Designing A Distributed Web-based Simulation Environment for Enabling Autonomous Systems Research

Benjamin N. Kelley* and Walter J. Waltz*
NASA Langley Research Center, Hampton, VA, 23681, USA

Andrew Miloslavsky† and Ralph Williams‡
Analytical Mechanics Associates Inc., Hampton, VA, 23666, USA

Abraham K. Ishihara§, Isaias Reyes¶ and Husni R. Idris‖
NASA Ames Research Center, Mountain View, CA, 94035, USA.

In the continued pursuit of creating a future with robust Urban Air Mobility (UAM) operations defined as safe and efficient air traffic operations in metropolitan environments for both piloted and autonomous systems, development of the concepts, technologies, and procedures to establish this UAM ecosystem remains an active area of research. In particular, as autonomous systems continue to grow in both complexity and use throughout UAM concepts the need for simulation environments to both test individual components and systems and to study the complex interactions between them is paramount. In this paper we address design considerations, technologies, and challenges of adapting native simulation environment application concepts to an interactive and distributed web-based framework. The proposed web-based design allows for easier and wider access for developing, testing, integrating, and studying emergent behaviors of complex autonomous systems interaction. We demonstrate the utility of the proposed approach by showing multi-agent interaction and emergent behavior in two scenarios: (1) autonomous urban air mobility vehicles flying in a convoy and (2) interaction of a convoy with a search and rescue operation.

I. Introduction

Collective autonomous mobility (CAM) is the future of urban air traffic integration that envisions safe and efficient aviation transportation utilizing autonomy and automation to operate and transport passengers or cargo at lower altitudes. As unmanned aircraft systems (UAS) become more affordable and available there is increased need for UAS traffic management in urban and sub-urban environments. Addressing this challenge, the CAM ecosystem considers multiple services such as, flight plans, and purposes such as public safety, deliveries, surveillance, weather monitoring, news reporting, agriculture, mapping, entertainment, disaster relief and support [1]. The concept of CAM is a distributed web-based system that provides users with an API supported by SignalR for isolated algorithm development or a simulation environment to evaluate the integration of one or more unmanned traffic services in a virtual airspace with multiple participants. Proof of concept services are limited to essential behaviors and operations such as trajectory planning, collision avoidance, vertical take off, and specifying convoy system constraints.

In the remainder of this paper the authors illustrate the system architecture and processes of the web-based simulation. Section II details the web-based design with the role and purpose of the Unity game engine and SignalR for communication and integration of services. An initial case study is reviewed in Section III providing insight to convoy services that utilizes the developed architecture. Finally, initial findings and future considerations are presented in Section IV.

*Research Computer Scientist, Autonomous Integrated Systems Research Branch
†Programmer II
‡Scientist, Senior AIAA Member
§Chief Technical Advisor Engineering Systems, KBR, AIAA Member
¶Software Engineer, KBR
‖Research Aerospace Engineer, Aviation Systems Division, AIAA Associate Fellow

