Flight Demonstration of Unmanned Aircraft System (UAS) Traffic Management (UTM) at Technical Capability Level 4

Joseph Rios[1], Arwa Aweiss[2], Jaewoo Jung[3], Jeffrey Homola[4], Marcus Johnson[5], Ronald Johnson[6]
NASA Ames Research Center, Moffett Field, CA, 94035, USA

The NASA Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Project executed the fourth and final UTM Technical Capability Level demonstration between May and August 2019. Two Federal Aviation Administration (FAA)-designated UAS test sites managed the range, partners, and operations to meet the requirements set forth by the UTM Project. All stakeholders supported the execution of the flight testing through close collaboration. Results of the demonstration indicate the viability of the UTM concept to manage large scale operations and contingencies in an urban environment. The demonstration also provided insight into key technological gaps that must be addressed before such operations are routine, safe, and efficient. Standardization efforts related to UTM and the industry participants of those efforts can leverage the results and experiences of this flight activity to accelerate and more firmly ground forthcoming standards. The FAA and other regulators will be able to leverage results to inform future rule-making and identify additional gaps that require further analysis.

I. Introduction

UTM is a novel approach to managing the airspace for small UAS (sUAS) operations. In the United States, UTM is envisioned as "the manner in which the FAA will support operations for sUAS operating in low altitude airspace [1]." UTM is novel in the sense that it does not rely on a centralized system to provide management services, as they have been traditionally provided for aviation. "UTM utilizes industry's ability to supply services under the FAA's regulatory authority where these services do not currently exist. It is a community-based traffic management system, where the Operators and entities providing operation support services are responsible for the coordination, execution, and management of operations, with rules of the road established by FAA [1]."

UTM is both a federated set of services and a framework for managing low-altitude sUAS operations. It is part of the National Airspace System and interoperable where necessary with traditional Air Traffic Management (ATM) and Air Traffic Control (ATC). UTM was designed to meet the needs of several stakeholders including the operators for sUAS and the FAA. The UTM ecosystem can offer services for flight planning, communications, separation, and weather, among others. This novel approach to managing air traffic leverages UAS Service Suppliers (USS) to interoperate and support operators in sharing their intents, strategically deconflicting, providing appropriate airspace updates, and other key functions. For more details on the UTM concept of operations, see Ref. [1] and Ref. [2].

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[1] Research Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Senior Member.
[2] Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Senior Member.
[3] Aerospace Technologist, Aviation Systems Division, Mail Stop 210-6, Senior Member.
[4] Aerospace Technologist, Human Systems Integration Division, Mail Stop 262-4.
[5] Research Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Member.
[6] Aerospace Engineer, Aeronautics Research Directorate, Mail Stop 210-3, Senior Member

A series of four Technical Capability Levels (TCLs) were defined by NASA to develop and test the increasing capabilities of UTM needed to manage more complex UAS operations. NASA successfully progressed through several phases of flight testing, with TCL4 being the final such demonstration. The major events are summarized in Figure 1. The tests were performed at different test locations, including the FAA-designated UAS test sites.

Figure 1. Summary of major NASA UTM flight testing activities.

The final TCL, TCL4, demonstrated sUAS operations with the following features as defined by the NASA UTM concept of operations [2], supported by the UTM System:

1. Beyond-visual-line-of-sight operations
2. Urban environments, higher densities
3. Autonomous vehicle-to-vehicle (V2V) capabilities, Internet-connected systems
4. Large-scale contingency mitigation

The TCL4 environment and capabilities were planned to support use cases for news gathering, deliveries, and personal use. These capabilities and use cases were additive from the previous TCLs and thus encompass interactions with manned aviation, individual operation contingency management, vehicle tracking, and public safety operations, amongst others. A goal of TCL4 was to investigate system responses to real-world events related to these use cases. For example, UAS-to-UAS and UAS-to-manned aircraft encounters, weather events, and emergency priority operations.

