UAS Traffic Management (UTM) Simulation Capabilities and Laboratory Environment

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Abstract—**NASA has engaged in collaborative research with the FAA and many other stakeholders in government, industry, and academia to explore the concepts and requirements necessary to enable the safe and scalable application of small unmanned aircraft systems (UAS) in low-altitude airspace. In this effort, the UAS Traffic Management (UTM) project has developed a multi-faceted simulation component that supports near-term live flight testing in addition to further term concept exploration. This paper provides an overview of the simulation capabilities currently available as part of the UTM project and the laboratory environment in which they are applied.**

Keywords—UAS; UTM; simulation; laboratory

I. INTRODUCTION

The types and number of proposed civil and commercial applications of unmanned aircraft systems (UAS) are numerous. From security, to disaster management, to parcel delivery, the opportunities and potential benefits afforded by UAS applications abound. The growth in existing exemptions and forecasts are a testament to the desire to pursue these opportunities and are indicative of the growing demand for access to the National Airspace System (NAS) for UAS. For example, an analysis of Section 333 exemptions granted by the FAA, which allows small UAS operators access to low-altitude airspace for commercial use, showed that there was an increase in the rate of exemptions granted from six to 249 in the first nine months of the program [1]. The increasing trend has continued with over 1,000 exemptions granted in January and February of 2016. The FAA's aerospace sales forecast of small commercial UAS also projects an increase in line with the trend for exemptions where sales are forecast at 0.6 million units in 2016 and to rise to 2.7 million units by 2020 [2].

Given the clear demand for the many applications of small UAS, NASA has been engaged in a research and development effort with UAS Traffic Management (UTM) to develop and evaluate the concepts, technologies, and requirements necessary to enable safe, scalable, and equitable access to low-altitude airspace for small UAS [3]. NASA has also been working closely with the FAA through a Research Transition Team (RTT) to explore the problem space together in order to gain a better collective understanding of the technologies, architecture, data exchanges, etc. necessary to realize the goals of UTM. A number of stakeholders and partners from government, industry, and academia have also been engaged in this collaborative endeavor.

To explore the requirements and concepts needed for an environment in which the many applications of small UAS and the numbers of envisioned operations is realizable, it is not feasible from a cost or safety standpoint to exclusively test through live flight operations. In that regard, a number of simulation capabilities are utilized in support of UTM research that serve as a platform for different aspects of the project such as software development and testing, flight test support, and Human Systems Integration (HSI) research. Another affordance provided by the simulation capabilities that have been developed is the ability to simulate and test the different types of operations and environments that emerge in the process of concept development. This ability provides a glimpse into the possibilities that exist, and helps to guide and inform the research and development process.

The Airspace Operations Laboratory (AOL) at NASA Ames Research Center hosts the initial test environment that has been implemented as a UTM laboratory [4]. This paper will describe the various aspects of the simulation capabilities used in support of UTM research. The architecture and tools available will be discussed in addition to the role that simulation has played thus far. The UTM laboratory environment in which the simulation capabilities are developed and applied will be presented as well.

II. LABORATORY AND SIMULATION ARCHITECTURE

The progression of UTM is divided into four technical capability levels (TCL). Each TCL is differentiated by the level of risk associated with the assumed environment and the types of operations envisioned. Fig. 1 presents an overview of each TCL where one can see the increase in complexity and risk moving from TCL1 to TCL4. Each capability level is expected to have a 12-18 month simulation and development cycle culminating in live vehicle flight demonstrations at the end of each TCL.

A research platform has been developed to enable the testing of capabilities encompassed by a given TCL. This platform is comprised of a set of web services that are accessible from a remote server by clients that have been implemented according to the published interface control document (ICD) [5]. Development of this research platform is

ongoing, which requires multiple servers to host the software and services that are in different stages of development. Fig. 2 presents the current architecture where a number of separate platforms have been established internally within the AOL and the outward facing current release is also available.

