Safety Bubble Control for Coordination of Multiple Unmanned Aircraft Systems

安全气泡控制多无人机系统协同

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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).

摘要: 本文提出了一个针对近距离操作的多无人机系统 (UAS) 的统一碰撞避免控制和协同模型。碰撞避免行为基于气体粒子的弹性碰撞。通过传感器融合架构在每个代理周围创建一个安全气泡，使得碰撞避免控制具有感知与避障 (SAA) 行为。安全气泡的尺寸根据基于 UAS 能力和邻近代理数量的量化碰撞风险动态变化。同时考虑环境或空域的天气条件以及减轻第三方伤亡的问题。最终目标是确保协调和非协调 UAS 执行的操作安全，因为这些系统在国家空域系统 (NAS) 中变得越来越受欢迎。

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

关键词: 无人机系统，感知与避障，集中控制，分散控制。

1. INTRODUCTION

1. 引言

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.

无人航空系统 (UAS) 的商业应用在全球范围内迅速增长。自从美国联邦航空管理局 (FAA) 实施了第 107 部分立法 (Dorr, L. 和 Duquette, A. (2016)) 以来，UAS 已经超越了研究和爱好者导向的视角。现在可以看到 UAS 执行精准农业任务、包裹递送、基础设施检查应用等。遗憾的是，目前仍存在一个空白，即如何确定在国家级空域系统 (NAS) 中近距离工作的多个 UAS 之间的协调和安全性等级。这种情况确实具有挑战性，因为 UAS 可能属于不同的公司或机构，具有不相关的功能和非标准化的感知与避让 (SAA) 能力。此外，期望 UAS 以协调的群聚行为运行是不现实的，因为不同的团队可能会有不同的指

令和不同的操作协议，这由它们的所有者、公司或机构决定。因此，不可能期望这些独立系统之间或不同协调团队之间存在标准的通信渠道。基于这些事实，UAS 平台的碰撞避免技能将完全取决于它们固有的 SAA 能力。遗憾的是，一种能够完全缓解空中碰撞的独立 SAA 机制仍然不可用。这个问题在另一种方式上也是危险的，因为 UAS 在坠毁后很可能会变成自由下落的抛射物，反过来，可能会伤害旁观者或损坏财产。

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.

本文提出的研究旨在为多个无人机系统 (UAS) 在虚拟航路细胞内运行制定一种可靠的 SAA 策略。我们的方法受到气体粒子从其他粒子或封闭系统边界弹开的动态行为的启发，并利用了这种行为。所提出的反弹机制假定适用于具有全方位运动能力的 UAS。将所提出模型实施到具有不同运动特性的 UAS 上，例如固定翼无人机，不在当前研究范围内。我们的工作提出了一个 UAS 至 UAS 安全距离模型，该模型利用范围传感器并在 UAS 周围形成一个弹性气泡。UAS 安全气泡根据航路条件，例如风速，收缩和扩张，同时它还纳入了特定制造商的安全距离建议，作为额外的安全层。为了减轻关键的 UAS 操作错误，即碰撞，定义了一个错误安全距离方程。该模型也是基于 UAS 风险缓解方程的基础，后者同样受到气体粒子机械行为的启发。该方程根据不同的航路体积配置确定风险程度。驱动风险缓解方程的风险参数包括:(i) 由于风速条件导致的 UAS 安全距离误差，(ii) 航路中包含的 UAS 数量的影响，以及 (iii) 为减轻第三方伤亡风险而设定的每飞行小时最大系统故障率。最终，我们的工作为实施安全的超视距 (BVLOS) 协调 UAS 航路等与其他密切相关的 UAS 应用推进了知识。

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

本文档的组织结构如下。第 2 节描述了本文解决的问题。接下来，第 3 节介绍了我们的主要成果，一种统一的 UAS SAA 分布式控制策略，辅以集中控制以协调多个代理。在第 4 节中，提供了数值结果以验证所提出系统的动态性和安全性。最后，第 5 节提供了一些结论和对未来工作的想法。

2. PROBLEM STATEMENT

2. 问题陈述

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

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restrictions on UAS operational conditions.