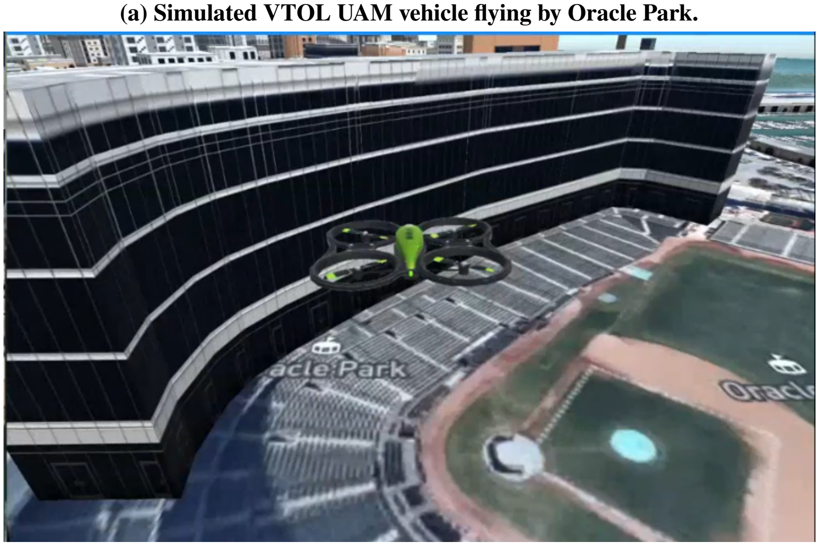
II. Web-based Simulation System Design

As autonomous systems grow in complexity, simulation environments have become an invaluable tool for advance autonomous system research. Many times conducting physical tests and experiments can have significant barriers, such as being time-consuming, expensive, or perhaps dangerous, making simulations an appealing alternative and vital tool. Previous NASA autonomous systems research led to the development of a lightweight Unity game engine based simulation tool called the Baseline Environment for Autonomous Modeling (BEAM) [2]. BEAM's focus on providing a lightweight distributed multi-agent simulation environment that can be easily extended has quickly made it a valuable and useful tool for many NASA research efforts[3].

While BEAM continues to be further developed and support other research efforts, the simulation system needs for this project required additional features that BEAM was not originally designed to support. BEAM was developed as a stand-alone native Unity application that utilizes the Distributed Data Services (DDS)[4] for local area network communication for multiplayer interaction and external research code integration, while this effort called for a system with a much wider reach and end-user client interaction and integration. This led to the design of a web-based tool modeled after the same conceptual design of BEAM.

Like BEAM, this new web-based distributed simulation environment is realized by the Unity game engine, but is built for the web using WebGL. Figure 1 shows various simulated agents within the system.

(a) Simulated VTOL UAM vehicle flying by Oracle Park.



(b) Simulated quadrotor flying within Oracle Park.

Fig. 1 Simulated agents flying within the system.

Bi-directional communication between the server and clients is facilitated by websockets using Microsoft's SignalR[5] communication protocol. Figure 2 shows an high-level overview of the deployed system and how external applications and not only the end-user web browsers can communicate amongst connected peers via SignalR. These external applications allow for new UAM services and research algorithms to be integrated into the simulation ecosystem to interact with the simulated agents.