Capability 1	Capability 2	Capability 3	Capability 4
• Airspace volume use notification • Over unpopulated land or water • Minimal general aviation traffic in area • Contingencies handled by UAS pilot • Enable agriculture, firefighting, infrastructure monitoring	• Beyond visual line-of-sight • Tracking and low density operations • Sparsely populated areas • Procedures and "rules-of-the-road" • Longer range applications	• Beyond visual line-of-sight • Over moderately populated land • Some interaction with manned aircraft • Tracking, vehicle-to-vehicle, internet connected • Public safety, limited package delivery	• Beyond visual line-of-sight • Urban environments, higher density • Autonomous, vehicle-to-vehicle, internet connected • Large-scale contingencies mitigation • News gathering, deliveries, personal use

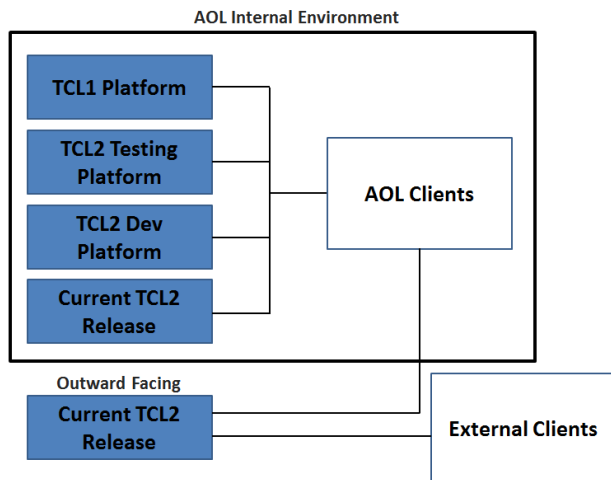Fig. 1.   UTM Research Technical Capability Levels

Fig. 2.   Current architecture of research platform development

With reference to Fig. 2, the AOL internal environment is shown to consist of four research platform instances. The TCL1 Platform hosts the software that was released as the transition was made from TCL1 to TCL2. The TCL1 capabilities that were developed and tested remain functional and accessible for demonstration and comparative purposes. The TCL2 Testing Platform hosts the latest version of software that has gone through preliminary unit testing and deemed ready for more rigorous testing in the AOL before deployment to the outward facing server. The testing of new features and client compatibility is primarily done on the TCL2 Testing Platform, which is an important step in the preparations for flight tests and demonstrations. The TCL2 Dev Platform hosts recent builds of the software that must first undergo basic testing before deployment to the testing platform. The Current TCL2 Release server hosts the same version of the software that is on the outward facing server. Having an internal copy of what is outwardly accessible allows for isolated internal testing that will not impact external clients (and vice-versa). This provides researchers with greater control of the test environment while using the most stable version of the software. The outward facing research platform is external to the AOL environment, but is accessible by the laboratory's many clients. It is also accessible from other external clients that are properly credentialed. This research platform is the primary platform used in the live field tests and UTM flight demonstrations. The accessibility of the AOL's clients and other simulation capable partners provides live, virtual, constructive (LVC) capabilities where simulated traffic can be inserted into the live test environment to test interactions that would not be possible or advisable with physical vehicles alone.

III. CLIENT AND APPLICATION DEVELOPMENT

The published ICD provides developers with the information necessary to develop clients and software applications that interface with the UTM research platform. The UTM research team has developed a number of clients and applications that provide simulated and live flight capabilities as well as the display of UTM information and the ability to interact with the UTM research platform.

A. Flight Related Client Development

In the context of UTM, a client is what provides external applications the ability to connect to and interact with the research platform. One type of client that has been developed is related to simulated and live flight operations within the UTM environment. There are currently two main clients in use with regard to flight that have been developed internally.

1) Python Client

The first client is a Python-based application that has been the primary client used by the UTM research team for live flight testing and demonstration. It has also been used in preparatory simulations leading up to flight events. In its current form, the client interfaces with the Mission Planner ground control station application to create operational plans and volumes based on waypoint path definitions. The client is able to establish a web-based connection to the UTM research platform, which allows the operator to submit plan proposals and receive message responses from the research platform. During live and simulated flight, the client is also able to send vehicle position updates to the research platform. The client also enables the sending and receiving of messages regarding the associated operation.