II. Approach

To engage the FAA-designated test sites in the TCL4 testing, six of the FAA-designated UAS test sites were provided a Statement of Work (SOW) to which they provided proposals. The SOW was written with detailed scenarios and technical requirements. A lesson learned by the UTM Project and the test sites from previous UTM flight tests (specifically TCL1, National Campaign I [3], TCL2 [4, 5], National Campaign II [6], and TCL3 [7, 8]) was that too much flexibility in the scenario requirements led to inadequate coverage of Project goals and discrepancies in trying to compare results across test sites. Thus for TCL4, five specific scenarios with key characteristics and test events, including a mix of live and simulated operations, were provided as part of the SOW. NASA evaluated the SOW responses and selected the Nevada Institute for Autonomous Systems (NIAS) and the Lone Star UAS Center of Excellence & Innovation (LSUASC) located in Nevada and Texas, respectively, to execute the TCL4 Demonstration. The test sites were responsible for forming their team of industry, government, and community partners, developing test plans per the SOW, and ultimately executing the flight tests to provide the required data to NASA. In total there were 27 unique industry and city partners across the two sites.

A. Scenarios

The primary research goals of TCL4 were to collect data to understand the requirements regarding safely enabling large-scale beyond visual-line-of-sight (BVLOS) sUAS operations in urban environments; evaluate the small UAS Detect and Avoid, Communications, Navigation, and Remote ID technologies available at the time of the demonstration; evaluate UTM services being developed to address technical and operational challenges of urban operations; and identify gaps in the capabilities of current technology which would be needed to enable urban operations. The TCL4 demonstration was scenario-driven and integrated different research objectives into each scenario. The five scenarios were created and designed by NASA to represent a "day in the life of UAS operations" in a geographic region and focused on the research challenges associated within various UTM focus areas.

Scenario 1

In an urban environment, nominal high density UTM operations are taking place with multiple mission types and use cases being carried out. A simulated weather event is forecast to impact the area, which results in a warning region being established in the form of a UAS Volume Reservation (UVR). Operators with current or planned operations within the UVR geometry respond by returning to the launch point, re-planning to utilize an identified safe landing location that is de-conflicted from other operations, or avoiding takeoff from within the UVR.

Scenario 2

A pop-up concert takes place at a local venue that results in a number of UTM operations in the area supporting a variety of use cases reaching medium to high density traffic levels. An incident, like a fire or a medical emergency, occurs at the concert resulting in a UVR being established to allow for a Public Safety UTM response and clearance of non-essential operations from the area. Those operations clearing the UVR must replan and de-conflict to ensure safe exit. UTM-enabled Remote ID is used to identify and contact operators that have not cleared the area. Special access to the UVR is granted for news coverage in addition to the public safety vehicles.

Scenario 3

UTM operations are being conducted in the vicinity of an active airport with a medium density of sUAS operations. Reported events take place that require Remote ID of specific operations as well as security responses to monitor situations near the airport. Piloted general aviation aircraft are conducting flights in the area and one aircraft's path results in a conflict with a UTM operation's operation volume with a subsequent response from the UAS operator. Another operation experiences a loss of communication that results in the transition to a Rogue state, communicated to nearby operations with resulting maneuvers to avoid.

Scenario 4

High density UTM operations are taking place in an urban environment. A simulated low battery situation forces a vehicle to land quickly, which requires nearby operations to re-plan and avoid the landing vehicle. Later, large-scale loss of communication and navigation events are experienced that require contingency management procedures in response. Remote ID is requested to identify vehicles that are reported to be congregating in a particular area during the events.

Scenario 5

Multiple events are taking place in a suburban area, which draws a gradually increasing number of sUAS performing a variety of supporting missions. The increase in density is accommodated through strategic deconfliction that eventually requires UAS Service Supplier (USS) negotiations for re-planning or agreement to allow overlapping Operation Volumes. Operational density in one area increases with subsequent negotiations that result in shared airspace for multiple vehicles and a transition to cooperative separation. One USS supporting multiple operations experiences a critical failure, which results in contingency management procedures for affected flights and a switch to an alternate USS where able.

B. Test characteristics

Test Characteristics (CH) were used to help define the flight environment in which operations were to be conducted, and the types of flight profiles needed to fulfil a given scenario. The general categories of CHs are described in Table 1.