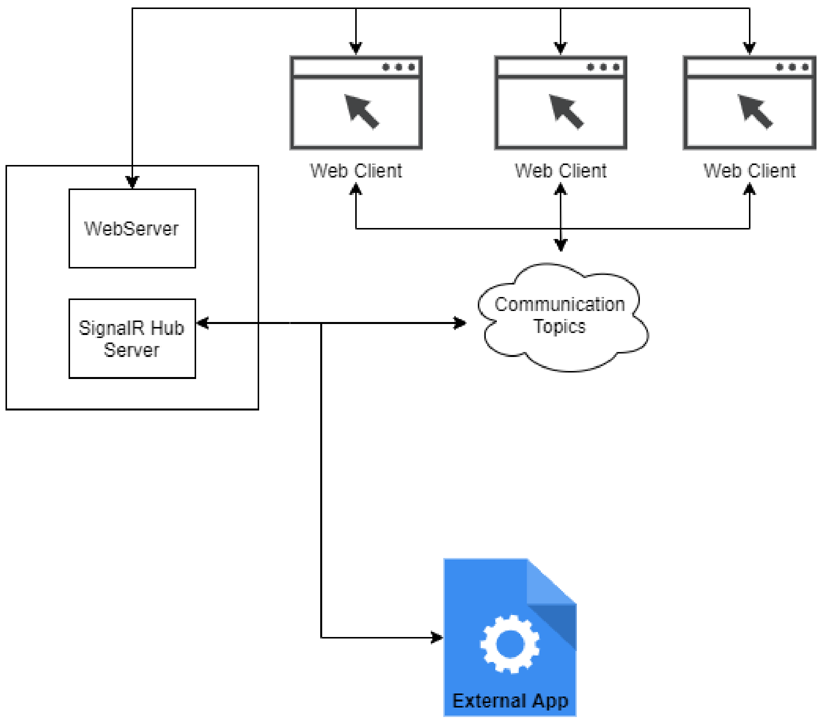


Fig. 2 Overview of Web-based system

Using a technology such as SignalR allows for the development of a publish-subscribe style communication architecture, which as has been a demonstrated effective communication design for the development of autonomous systems [6][7][8][9]. Publish-subscribe architectures allow for the development of systems which are modular and flexible, where data producers and consumers are more loosely coupled and less dependent on the implementation details of their peers.

This publish-subscribe modular approach leads to a data-centric design where data represents the information between nodes, services, and vehicles that will be evaluated for emergent behaviors and statistical parameters regarding the integration of these services. The web server hosts a SignalR communication hub which clients connect to and offers a variety of communication topics with strongly typed data types. These communication topics and associated data types allow for the simulation end-points to participate together in the same simulated environment by facilitating the exchange of agent status information and world events. Figure 3 shows the basic communication topics available and required for the browser application clients to engage in a shared simulated environment. Simulated agents publish announcements upon creation to alert other participants of their existence, type of vehicle, and owner. Once created agents begin regularly publishing state information updates which are used to update and reflect their object's representation in the remote connected peer's environments. Simulated agents also subscribe to the command topic for movement commands that could come from any user or connected application on the SignalR communication network.

External applications with access to the SignalR client library can also connect to the communication network as well. For example, the vehicle status messages can be subscribed to and vehicle commands published to by an external application to allow for the integration of more advanced 'on-board' intelligence modules such as advance navigation systems, mission management, etc. to extend the capabilities of the simulated agents. This method of external application integration is also the planned mechanism for allowing CAM to begin testing and evaluating UAM services such as convoys, veriport scheduling, conflict resolution, etc. and begin studying emergent behaviors when a complex ecosystem of services and agents are running simultaneously.

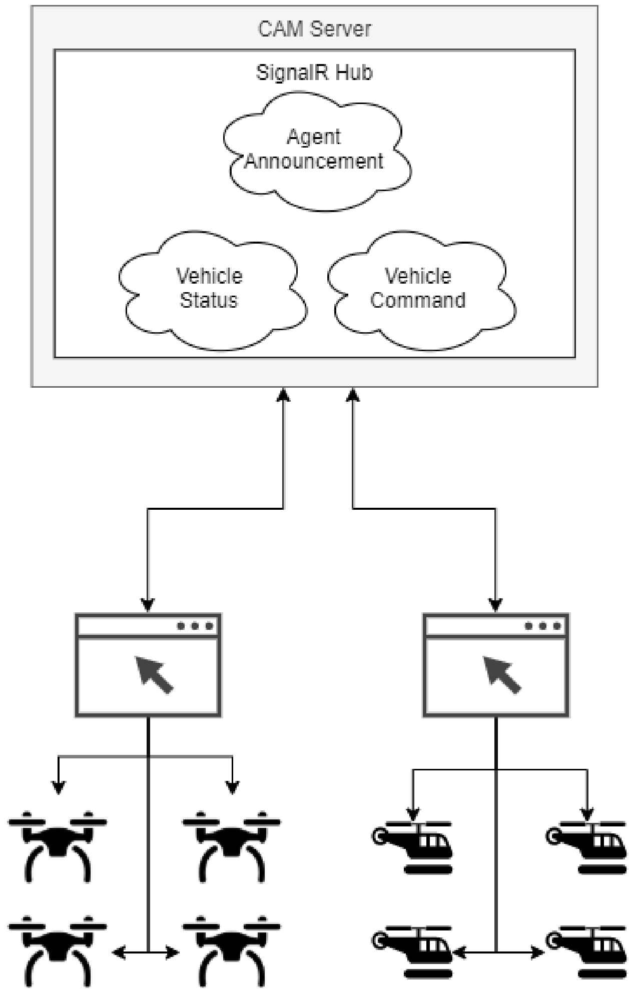


Fig. 3 Basic SignalR Communication Topics

III. Demonstrated Use Case

To demonstrate the utility of the proposed distributed web-based simulation architecture and approach, we show multi-agent interaction in two scenarios: (1) autonomous urban air mobility vehicles flying in a convoy and (2) interaction of a convoy with a multi-agent UAV search and rescue operation. Figure 4 shows an overview of the demonstration.