2) Multi-Aircraft Control System

The second client currently in use by the UTM research team is incorporated in the Multi-Aircraft Control System (MACS) [6]. MACS provides users with the ability to develop custom, map-aided flight profiles and operational volumes that can be submitted to the research platform. The MACS client is also capable of simulating the flight of fixed wing and multi-rotor UAS according to the developed profiles while sending position reports. Any number of flights is able to be operated in autonomous and manual modes. Controls provide the user the ability to perform specific maneuvers during flight, which is particularly helpful in simulating and testing off-nominal or contingency cases. Fig. 3 presents a configuration of a MACS operator station and UTM client interface, which includes the

UTM message window, vehicle control panel, map overview display, and route display.
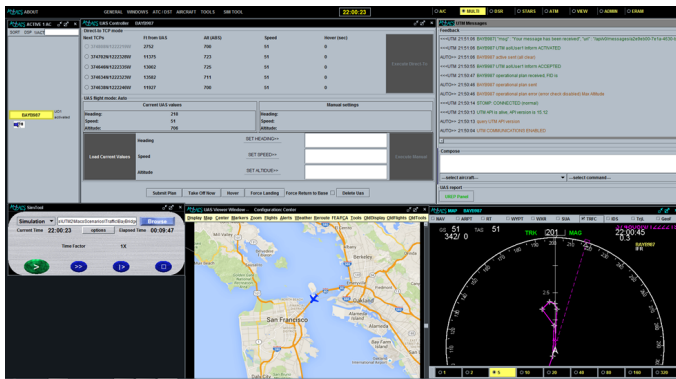

Fig. 3.   MACS operator station and UTM client interface

An additional feature incorporated into MACS is an interface to the Google Earth program. The interaction between MACS and Google Earth allows for vehicles that are being simulated in MACS to be rendered in Google Earth. Vehicle models are displayed in the appropriate geographic 3-D location and updated in real-time according to the position updates of the simulated flight in MACS. Fig. 4 presents an example of a simulated flight as it is viewed in Google Earth.

Fig. 4.   Simulated flight in MACS rendered and updated in real-time in Google Earth

B. Interactive Display Applications

1) Google Earth Gateway

The feature that allows MACS and Google Earth to communicate and display simulated flights was extended to become what is referred to as the Google Earth Gateway. Instead of connecting directly to a single instance of MACS for its vehicle position input, the Gateway connects via web sockets to the UTM research platform. This connection allows the Gateway to pull in position data for all active vehicles in the UTM system and, in turn, display any of them in Google Earth. The ability to read position data from the research platform not only means that the input source is no longer limited to a single MACS station, but that the Gateway is also

no longer limited to simulated flights. Because the UTM research platform is agnostic as to whether an operation is live or simulated, the Gateway is able to complement the LVC capabilities and activities by being able to display live and simulated traffic alike.

2) UTM Desktop Application

Another application that has been developed in the AOL for use in research and testing is a desktop UTM application. Early on it was understood that an important area of research was that of information display. The UTM desktop application connects to the research platform with elevated privileges that enable the operator to view information about all operations within the UTM environment and view them in a table and map format (Fig. 5). The desktop application is not limited, however, to simply displaying operations but allows users to interact with the UTM system through messaging and control of operational states. This application is currently in a re-design phase, but the nature of its purpose remains consistent by providing researchers a means to gain situational awareness and research platform interactivity during simulated and live testing, and helps researchers further understand the information and display needs of the UTM environment.
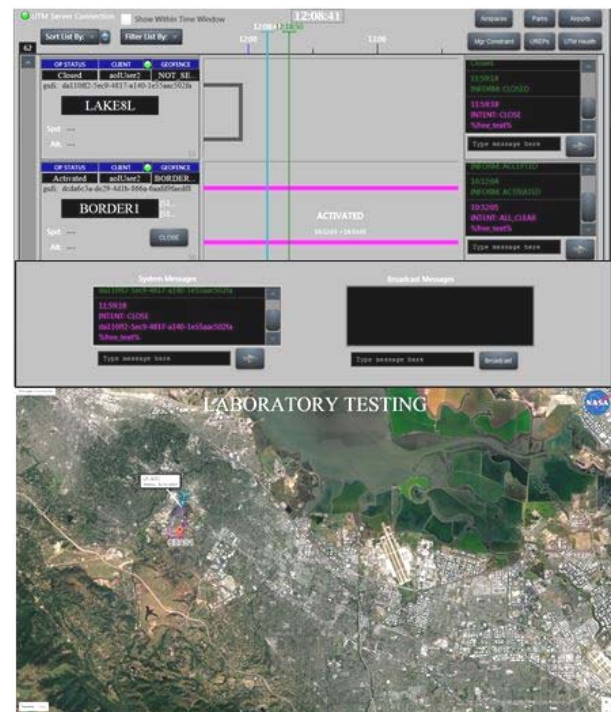

