elimit
No Turbulence	Test A1	Test D1	Test A2	Test D2	Test A3
Small Turbulence	Test B1		Test B2		Test B3
Large Turbulence	Test C1		Test C2		Test C3

a value for V_A could be calculated in order to be added into equation (2). Sphere packing geometrical calculations were done in order to understand how many agents can be fitted inside the bounded airway. Results from those calculations are given in Table 2.

NetLogo has a built-in function that allows to ask each agent what is their distance with respect to another agent, which assisted with the identification of possible collisions happening between UASs. In order to validate the accuracy of the measurements provided by NetLogo, two UAS-SSBs where situated next to each other with a opposite initial headings. They were programmed to separate away from each other, and then to bounce back from the borders of the UAS-CA until colliding with each other, and then repeating this behavior. The relative distance between agents was measured during 1000 ticks. A distance plot demonstrated harmonic motion with a minimum error, validating the capacity of NetLogo to generate reliable data to evaluate the E and R models. Figure 5 shows the results from the simulation.

Next, a test plan was proposed in order to analyze the impact of the E and R models in the simulated UAS-SSB and UAS-CA subsystems, see Table (3). The simulation considers a closed cell with a fixed number of agents inside of it. The goal is to observe if the increment of the E value

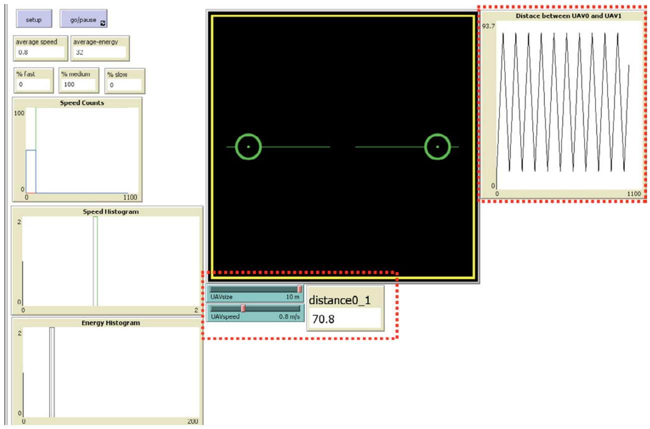

Fig. 5. Simulation of two UAS-SSB performing repetitive collisions. $E = 10$ pu, $U_s = 0.8$ pu/ticks.

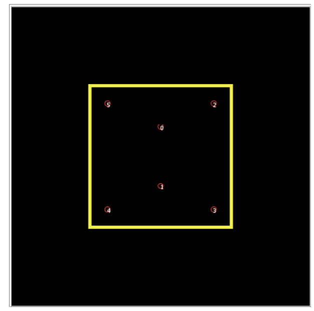

Fig. 6. Table 3, Test D1.

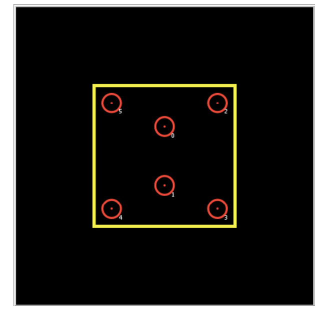

Fig. 7. Table 3, Test D2.

ensures that not actual collision happens in an ideal UAS-SSB operation. The following definitions are introduced:

Definition 1.- A collision is said to exist when the detected distance between agents is equal or less than $0.5{*}D_o$, where D_o is the length of a UAS with no safety bubble. Then, the following statement is given: *if distance* $UAS_{nm} \leq 0.5{*}D_o$, *then a collision occurred.*

Definition 2.- A "high-risk of collision" situation is said to exist when the distance between two UASs is between the lengths D_o and D_s, where D_s is the minimum safety distance recommendation given by the manufacturer. This situation is very close to become a collision due to sudden wind gusts among other nuances such as unexpected agents in the airway.

Definition 3.- A "medium-risk of collision" situation is said to exist when the distance between two UASs is between D_s and the recommended UAS-SSB E_{limit} range. This area depends on the ideal and proper operation of the UAS-SSB to keep UASs at a safe distance from each other.