考虑一组在虚拟航路或飞行走廊内导航的无人机系统 (UAS)，见图 1。UAS 可以是单独的代理，或者是协调的团队，合作完成特定任务。假定每个 UAS 配备了距离传感器的组合，使其周围形成一个感知气泡。飞行走廊的尺寸可能由例如 FAA 对 UAS 操作条件的限制来规定。

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.

主要目标是在飞行走廊内自主导航时，实施一种控制策略以协调多个 UAS 相互保持安全距离，并最终在空域系统 (NAS) 内保持安全距离。所提出的方法必须满足 UAS 的安全距离考虑、代理的速度、飞行走廊内的代理数量以及环境条件。最终，将开发一种新颖的安全无人机交通管理 (UTM) 网络来实现这些目标。

2.1 Control Objectives and Concept of Operation

2.1 控制目标与操作概念

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.

提出的 UTM 通过模拟虚拟弹性碰撞来制定多个 UAS 之间的交互，这种行为模仿了气体粒子的行为，在接触时存在即时的排斥力。实际上，碰撞发生在围绕每个 UAS 的感应系统之间，该系统被定义为 UAS 感知与避让安全气泡 (UAS-SSB)。控制策略依赖于每个代理如何感知 UAS-SSBs，以及这些气泡如何根据关键安全条件扩张或收缩。该模型已被调整以模拟具有全方位运动能力的 UAS，如多旋翼无人机。基于结果的未来工作将解决具有不同动态特性的 UAS。

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.

额外的控制过程涉及增强代理相互交互的环境。UTM 被划分为多个 UAS 协同空域 (UAS-CA) 单元，每个单元都有特定的边界和导航安全规则。通过计算离开和进入 UAS-CA 单元的 UAS 数量，可以控制在其限制内允许的 UAS 数量。

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.

图 1 所示的操作概念示例说明了提出的 UTM 系统。单元内的安全依赖于 UAS-CA 如何感知可能导致碰撞的条件。随着碰撞风险的增加，UAS-SSBs 应该覆盖更广泛的检测体积。最终目标是开发可靠的控制机制，以在代理之间保持安全距离 (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 implementa-

本文的研究并不是将提出的模型与其他基于群体的 UAS 避障模型进行比较，而是关注所提出模型的实施-

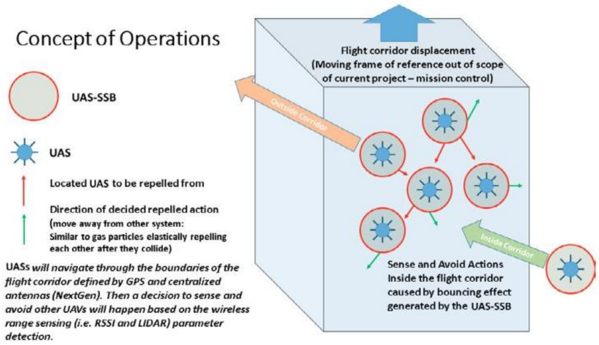

Fig. 1. A UAS Coordinated Airway cell, containing multiple UASs. Each agent is enhanced with a UAS Sense and Avoid Safety Bubble which is modeled based on gas particle behavior during head-on elastic collisions.

图 1. 一个包含多个 UAS 的 UAS 协同空域单元。每个代理都增强了一个基于迎头弹性碰撞期间气体粒子行为的 UAS 感知与避让安全气泡模型。

tion 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.

对一种多传感器检测技术的开发，该技术能够允许执行适当避障程序。这种检测能力，它使得能够自适应感测范围，被认为是 UAS-SSB 系统的基石。为此，研究了车辆之间的安全距离检测，并将其作为开发所提出模型的参考。在 (Qu, D. et al. (2014))、(Yanmaz, E. et al. (2013))、(Chiaramonte, R. B. et al. (2013))、(Bouachir, O. et al. (2014)) 和 (Ramasamy, S. et al. (2016)) 以及其中的参考文献中可以找到 UAS-SSB 实施的模型示例。

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

3. 主要结果: 安全距离 E 和风险因子 RF 的控制模型

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).