Fig. 5.   Desktop UTM application table and map view

3) Mobile UTM Application

An iOS application for mobile devices has also been developed for the display of information and interactivity with the UTM research platform. Able to be run from an iPhone or iPad tablet, this application is used extensively in support of software testing, simulations, and live flight operations. The application provides users with a connection to the research platform and displays information for operations, constraints, messages sent and received, as well as system status.

Information regarding flights within the UTM environment is presented in either a table view or Airspace map view (see Fig. 6). The operations presented in the table view are sortable and filterable according to the needs of the user. Selecting a specific operation in the table view results in a detailed map view of that operation, which includes its operational state and geographies, operator details, and a history of messages sent and received by the vehicle's operator. The application also provides users the ability to interact directly with the research platform and operations as well. Another feature of the mobile application is its ability to interact with the Google Earth Gateway described previously. This interaction allows the user to select specific operations and remotely "push" them onto a display for viewing in Google Earth. Similar to the desktop application, the mobile application provides researchers with the means to explore the display and information requirements of the UTM environment.
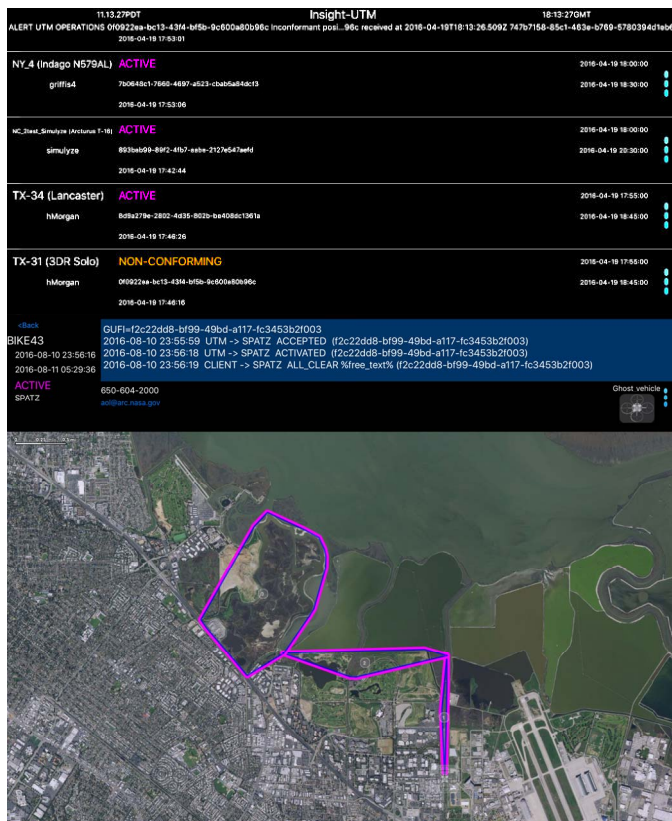

Fig. 6. Mobile UTM application table (top) and airspace (bottom) views

IV. SIMULATION AND SUPPORT ACTIVITIES

The research being performed in UTM covers many areas and requires broad support. The AOL's primary roles in this respect are preparations for live flight tests, concept development and testing through simulation, and LVC integration.