In order to simulate every scenario in Table 3 the following four dynamic parameters where modified: size of the airway, W_s, U_s, and the inclusion of a turbulence or a perturbation function. Three values of D_s (0, 5 and 10) were also tested. The size or length of the agents were also changed during the simulation.

Figure 6 and Figure 7 are illustrate the setup for scenarios D1 and D2 from Table 3. The objective of these tests was to verify that the proposed safety bubble model emulates the gas particles behavior when the particles are being compressed in smaller containers.

Every test described in Table 3 was performed and evaluated. From all 15 possible combinations of distances between agents, 15000 values were extracted and evaluated. A snapshot from Test A1 is shown in Figure 8, where six agents can be seen interacting with each other and maintaining safety distances. The results from this scenario are illustrated in Figure 9 as a histogram. The histogram has bars with different colors, where each color illustrates a different risk of collision. Distance values below D_o are identified as collisions and are plotted in red color. Distances between high-risk areas are associated with black bars (not seen in this specific scenario). Distances within

Fig. 8. A snapshot of Test A1, showing 6 agents interacting with each other and maintaining safety distances.

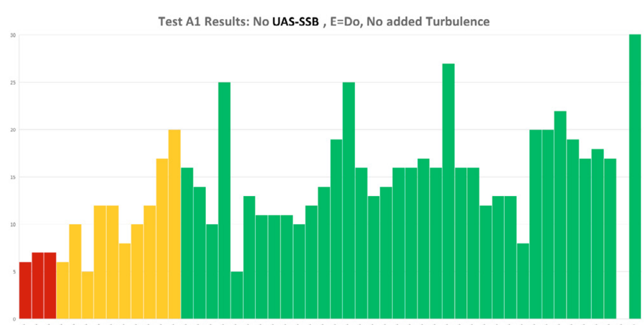

Fig. 9. Histogram showing relative distances for Test A1.

the E_{limit} range are colored yellow for medium-risk areas. The other bars were colored green signifying minimum-risk or no-risk areas.

The histogram shows a reduced amount of activity in the high-risk areas, the medium-risk area shows moderated activity, and the low-risk area exhibits the higher activity.

4.1 Observations and conclusions from additional tests

The outcomes from test A3 demonstrated that the system can successfully operate under ideal conditions as long as the UAS-SSB keeps expanding and contracting according to the proposed model, which ensures a reduction of a risk of collisions among the UAS. The outcomes from test D1 and D2 shown that the agents maintained a safe operation with no evidence of collisions even when the safety bubble size increases within the UAS-CA. Therefore, as long as the UAS-SSB receives feedback from the UAS-CA, the agent will navigate safely. Tests B1, B2, B3, C1,C2 and C3 exhibited collisions as expected, due to the disturbances affecting the system. The number of black bars in the histograms increased as the turbulence intensity increased. In these scenarios, the safety bubble is expected to increase the chances of survival of the UAS but on the other hand, there will be a higher risk of collision.

From these results, it can be concluded that, by implementing equation (2) and equation (3), we can considerably enhance the safety of multiple UASs operating in a flight corridor airway. Furthermore, it is worth mentioning that, if the area of the UAS-CA is appropriate for navigation purposes, the risk of collisions is considerably reduced. Therefore, designing the airway dimensions according to the characteristics of the UASs inside it, and the geometric recommendations by the equation (2) parameters, we can considerably enhance the safety of the navigation area.

5. CONCLUSIONS AND FUTURE WORK

The development of safety distance and risk factor models are the key components of this novel approach, which aims towards a unified collision avoidance and coordination model for multiple UAS operating in close proximity. The proposed method formulates the interaction of multiple agents by means of virtual elastic collisions emulating a gas particle-like behavior, in which an immediate repulsion exist upon contact. The performance of the proposed system was analyzed under different synthetic scenarios in NetLogo. Further experimentation beyond simulations will serve to prove that the proposed method can quantify collision avoidance performance. Experimental results can also help for identifying new risk mitigation capabilities within the system when collision does occur. A number of variables essential into allowing a UAS to operate within the NAS were also considered in these tests, for example, number of agents in the airway cell, weather conditions of the airway, and risk of causalities on the ground due to falling UAS. Ultimately, the implementation of a safety bubble for UAS (decentralized control approach) in combination with a coordinated airway cell (centralized control approach) has shown promising results towards the development of a novel UTM where UAS can safely navigate with minimum risk of collisions.