所提出的防碰撞和协调系统依赖于集中式和分布式行为的结合，旨在克服每种方法遇到的限制。具体来说，我们提出了一种方法，其中机器人本身具有自主智能和自主性 (分布式方法)，并通过智能自动化环境 (集中式方法) 进一步增强。

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.

主要成果在于开发了一个数学模型，用于结合所有识别的风险，以定义并保持无人机系统 (UASs) 之间的安全距离，同时额外考虑减轻第三方伤害。多代理系统 (MAS) 交互模型受到 (Wilensky, U. 和 Resnick, M. (1999)) 和 (Tisue, S. 和 Wilensky, U. (1999)) 结果的启发，其中每个代理被表示为气体粒子，代理之间的交互分析利用了麦克斯韦-玻尔兹曼分布。

3.1 The risk factor model RF.

3.1 风险因子模型 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

如前所述，每个 UAS-SSB 必须模拟气体粒子的动态行为，以便实现排斥/距离控制。为了达到这个目标，考虑以下理想气体定律方程

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

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

其中 n 代表粒子数量，V 是体积，T 是温度，R 是理想气体常数。方程 (1) 中的参数可以映射到涉及 UAS 的风险缓解方程中，如下所示

$$RF = \frac{n_U F_{TLS} E}{V_A} \tag{2}$$

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.

其中受到温度和压力的粒子 n 被映射为无人航空系统 (UAS) 的数量 n_U 。体积 V 被映射为 UAS 的气道体积 V_A 。温度 T 被映射为 UAS 安全距离规划中的误差 E ，该误差会根据风速条件的变化和制造商的建议而变化。理想气体常数 R 被映射为新方程中的 F_{TLS} ，使用了地面可能造成的伤亡数量和安全考虑的值 (Melnyk, R. et al. (2014) 和 Melnyk, R. (2013) 中计算)。具体来说，这个值描述了由于重量和穿透力，坠落的无人机对不同的 _population densities_ 造成的冲击。最后，压力 P 被映射为 UAS 碰撞的潜在损害风险值 RF 。我们可以将 RF 视为衡量 UAS-CA 内部施加的压力量的度量。最终，这种压力也会影响单元内 UAS 之间的安全距离。方程 (2) 是一个风险缓解模型，它规定了碰撞风险与多代理之间的安全操作距离之间的反比关系。具体来说，它计算了一个关系，其中参数 n_U 、F_{TLS} 和 E 被用来自适应地控制安全气泡的大小。因此，当 UAS 之间的安全距离增加时，碰撞风险将降低，反之亦然。

3.2 The safety distance model E .

3.2 安全距离模型 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.

安全距离的值应由 UAS-CA 不断更新并传输给 UAS-SSB。此参数将由 UAS-CA 系统对变化航路条件的观测进行调节，例如进入单元的无人机数量、单元边界内的当前风速条件，以及 UAS 的跨度 (直径)，还有 UAS 制造商关于保持安全飞行的建议。

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

安全距离 E 由两项组成: D_o 代表所需的最小安全气泡直径，即 UAS 的长度，以及 UAS 制造商基于风速条件推荐的安全系数 D_s 。

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

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.

其中 $W_{\text{airwayspeed}}$ 是航路的动态风速值。此模型允许通过适当计算代理之间的安全距离来增加在航路中运行的 UAS 数量，最终降低碰撞冲击的风险。

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.

E 可以通过 UAS-CA 单元中的 UAS 数量进行改进，因为数量越高，碰撞风险应该增加，反之亦然。同样的假设也适用于突发的强风速，这可能会危及 UAS 的安全运行。

3.3 UAS-SSB Sensor Fusion Implementation

3.3 UAS-SSB 传感器融合实现

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.