A. Flight Test Support

Throughout the course of each TCL, a number of live flight test activities are scheduled. The schedule culminates with a final flight activity that demonstrates the many capabilities encompassed by the given TCL. In support of these activities, the AOL leverages the available clients and applications described thus far as well as the simulation capabilities that they provide.

The first step in providing support for flight testing is in the development of flight profiles that the vehicles will fly. This effort starts by considering the activities that need to take place during each flight that will test and verify various aspects of the UTM software. This step involves developing the high level scenario that will address those aspects, and then considering what paths of flight will satisfy the scenario goals. Once the notional flight paths are decided upon, the next step involves developing the actual flight profiles for further testing.

The current ground control station software used internally is based on the open-source Mission Planner software. As such, flight profile development is done using Mission Planner, which can then be loaded directly onto the test stations and vehicles for the actual tests. Fig. 7 presents an example of this early process where a vehicle's flight profile is first being developed. At this stage, the path that the vehicle will fly is created using the Mission Planner interface. The path shown includes the waypoint positions, altitudes, and speeds according to the flight's mission and vehicle type.

Once the initial profile has been developed, a simulated vehicle is flown using Mission Planner in order to ensure that the parameters used are correct and the timing of the flight is appropriate for the endurance of the anticipated vehicle. Once a desirable profile is achieved, a waypoints file is output containing all of the profile's parameters. The resulting file can be used for control of the vehicle in an automated flight mode.
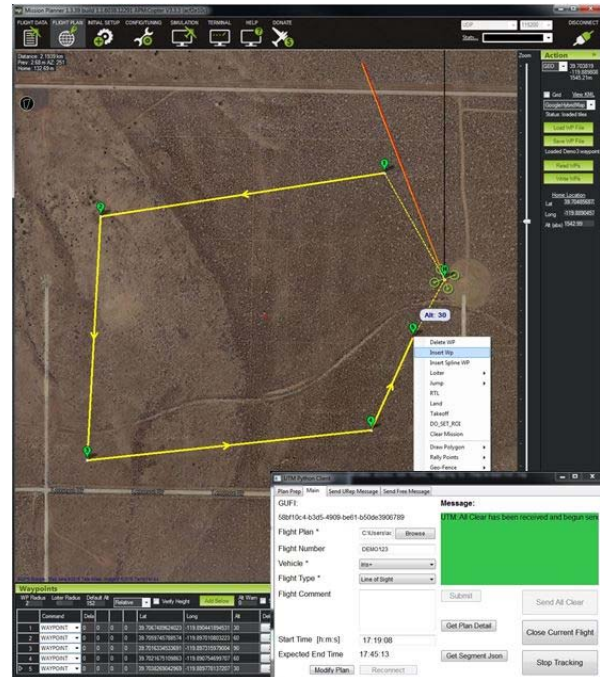

Fig. 7. Flight profile and volume development using Mission Planner and Python client (lower right)

The output waypoints file also serves another purpose, which is to provide the basis for the operational volumes that are sent to the UTM research platform and define the area that the vehicle will operate. The Python client discussed earlier and displayed in the lower right of Fig. 7 is able to read in a Mission Planner waypoints file and allows the user to group waypoints into desired operational volumes. The durations for each volume and their associated altitudes are also included. The resulting information can then be submitted to the UTM research platform as an operational plan to ensure that it does not violate any constraints and is accepted for flight. The operational plan can also be stored in a file to be used during flight activities.

B. Concept Development and Testing

Conducting flight tests and demonstrations is an important part in the progression of UTM. The tests provide an accurate assessment of the state of development and give insight into some of the more practical issues that operators may eventually face. However, the logistics and safety considerations involved in conducting live flight tests means that only a limited number of vehicles can participate and that the test environment needs to be tightly controlled. This leaves little room to examine some of the further term conceptual issues that may involve, for example, high density operations and large-scale contingency management.