Future work will consider the implementation of the UAS-SSB model in a real-time experiment. The first task will consider adding the safety bubble into ground mobile robots, in order to later update into UAS platforms (Ortega. G, et al. (2015)). The UAS-CA will then be enabled by means of a Motion Capture System or a GPS to further improve the results (Munoz Palacios, F. et al. (2017)). Specifically, the UAS-CA will be enhanced with the capability of denying access and rerouting agents once critical conditions are encounter within the cell. We will also evaluate the performance of UAS with higher maneuverability and advanced sensing devices in order to enhance the UAS-SSB (Munoz Palacios, F. et al. (2015)), and therefore improve the rate of survival of the agents

REFERENCES

Dorr, L. and Duquette, A. (2016). Federal Aviation Administration, Part 107. Fact Sheet Small Unmanned Aircraft Regulations (Part 107), pp. 1–3

Rangel, P. (2017). Safety Airway for Small Aerial Vehicles Using a Gas Particles Behavior Analogy. Doctoral Dissertation. The University of Texas at El Paso, ProQuest, 2017.

Qu, D. Chen, X. Yang, W. and Bian, X. (2014). Modeling of car-following required safe distance based on molecular dynamics. Math. Probl. Eng., vol. 2014, 2014.

Yanmaz, E. Kuschnig, R. and Bettstetter, C. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. Proc. - IEEE INFOCOM, pp. 120124, 2013.

Chiaramonte, R. B. Regina, K. and Jaquie, L. (2013). Collision Detection Using Received Signal Strength in FANETs. pp. 12741283, 2014.

Bouachir, O. Abrassart, A. Garcia, F. and Larrieu, N. (2014). A mobility model for UAV ad hoc network. Unmanned Aircr. Syst. (ICUAS), 2014 Int. Conf., pp. 383388, 2014.

Ramasamy, S. Sabatini, R. Gardi, A. and Liu, J. (2016). LIDAR obstacle warning and avoidance system for unmanned aerial vehicle sense-and-avoid. Aerosp. Sci. Technol., vol. 55, pp. 344358, 2016.

Melnyk, R., Schrage, D, Volovoi, V., and Jimenez, H. (2014). A third-party casualty risk model for unmanned aircraft system operations Reliab. Eng. Syst. Saf., vol. 124, pp. 105116, 2014.

Melnyk, R. (2013). A Framework for Analyzing Unmanned Aircraft System Integration Into the National Airspace System Using A Target Level of Safety Approach. Aerosp. Eng., vol. PhD, no. May, 2013.

Wilensky, U. and Resnick, M. (1999). Thinking in Levels : A Dynamic Systems Approach to Making Sense of the World. J. Sci. Educ. Technol., vol. 8, no. 1, pp. 319, 1999.

Tisue, S. and Wilensky, U. (1999). NetLogo: Design and implementation of a multi-agent modeling environment

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/ Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. 1999.

Wilensky, U. (2005). NetLogo GasLab Circular Particles model. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. 2005.

Ortega, G., Munoz, F., Espinoza Quezada, E., Garcia Carrillo, L.R., and Ordaz, P. (2015). Implementation of leader-follower linear consensus algorithm for coordination of multiple aircrafts. 2015 Workshop on Research, Education and Development of Unmanned Aerial Systems (RED-UAS), Cancun, 2015, pp. 25-32.

Munoz Palacios, F., Espinoza Quezada, E., Sanahuja, G., Salazar, S. Garcia, Octavio, and Garcia Carrillo, L.R. (2017). Test bed for applications of heterogeneous unmanned vehicles. International Journal of Advanced Robotic Systems, vol. 14. issue 1.

Munoz Palacios, F., Espinoza Quezada, E., Gonzalez, I., Garcia Carrillo, L.R., Salazar, S. and Lozano, R. (2015). A UAS obstacle avoidance strategy based on spiral trajectory tracking. 2015 International Conference on Unmanned Aircraft Systems (ICUAS), Denver, CO, 2015, pp. 593-600.