A. Convoy Applications in UAM

High density operations may become prevalent in the urban setting motivating the need for more efficient modes of operation. Autonomy will play a central role to enable scalability of operations by removing the barrier of human-centric centralized traffic control. UAM vehicles grouped in convoys have the potential to lead to improved utilization of the airspace, reducing the workload of human airspace controllers, and thereby increasing the autonomy of the system overall. Convoys are meant to be a collection of vehicles that share a common velocity profile and are bounded in a sense to be made precise below. For example, a convoy of cars on a highway share a common velocity typically set by the leader of the convoy, which can result in increasing throughput. A slower driver in the right lane, might find it advantageous to join a faster moving convoy on the left if the velocity profile is acceptable.

These decisions depend on various objective functions and vehicle performance characteristics. As aircraft approach their destination they are merged and compressed and once their desired spacing is achieved their speeds are matched such that they maintain their spacing as one object. In this manner controllers are able to monitor and control a larger number of aircraft that are chained together, thus increasing airspace capacity [10]. As the future UAM environment

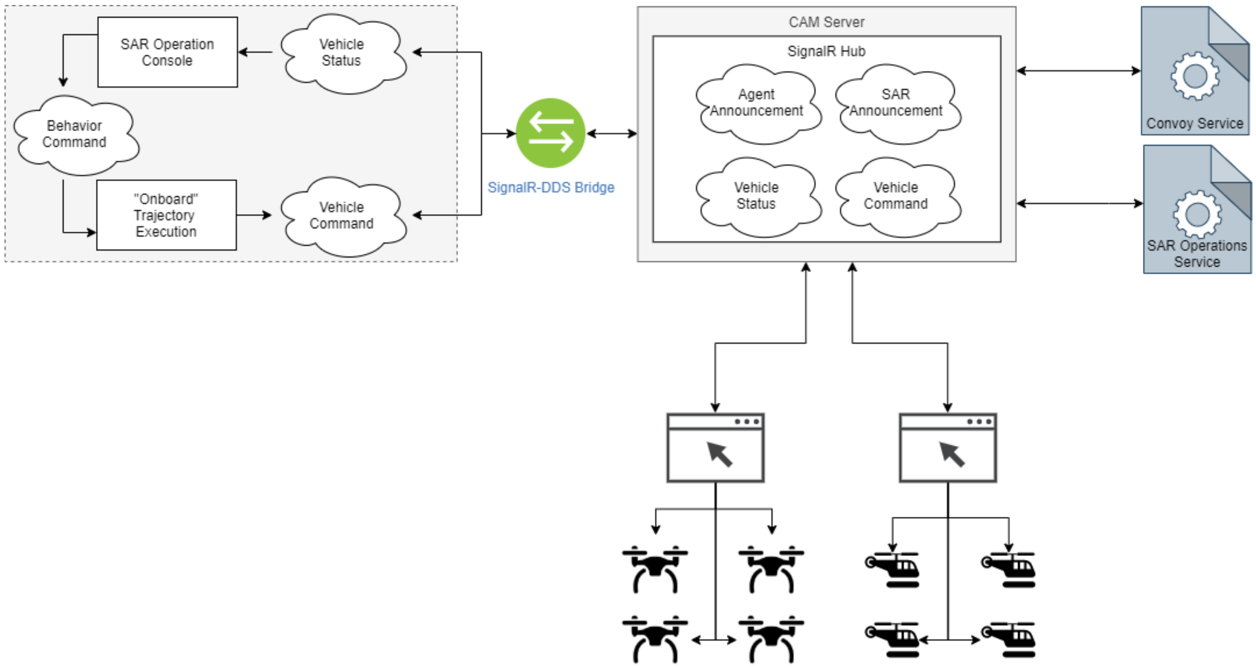


Fig. 4 Overview of Demonstrated Use Case

expects higher traffic density, centralized human-based control becomes infeasible and distributed autonomous schemes become critical. Convoys emerging and forming in a distributed manner is envisioned in this paper as a mechanism to increase scalability by enabling a small number of human operators to supervise convoys of a large number of vehicles as one cohesive object and by enabling traffic structure to emerge when and where needed, for example to avoid weather hazards, rather than being imposed a priori through.

A review of the convoy characteristics are provided below and the reader is encouraged to review [11] for further reading on the development of urban convoy development.

Definition III.1 *An N-convoy consists of a collection of N agents, each governed by the following nonlinear ordinary differential equation:*

$$\begin{cases} \dot{x}_i = v_i \\ \dot{v}_i = \beta \sum_{j=1}^{N} \beta_{ij} \left(v_j - v_i \right) + l_i \\ x_i(t_0) = x_{i0}; v_i(t_0) = v_{i0} \end{cases} \tag{1}$$