The UTM simulation capabilities provide the means to develop and test conceptual aspects in a safe and repeatable environment. These capabilities have also proven to be an effective way to test new features and functions of the software before deployment to the outward facing research platform.

The primary software used for simulation has been MACS. Prior to UTM, MACS has been used in the AOL and elsewhere to conduct human-in-the-loop research in the areas of air traffic control and management. Its adaptation to UAS Traffic Management has enabled researchers and developers to leverage some of the existing features and functionality in order to be able to relatively quickly create and test specific types of interactions and situations.

An important part of creating the types of complexity needed to test concept areas is scenario development. Researchers can take existing and proposed use cases, or develop their own with respect to testing, and translate them into operations that will exist on the UTM research platform and are observable through the many available display applications.

To develop scenarios, MACS includes a number of scenario editing features. Fig. 8 presents the scenario editor interface in MACS. The upper middle portion in the figure shows the scenario editor map feature with a defined path of flight. Use of the map enables the scenario developer to plan operations with a degree of precision, and to see how multiple operations may interact through the editor's time controls.

An operation's path can be developed by first extending a vehicle's route and pointing and clicking at each point that a new waypoint, hover, or landing point is desired. The window in the upper left portion of Fig. 8 presents the list

representation of a flight path, which enables the user to specify different values for a given waypoint (e.g., altitude, speed, hover time, etc.) as well as the leg parameters between points. The upper right portion of Fig. 8 shows the operational volume editing feature in the scenario editor where the user can specify the lateral and vertical area in which the operation is expected to remain within and the duration as well. Note that the example includes a single volume. This is indicative of TCL1 operations where an operation's volume occupied the specified location for the entirety of its duration. In TCL2, segmented operational volumes were introduced that allowed for multiple volumes to be associated with a single flight with different individual durations. This feature results in the airspace occupying less space per volume and each volume can time out in succession, releasing the airspace for other users. Fig. 9 presents the editing capability in MACS where a user can specify features of a flight's operational volumes.
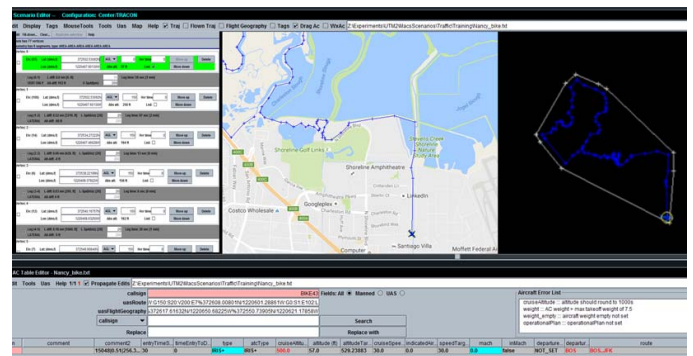

Fig. 8. Flight profile development using scenario editing features in MACS
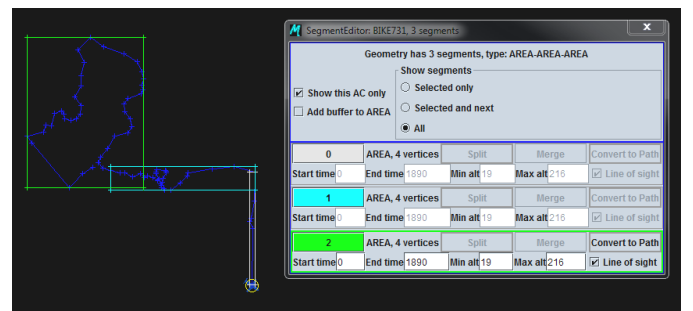

Fig. 9. TCL2 multi-segment editing feature in MACS

C. Live, Virtual, Constructive (LVC) Activities

In addition to simulations, research in the area of UTM requires multiple live flight tests and demonstrations. While the live aspect of the tests demonstrates certain functionalities and approaches to meeting requirements, there are limitations to what can be accomplished given cost and safety considerations. UTM research platform and simulation capabilities enable an LVC testing environment through the ability to integrate simulated flights and services with live flights. This type of environment allows researchers to evaluate features that would otherwise not be practical to test in a live setting such as high density operations or off nominal events with vehicles in close proximity.