为 UAS-SSB 提出的传感器融合架构涉及多个传感器的互联，每个传感器都具备特定的能力、灵敏度和感知范围。多种传感器的组合，可能是例如超声波、射频和光学测距仪，预计将在 UAS 周围形成一个多感知层。由于每个传感器都将有不同的局限性，UAS-SSB 内的每一层都必须根据传感器的反应时间和感知优先级来适应。

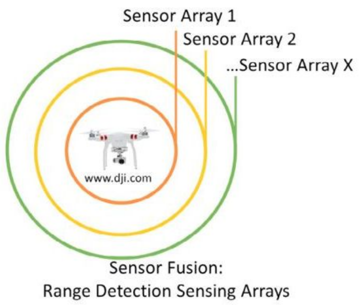

Fig. 2. UAS-SSB Sensor Fusion Layers.
图 2. UAS-SSB 传感器融合层。

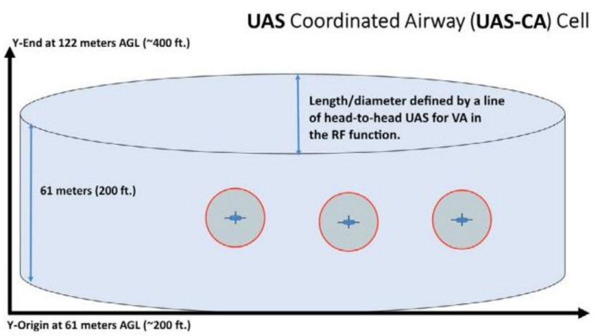

Fig. 3. Individual UAS-CA Boundary Conditions.

图 3. 单个 UAS-CA 边界条件。

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.

图 2 显示了基于多感知层方法的无人机 (UAS) 安全气泡。有了这个功能，每个 UAS 能够感知附近 UAS 的不同接近级别，并能够相应地做出反应。需要通过实验确定传感器层的数量、优先级、协调和灵敏度。还应考虑飞机的功耗和任务能力。

3.4 UAS-CA and UAS-SSB Coordination

3.4 UAS-CA 与 UAS-SSB 协调

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.

在 UAS-CA 单元内检测 UAS 可以通过诸如全球定位系统 (GPS) 和自动依赖监视广播 (ADSB) 应答器等众所周知的技术实现。然后，可以根据 FAA 关于飞机在空域中导航的建议来定义单个单元。图 3 概括了根据 Part 107 法规为定义单个单元而采纳的 FAA 安全考虑。图 4 显示了多个启用 UAS-SSB 和 UAS-CA 单元信息的 UAS 的 2 维交互视角。

UAS-CA Cells Operation (2D View from Above)

UAS-CA 单元操作 (俯视图 2D)

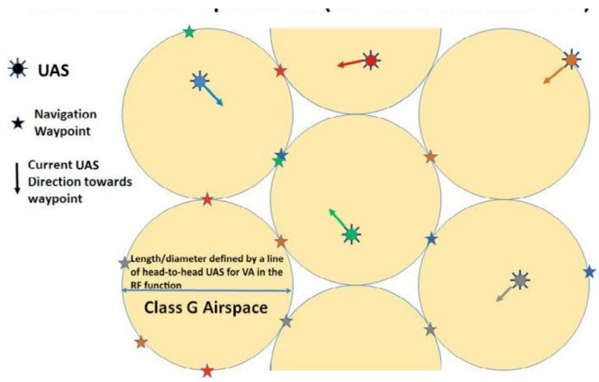

Fig. 4. UAS-CA Cluster planar (upper) view: a 2 dimensional perspective of multiple UAS making use of the UAS-CA cells for interacting with each other.

图 4. UAS-CA 群集平面 (上层) 视图: 多个 UAS 利用 UAS-CA 单元相互交互的 2 维视角。

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

4. 分析和比较 R 和 E 方程变量影响

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.