where $\beta > 0$; $\beta_{ij} : \bar{\mathbb{R}}^+ \to \bar{\mathbb{R}}^+$ *represents the influence agent* j *has on agent* i *and is given by*

$$\beta_{ij} = \zeta_{ij}\phi(\|x_i - x_j\|) \tag{2}$$

where

$$\zeta_{ij} = \begin{cases} 1 & \text{if } j \text{ connects to } i \\ 0 & o/w \end{cases} \tag{3}$$

and $\phi : \bar{\mathbb{R}}^+ \to [0, 1]$ *is a non-increasing, non-negative function with compact support, that is, there exists a* $\sigma > 0$ *such that* $\phi(r) = 0$ *for all* $r \geq \sigma$ *with* $\phi(0) = 1$; $l_i : \bar{\mathbb{R}}^+ \to \mathbb{R}$ *represents attraction, repulsion, and leadership terms;* $(x_{i0}, v_{i0}) \in E \times E$ *denote the initial conditions of agent* i *where* $E = \mathbb{R}^d$ *and* $d \in [1, 3]$, *and* $i \in \{1, 2, \ldots, N\}$.

Definition III.2 (Agent Influence) *Agent* j *is said to influence agent* i *at time* $t \geq t_0$ *if* $\beta_{ij} > 0$.

Remark 1 *ζ_{ij} is a pre-configuration term that represents the existence of a connection from agent j to agent i. ϕ represents the strength of the connection between agents, if it exists, and σ, a finite sensing or communication distance. In the case of sensing, this could represent on-board radar, or in the case of communication, Dedicated Short-Range Communications (DSRC). In both cases, and for different reasons, uncertainty, errors, time-delay, etc., can exist. We do not consider any of these aspects in this paper. An example of ϕ that is also continuously differentiable is given by:*

$$\phi(s) = \begin{cases} 1 & \text{if } s \in [0, \sigma/2) \\ e^{-\left(\dfrac{(s-\sigma/2)^2}{\sigma^2 - s^2}\right)} & \text{if } s \in [\sigma/2, \sigma) \\ 0 & \text{if } s \in [\sigma, \infty) \end{cases} \tag{4}$$

By Definition III.2, agent j influences agent i if and only if agent j is connected to agent i and that connection has non-zero strength.

B. UAV Operations Within The National Airspace

While CAM's primary objective is to support advanced UAM research and technologies, it would be to our detriment to overlook the future of UAV operations within urban environments. Research and development efforts continue to grow rapidly for the use of small UAVs for operations such as package delivery, mapping, surveying, or utility and infrastructure inspection. There remains little doubt that the future will be one where UAM vehicles will share the airspace with UAV operations to some degree. To this end, the UAV simulation capabilities from the BEAM simulation upon which this system is based were ported over to the web environment.