A recent example of LVC applications in UTM research was a large-scale demonstration referred to as the National Campaign [7]. In this demonstration, six FAA test sites across the United States conducted multiple, simultaneous operations. The UTM research platform unified these operations and provided a common operating picture in which all participating vehicle clients were connected and provided operation plans and vehicle position updates.

The event took place over the course of three hours. The first hour was dedicated to live flights where a total of 27 flights were conducted and a maximum of 20 simultaneous flights occurred at a given time. In the second hour, simulated traffic from the AOL was introduced to the UTM environment and integrated with the live flights. Over the course of the second hour, a total of 45 flights were conducted. Of that total, 24 flights were performed by live vehicles while the remaining 21 were simulated. A maximum of 33 simultaneous operations were achieved at a given time in the second hour. For the final hour of the National Campaign, the test sites were allowed to complete as many flights as desired with the same allowances for simulated flights. This meant that when an operation ended, it was re-deployed and entered the UTM research platform as a new and unique operation. Over the course of the final hour, a total of 100 unique flights were conducted. Of those 100 operations, 54 were live flights while 46 of the remaining flights were simulated from the AOL as well as an external partner. A maximum of 43 simultaneous flights took place at a given time in the last hour. Fig. 10 provides a visualization of the number of flights that took place in the final hour with a breakdown of the live and simulated flights' contributions to the number over time.
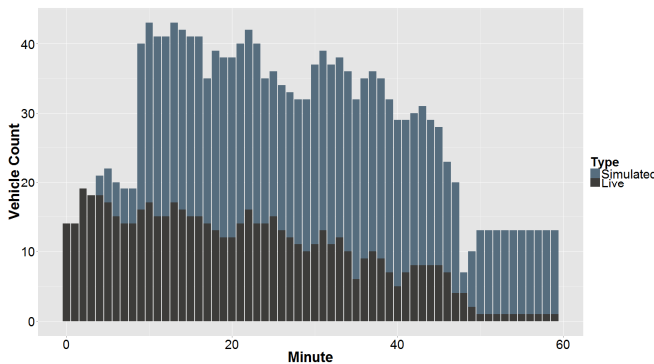

Fig. 10. Plot of live and simulated traffic in the final hour of the National Campaign

The simulated flights used in the National Campaign were developed in the simulation laboratory and designed to take place near the planned live operations. The intent of these simulated flights was to increase the density of operations, provide additional complexity for the research platform to accommodate, and to more formally test the UTM LVC capabilities. The UTM research platform is agnostic as to whether the external data coming in is from live or simulated flights. Fig. 11 presents an example of this where the position data reported from live and simulated traffic are plotted in relation to the lateral boundaries of their protected geographies. Although the colors of the plotted paths are intentionally different to provide easier differentiation, it should be clear that the flights represented are essentially the same from a system perspective. This provides support and a rationale for using LVC capabilities to test areas of the UTM concept that are impractical to do so by solely using live flights.
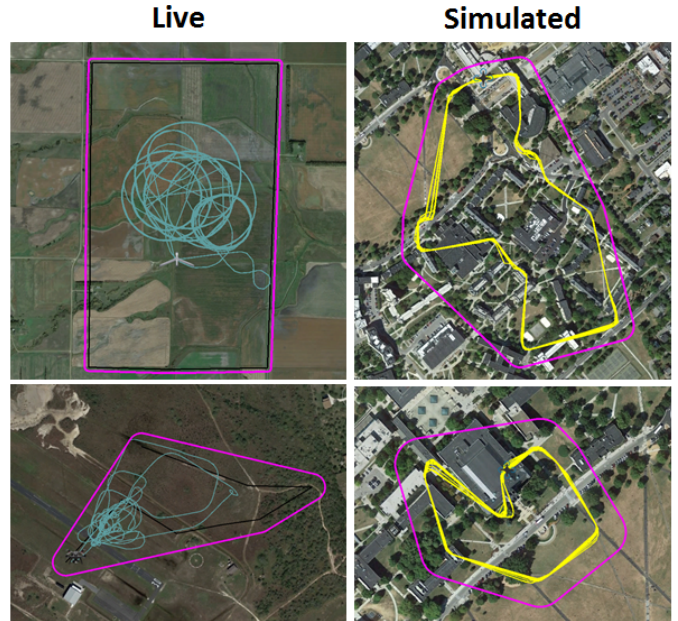