UAS-CA 与 UAS-SSB 之间的交互被适配为 MAS 控制策略。每个 UAS-SSB 被定义为一个具有编程行为的代理，这些行为确保其能在由 UAS-CA 控制的的环境中安全导航。空气单元格内的代理行为通过类似于盒子中气体粒子行为 (Wilensky, U. (1999)) 的相似行为来描述。采用了 GasLab 圆形粒子 MAS NetLogo 模拟程序 (Wilensky, U. (2005))，并进行了修改，以评估安全距离模型的实施。

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.

修改后的 NetLogo 模型将粒子视为 UAS-SSB。参数如气道大小、初始 UAS 速度和风速由用户定义。E 的值自动计算并传输给每个 UAS-SSB。假设 UAS-CA 单元格的边界是一个地理围栏，代理将会从其弹开。同样，如果 UAS-SSB 相撞，它们也会相互弹开。模拟计算了 UAS-SSB 的边界感知到另一个 UAS-SSB 边缘或 UAS-CA 边界的时长。如果没有检测到碰撞，UAS 将继续以其当前速度和方向前进。代理之间的动能交换受到 (Wilensky, U. (2005)) 中粒子相互作用的启发。模型中的所有 UAS-SSB 假设具有相同的质量，以便它们是弹性的。

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.

我们的研究工作是在 NetLogo 中模拟方程 (2) 和方程 (3)，以评估实现的安全属性。我们保留气体粒子的行为不变，以验证 UAS-粒子类比方法。方程 (2) 和方程 (3) 中的新规则被添加到每个代理中，以观察它们在微观层面的行为对整体环境 (宏观层面视角) 的影响。模拟 E 模型的详细信息如表 1 所示。

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, rameters for the Safety and Dynamic analysis of the R Model and UAS-CA Capacities

本研究选取了一个二维正方形的 UAS-CA 细胞，根据启发式的 UAS 长度/直径规格进行选择。运行时间以刻度 (ticks) 定义，相当于主模型中的秒，像素用于描述尺寸。有了这些信息，参数用于 R 模型和 UAS-CA 能力的安全和动态分析

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

表 1. NetLogo 多代理模拟参数，用于 E 模型的安全和动态分析

Key	Magnitude	Unit	Description
Eideal	9	pu	The ideal recommended SAA safety distance
NetLogo Multiagent Simulation Defined Parameters for the E model			
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			
kw	4,375	unit less	kw gain for the UAS-SSB
Elimit	14	pu	Overall consideration E value for maximum ”at least” sensor range

关键	数量级	单位	描述
E 理想	9	pu	理想推荐的安全距离 SAA
NetLogo 多代理模拟为 E 模型定义的参数			
UAS 制造商参数			
补丁单元 (pu)	4.6535	像素	每个补丁单元 (pu) 的像素幅度测量
Do(此处为符号，未提供上下文，保留原样)	2	pu	无人航空系统-支撑结构直径 (UAS 最大轮距)
Ds(此处为符号，未提供上下文，保留原样)	5	pu	制造商推荐的安全距离
Us(此处为符号，未提供上下文，保留原样)	10	pu/滴答 (此处为符号或单位，未提供上下文，保留原样)	无人航空系统-支撑结构能达到的最高速度限制
Ws(此处为符号，未提供上下文，保留原样)	8	pu/滴答 (此处为符号或单位，未提供上下文，保留原样)	无人机系统-结构支撑梁的最大风速阻力能力
时间参数			
ts	0.5	计数器	侵入无人机系统-结构支撑梁的最小距离检测推荐时间
ta	0.4	计数器	无人机系统-结构支撑梁反应最小位移推荐时间
tr	0.9	计数器	无人机系统-结构支撑梁总安全裕度反应推荐时间
公式 4.23 (E) 参数			
kw	4,375	无量纲	UAS-SSB 的千瓦增益
Elimit	14	pu	考虑整体 E 值以获得最大“至少”传感器范围