The simulated UAV agents are capable of vehicle dynamics and can respond to SignalR commands for external control. As with BEAM, the simulated UAVs only offer station keeping and attitude, velocity, or way-point control with the intention that more advance autonomous capabilities will be provide via external framework integration. Since SignalR is not a typical communication protocol for traditional autonomous system frameworks such as NASA Langley Research Center's Autonomous Entity Operational Network (AEON), a SignalR-DDS bridge was also developed to enable the integration of AEON-based autonomous system modules as shown in Figure 4.

C. Integrated Demonstration

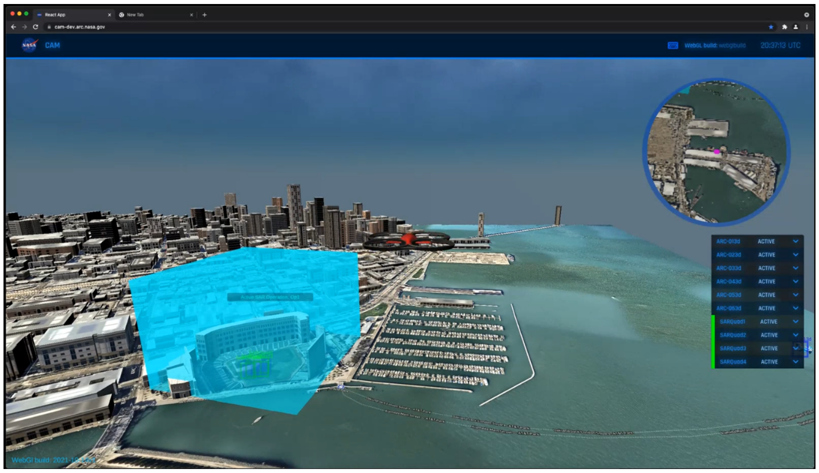
To illustrate the functionality of the purposed system, we developed and conducted an integrated demonstration scenario of the convey service dynamically replanning and adjusting to a disturbance in real-time caused by a UAV operation within its nominal trajectory. For the purposes of this demonstration, the UAV operation presented is a multi-agent coordinated Search And Rescue (SAR) operation. We developed a SAR Service to facilitate the SAR operation by allowing an operator to publish SAR announcement messages via SignalR with the geographical location of the SAR operation and task the simulated UAVs with their search missions and trajectories. The agents participating in a convoy will respond upon receiving the SAR announcements by avoiding the airspace.

As shown in the overview in Figure 4, the demonstration highlights the key components of the simulation system discussed above. Multiple browser instances, each containing several simulated agents, operate within the same share simulated environment by communicating via the SignalR hub, the SAR Service application exercises how external applications can connect to the system and the SignalR-DDS bridge highlights a method for how existing autonomous system frameworks might integrate into the system to expand the autonomous agents' capabilities.

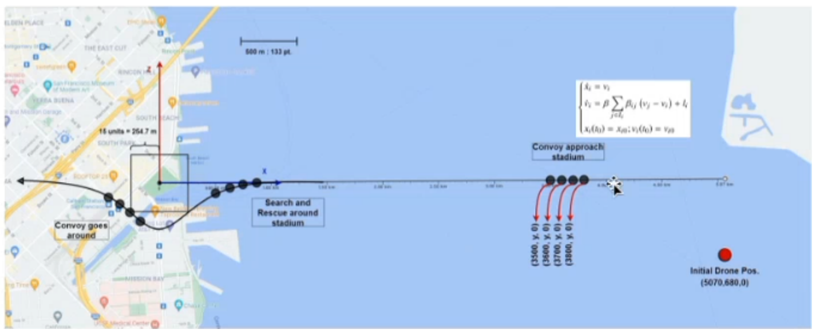
For this demonstration, a convoy is traveling with a nominal trajectory that would take it over Oracle Park in San Francisco. During flight a multi-agent SAR operation is conducted within the stadium and the SAR announcement request a no fly-zone within the surrounding area. Figure 5a shows the SAR operational area being displayed to the user upon receiving the SAR announcement from the SAR operator. Figure 5b shows the expected rerouting of the convoy agents and Figures 5c and 5d show the convoy approaching the SAR operational area and successfully avoiding the zone.