Fig. 11. Plots of live (left column) and simulated (right column) traffic from the National Campaign

V. LABORATORY ENVIRONMENT

Located at NASA Ames Research Center, the Airspace Operations Laboratory hosts the initial test environment for UTM. Although the entire facility can and has been used to support research efforts in UTM, the majority of the work is concentrated in two particular areas. The first area is a smaller development room that houses six desktop workstations and a number of mobile devices. This area of the laboratory is typically where flight profiles and scenario development take place. It is also where the majority of software testing occurs. The desktop workstations are all networked with all of the other workstations in the laboratory and are able to run MACS. These workstations also have Mission Planner installed as well as the Python client, which provides researchers with alternatives in flight profile development and testing.

The other UTM research area in the AOL similarly has a number of networked desktop workstations and mobile devices. Most notably, this area also contains a large, twelve-screen display wall (Fig. 12). Given the layout of this particular area, it is primarily used for demonstrations and situation awareness during flight tests and events such as the National Campaign. The display wall is configurable to show a number of different applications and perspectives of operations. Fig. 13 presents the configuration used during the National Campaign event. The left display wall in the figure is shown to host the map displays of six UTM desktop applications that are in the lab area. The left panels of the right display wall show the

airspace views of the mobile UTM application. The remaining panels of the right display wall are shown to have independent Google Earth instances running. These displays are connected to the UTM research platform via the Google Earth Gateway application, which displays a selected flight in Google Earth with real-time updates based on the vehicle's reported position. An additional feature of the setup just described is the ability to selectively view specific flights on the display wall's Google Earth displays. This is done through the mobile UTM application's "push-to-wall" feature in which a particular flight of interest is accessed through the Operations or Airspace page of the application, a specific display panel is selected to "push" the flight's view to, and then the display shifts to the selected flight and begins tracking immediately.

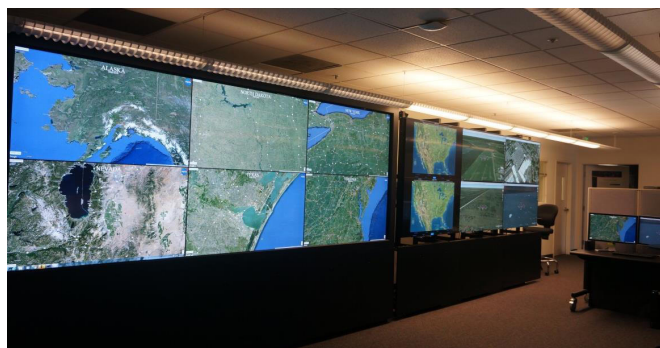Researchers in the foreground of the display wall showing the desktop UTM application

Fig. 12. Display wall configuration

VI. FUTURE WORK

As the UTM concept and development efforts evolve, the research performed in the AOL and the capabilities available will adapt accordingly. For example, as architectures are proposed for data exchanges and distributed service supplier environments, research and testing will be done to better understand the requirements and issues surrounding the different possibilities. Work will also begin to explore the human/autonomy teaming aspect of envisioned operations as well as contingency management in that context. Collaborative research is also underway to examine the integration of UTM with disaster relief management systems and the interaction of manned and unmanned aircraft systems. These are but a few of the directions that will be taken as research continues in UTM.

VII. CONCLUSION

The UTM project and the research efforts involved require significant use of simulation capabilities. NASA has developed a powerful research and development platform capable of addressing the multitude of questions that need answers in moving forward. The UTM laboratory is ideally suited to progress the state of UTM research and knowledge through its many capabilities and the infrastructure developed to support further efforts.

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