Table 2. NetLogo Multiagent Simulation Pa-
表 2. NetLogo 多代理模拟参数-

Key	Magnitude	Unit	Description	
NetLogo Multiagent Simulation Defined Parameters for the RF MODEL				
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	pu2	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	pu2	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	

关键	幅值	单位	描述	
NetLogo 多智能体仿真定义的射频模型参数				
方程 2(RF) 和 UAS-CA 参数				
Nmax	5	海龟	最大推荐无人机系统-辅助定位系统容量	
n	1 至 6	海龟	模拟中使用的无人机系统-辅助定位系统的范围	
dr	15	无量纲	图块区域和碰撞分析的距离关系	
FTLS	表格	4.8	归一化最大系统故障率以满足地面 TLS	
E 2D 极限	153.94	pu2	圆形 UAS-SSB 区域尺寸限制用于正方形 UAS-CA 航道	
LA	84	pu	正方形 UAS-CA 所需的航道边长	
VA	7056.00	pu2	正方形 UAS-CA 区域尺寸	
圆形排列	0.91	%	2-D UAS-CA 的圆形排列系数	
测量的 UAS-CA 容量极限	45.84	海龟	VA/E 2D 限制 UAS-CA 单元 UAS-SSB 测量容量	
实际 Elimit UAS-CA 容量	41.57	海龟	VA/E 2D 限制 UAS-CA 单元 UAS-SSB 圈形排列考虑容量	

Table 3. Evaluation Plan for equation (2) and equation (3)
表 3. 方程 (2) 和方程 (3) 的评估计划

Testing plan to Analyze the Dynamic and Safe Operation of Equation (2) and Equation (3) Parameters					
SAFETY CHAOS	No UAS-SSB		Fixed UAS-SSB		Variable UAS-SSB
	E=Do		$E = Ds$		$E =$ 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

测试计划以分析方程 (2) 和方程 (3) 参数的动态和安全运行					
安全混沌	无 UAS-SSB		固定 UAS-SSB		可变 UAS-SSB
	E=Do		$E = Ds$		$E =$ Elimit
无湍流	测试 A1	测试 D1	测试 A2	测试 D2	测试 A3
小尺度湍流	测试 B1		测试 B2		测试 B3
大尺度湍流	测试 C1		测试 C2		测试 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.

可以计算 V_A 的一个值，以便将其添加到方程 (2) 中。进行了球体打包几何计算，以了解有多少代理可以适应在受限气道内。这些计算的结果如表 2 所示。

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.

NetLogo 具有内置功能，允许询问每个代理与其他代理的距离，这有助于识别无人机系统 (UAS) 之间可能发生的碰撞。为了验证 NetLogo 提供的测量数据的准确性，将两个无人机系统安全间隔缓冲区 (UAS-SSB) 放置在彼此旁边，初始航向相反。它们被编程为彼此分离，然后从无人机系统碰撞回避 (UAS-CA) 的边界弹回，直到相互碰撞，然后重复此行为。在 1000 个时间步长内测量了代理之间的相对距离。距离图显示了最小误差的谐振动，验证了 NetLogo 生成可靠数据以评估 E 和 R 模型能力。图 5 显示了模拟结果。

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

接下来，提出了一个测试计划，以分析 E 和 R 模型对模拟的无人机系统安全间隔缓冲区 (UAS-SSB) 和无人机系统碰撞回避 (UAS-CA) 子系统的影响，见表 (3)。模拟考虑了一个封闭单元格，其中包含固定数量的代理。目标是观察 E 值的增加

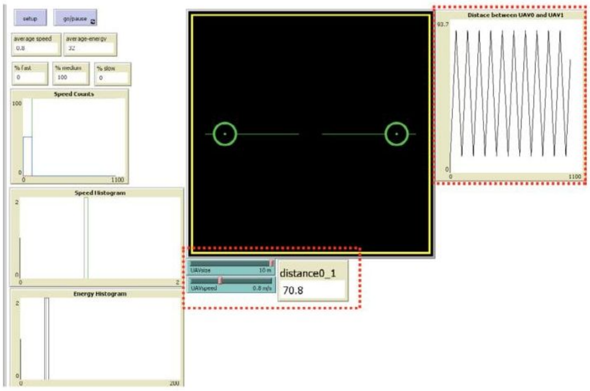

Fig. 5. Simulation of two UAS-SSB performing repetitive collisions. $E = 10\text{pu}, U_s = 0.8\text{pu}/$ ticks.