IV. Conclusion

The proposed distributed web-based simulation environment has already proven to be a useful tool and shows promise to be further developed into a versatile tool to assist in the study of UAM technologies. The publish-subscribe approach allows for a system that can be modular and easily extensible as the ecosystem of integrated UAM services continues to grow and more complex emergent behaviors studies are conducted.

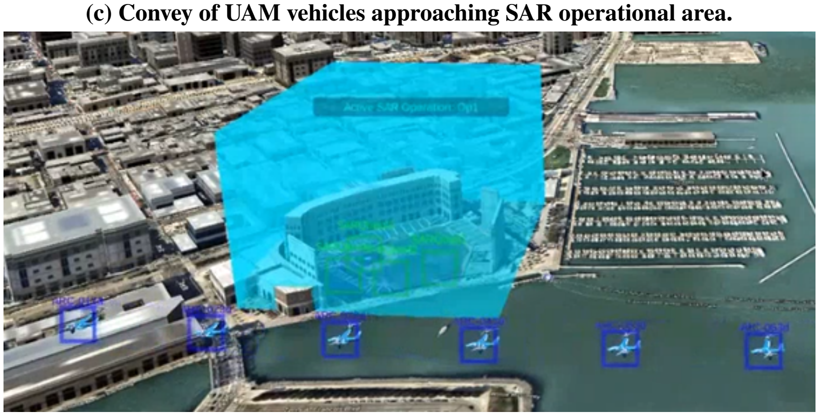


(a) Search and Rescue (SAR) operational area visualization.



(b) Expected Rerouting of convoy's nominal path after being disrupted by SAR operation.

(c) Convey of UAM vehicles approaching SAR operational area.



(d) Convey of UAM vehicles avoiding SAR operational area.

Fig. 5 Integrated Demonstration Overview.

There are several planned improvements and continuing development efforts for this work. One such improvement addressed a significant draw back to the system design proposed in this paper by having the client browser's WebGL application(s) maintain ownership and simulation responsibilities of the simulated agents is if/when a browser disconnects from the SignalR hub the associated agents will cease to exists within the shared simulation environment. There is currently no notion of persistence of agents beyond the browsers' sessions. A prototype has already been developed for adapting the deployed server as shown in Figure 6. By adding a headless Unity instance that runs on the server, ownership of agents can be passed to the server allowing for long term persistence even after the browser session has ended.

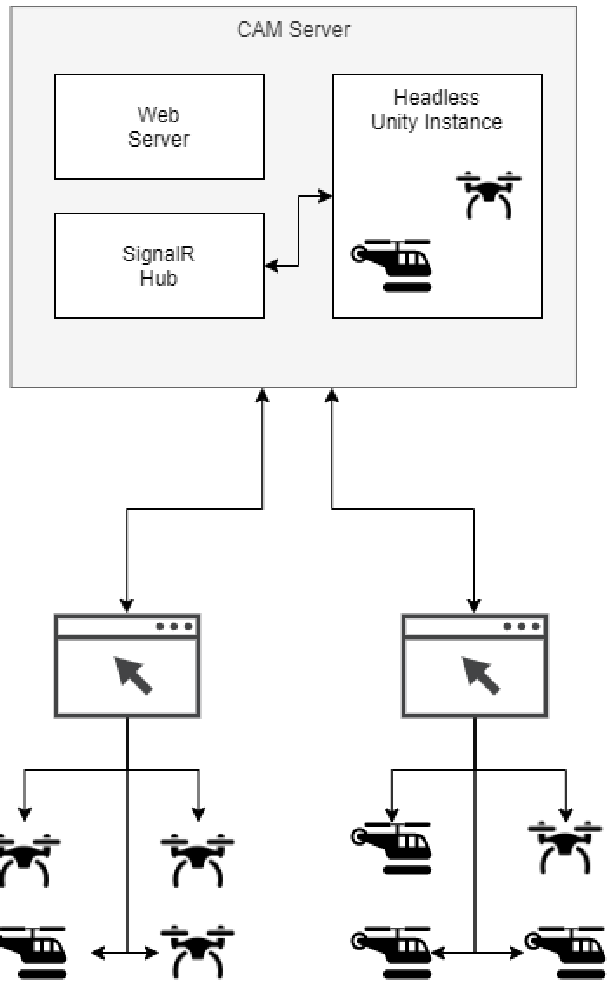


Fig. 6 Purposed Server-side Persistence Approach

Other planned future development is expansion of supported UAM vehicle platforms and services. Future demonstrations are already being planned for addition of the ability to spawn and configure veriport infrastructure agents and the integration of and evaluation of vertiport scheduling algorithms. The development of weather services, trajectory conflict resolution services, and communication bandwidth modeling are also active areas of research for future integration.

Acknowledgments

The authors would like to thank the entire CAM team, led by Dr. Husni R. Idris, and the Autonomous Systems (AS) Sub-Project of the NASA Aeronautics Research Mission Directorate (ARMD)'s Transformational Tools and Technologies (TTT) project for supporting this work.

References

[1] Kopardekar, P., Rios, J., Prevot, T., Johnsonr, M., Jung, J., and Robinson, J., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," AIAA Aviation, 2016.

[2] Kelley, B. N., Williams, R. A., Holland, J. L., Schnarr, O. C., and Allen, B. D., "A persistent simulation environment for autonomous systems," *2018 Aviation Technology, Integration, and Operations Conference*, 2018, p. 4015.

[3] Kelley, B. N., and Vaughan, M., "A Distributed Simulation-to-Flight Framework to Support Investigating Trust/Trustworthiness in Multi-Agent Systems," *AIAA Scitech 2021 Forum*, 2021, p. 1772.

[4] Pardo-Castellote, G., "Omg data-distribution service: Architectural overview," *23rd International Conference on Distributed Computing Systems Workshops, 2003. Proceedings.*, IEEE, 2003, pp. 200–206.

[5] "Real-time ASP.NET with SignalR," http://www.signalr.net/, 2021.

[6] Vaughan, M. P., and Kelley, B. N., "Bootstrapping Multi-Agent Unmanned Aerial Vehicle (UAV) System Integration Using Ground-Based Assets: Lessons Learned," 2021.

[7] Cross, C. D., Motter, M. A., Neilan, J. H., Qualls, G. D., Rothhaar, P. M., Tran, L., Trujillo, A. C., and Allen, B. D., "Towards an Open, Distributed Software Architecture for UXS Operations," 2015.

[8] Quigley, M., Conley, K., Gerkey, B., Faust, J., Foote, T., Leibs, J., Wheeler, R., Ng, A. Y., et al., "ROS: an open-source Robot Operating System," *ICRA workshop on open source software*, Vol. 3, Kobe, Japan, 2009, p. 5.

[9] Thomas, D., Woodall, W., and Fernandez, E., "Next-generation ROS: Building on DDS," *ROSCon Chicago 2014*, Open Robotics, Mountain View, CA, 2014. https://doi.org/10.36288/ROSCon2014-900183, URL https://vimeo.com/106992622.

[10] Idris, H., and Shen, N., "Estimating airspace capacity based on risk mitigation metrics," *Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), Chicago*, 2013.

[11] Ishihara, A., Idris, H., and Xue, M., "A Framework for Sense and Follow Convoys for Collective Autonomous Mobility," AIAA Aviation, 2021.