图 5. 两个无人机系统安全间隔缓冲区 (UAS-SSB) 进行重复碰撞的模拟。$E = 10\text{pu}, U_s = 0.8\text{pu}/$ 时间步长。

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

确保在理想的无人机系统安全间隔缓冲区 (UAS-SSB) 操作中不会发生实际碰撞。引入以下定义:

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.

定义 1.- 当检测到的代理之间的距离等于或小于 $0.5 * D_o$ 时，被认为存在碰撞，其中 D_o 是没有安全气泡的无人机的长度。然后给出以下陈述: 如果距离 $UAS_{nm} \leq 0.5 * D_o$ ，则发生了碰撞。

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.

定义 2.- 当两个无人机系统 (UAS) 之间的距离在 D_o 和 D_s 之间时，存在“碰撞高风险”的情况，其中 D_s 是制造商推荐的最小安全距离。由于突然的风暴等因素，这种情况非常接近发生碰撞，例如空域中出现的意外代理。

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 Elimit range. This area depends on the ideal and proper operation of the UAS-SSB to keep UASs at a safe distance from each other.

定义 3.- 当两个无人机系统 (UAS) 之间的距离在 D_s 和推荐的 UAS-SSB Elimit 范围之间时，存在“碰撞中风险”的情况。这个区域取决于 UAS-SSB 的理想和适当操作，以保持无人机系统之间的安全距离。

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.

为了模拟表 3 中的每一种情况，以下四个动态参数被修改: 气道的大小，W_s, U_s ，以及引入湍流或扰动函数。还测试了 D_s $(0, 5$ and 10) 的三个值。在模拟过程中，代理的大小或长度也被改变。

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.

图 6 和图 7 展示了表 3 中 D1 和 D2 情况的设置。这些测试的目标是验证所提出的安全气泡模型能否在粒子被压缩到更小的容器中时模拟气体粒子的行为。

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

表 3 中描述的每一项测试都已执行并评估。从代理之间可能的 15 种距离组合中，提取并评估了 15000 个值。图 8 展示了测试 A1 的一个快照，其中可以看到六个代理相互交互并保持安全距离。该场景的结果在图 9 中以直方图的形式展示。直方图的柱子有不同的颜色，每种颜色代表不同的碰撞风险。低于 D_o 的距离值被识别为碰撞，并以红色表示。高风险区域之间的距离与黑色柱子相关 (在这个特定场景中看不到)。距离在

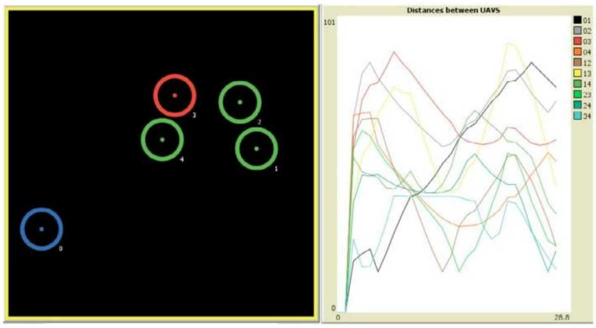

Fig. 8. A snapshot of Test A1, showing 6 agents interacting with each other and maintaining safety distances.

图 8。测试 A1 的快照，显示 6 个代理相互交互并保持安全距离。

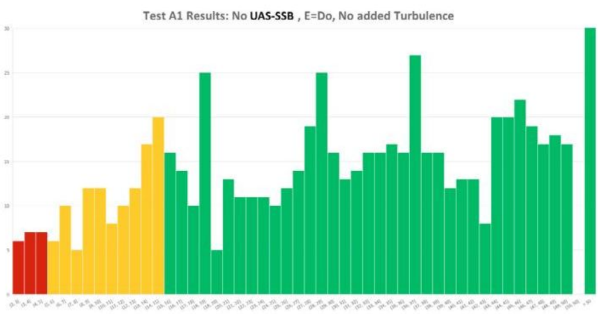

Fig. 9. Histogram showing relative distances for Test A1.

图 9。显示测试 A1 相对距离的直方图。

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

E_{limit} 范围内的距离被涂成黄色，代表中等风险区域。其他柱子被涂成绿色，表示最小风险或无风险区域。

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.

直方图显示高风险区域的活动量减少，中等风险区域活动适中，而低风险区域活动量较高。

4.1 Observations and conclusions from additional tests

4.1 额外测试的观察与结论

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.

测试 A3 的结果表明，只要无人机系统安全缓冲区 (UAS-SSB) 根据提出的模型持续进行扩张和收缩，系统就能在理想条件下成功运行，这确保了无人机之间碰撞风险的降低。测试 D1 和 D2 显示，即使在无人机碰撞避免区域 (UAS-CA) 内安全气泡大小增加的情况下，代理也能保持安全运行，没有碰撞的证据。因此，只要无人机系统安全缓冲区接收到无人机碰撞避免区域的反馈，代理就能安全导航。测试 B1、B2、B3、C1、C2 和 C3 如预期那样显示出碰撞，这是由于系统受到干扰的影响。当湍流强度增加时，直方图中的黑色条形数量增加。在这些场景中，安全气泡预计将增加无人机的生存机会，但另一方面，碰撞风险也会增加。

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.

从这些结果可以得出结论，通过实施方程 (2) 和方程 (3)，我们可以显著提高多个无人机在航路空中走廊中运行的安全性。此外，值得一提的是，如果无人机碰撞避免区域 (UAS-CA) 的面积适合导航目的，碰撞风险将大大降低。因此，根据无人机内部特性和方程 (2) 参数的几何建议来设计航路尺寸，我们可以显著提高导航区域的安全性。

5. CONCLUSIONS AND FUTURE WORK

5. 结论与未来工作

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.

安全距离和风险因素模型的开发是这种新颖方法的关键组成部分，该方法旨在为近距离操作的多个无人机系统 (UAS) 构建一个统一的避障和协调模型。提出的方法通过模拟虚拟弹性碰撞来表述多个代理之间的交互，这种行为类似于气体粒子的行为，在接触时存在即时的排斥力。在 NetLogo 中，对不同合成场景下提出系统的性能进行了分析。超出模拟的进一步实验将证明所提出的方法能够量化避障性能。实

验结果也有助于在发生碰撞时识别系统内的新风险缓解能力。在这些测试中还考虑了一些关键变量，这些变量对于允许无人机系统 (UAS) 在美国国家空域系统 (NAS) 内运行至关重要，例如，空域单元内代理的数量、空域的天气条件以及由于无人机坠毁而对地面造成伤亡的风险。最终，为无人机系统 (UAS) 实施安全气泡 (去中心化控制方法) 与协调空域单元 (集中控制方法) 相结合，已经显示出对未来通用空中交通管理系统 (UTM) 发展的前景，在该系统中无人机可以安全导航，最小化碰撞风险。

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

后续工作将考虑在实时实验中实施 UAS-SSB 模型。第一个任务将考虑将安全气泡添加到地面移动机器人中，以便后续更新到 UAS 平台 (Ortega. G, et al. (2015))。然后，将通过运动捕捉系统或 GPS 启用 UAS-CA，以进一步改进结果 (Munoz Palacios, F. 等人 (2017))。具体来说，UAS-CA 将增强具有拒绝访问和重定向代理的能力，一旦在单元内遇到关键条件。我们还将评估具有更高机动性和先进传感设备的 UAS 的性能，以增强 UAS-SSB(Munoz Palacios, F. 等人 (2015))，从而提高代理的生存率

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