Table 1. Summary of Test Characteristics for the TCL4 Flight Demonstration.

Category	Description	Scenarios
Density of Operations	Number of UAS airborne within an identified area	1, 2, 3, 4, 5
Tempo of Operations	Number of takeoffs and landings within an identified area	1, 4, 5
Operation Volume Types	Area Based Operation Volumes (ABOV) or Transit Based Operation Volumes (TBOV) identified in an operation	1, 2, 3, 4, 5
Airspace Type	Operation in controlled or uncontrolled airspace	1, 2, 3
Ground Obstructions	Operation proximity to structures / buildings	1, 4
Obstruction Types	Operation proximity to Dynamic or Static obstructions	4, 5
Automated Launch/Land	UAS launch or land location relative to operator location (co-located or remote)	1, 3, 4, 5
Flight Profiles	General classes of flight profiles such as linear inspection, and area inspection	1, 2, 3, 4, 5
Launch/Landing Profiles	UAS launch or land at combinations of ground and rooftop locations	1, 4
USS Negotiations	USS requests for modifications of operations managed by other USS	1, 2, 3, 5
Priority Operations	Operations constrained by navigational capability (in-flight emergency) or responding to priority missions (public safety)	2, 3, 4
Remote UAS ID	UAS identification through or not through the USS network, by a terrestrial or aerial entity	2, 3, 4

USS Participation	Number of USS supporting operations and sharing data per USS specifications	1, 2, 3, 4, 5

C. Test Events

Test Events (TE) were used to induce changes to the environment or operation with the intent of exercising different technologies and procedures. The general categories of TEs are described in Table 2.

Table 2. Summary of Test Events for the TCL4 Flight Demonstration.

Category	Description	Scenarios
UAS Volume Reservations	An airspace restriction is enacted which limits the availability of the airspace to certain vehicles	1, 2
Conflicts	A UAS comes within a defined range of either manned aircraft, obstacle, or another UAS	1, 2, 3, 4, 5
Safe Landings	Landings within/outside of operation volumes, with operational/non-operational safe landing capability	1, 2, 3, 4
USS Impact	A USS is lost (stops providing service), or an Operation changes to a different USS	5
Unexpected Unmanned Aircraft (UA) Behavior	UA has an inflight accident or is flying in a reckless manner	4
Loss of C2	Small scale and large scale loss of C2 link based on the number of operations airborne	2, 3, 4, 5
Loss of Navigation	Small scale and large scale loss of navigation based on the number of operations airborne	2, 3, 4, 5
Remote UAS ID Query	UAS identification through or not through the USS network	2, 3, 4

III. Measures of Performance

Each UTM high-level requirement, originally presented in the NASA UTM ConOps document [2], has an associated Measure of Effectiveness (MOE). Ref. [9] states that an MOE is a “measure by which a stakeholder's expectations will be judged in assessing satisfaction with products or systems produced and delivered in accordance with the associated technical effort.” In addition, “[a]n MOE is typically qualitative in nature or not able to be used directly as a ‘design-to’ requirement.” Each MOE is supported by multiple MOPs, which are quantitative in nature. This approach and these terms are detailed in the NASA Systems Engineering Handbook [10], and a depiction is shown in Figure 2.

NASA identified twenty key Measures of Performance (MOPs) for TCL4, categorized into one or more of four categories as shown in Figure 3: data and architecture; sense and avoid; communications and navigation; and concepts. These categories align with the FAA-NASA Research Transition Team on UTM subgroups [11].

Figure 2. Relationship of high-level requirements, MOEs, and MOPs.

Concept	Concept/Arch	Architecture	Comm and Nav	Sense and Avoid
Pilot Assessment	Contingency Plan Response	Strategic Deconfliction Rate	Safe Landing Rate	Flight Containment
High Density Operations	Dynamic Priority Operation Replan	Dynamic Restriction Replan	Nav Loss During Conflict	V2V Reception
BVLOS Operations	Public Safety Deconfliction	USS Endpoint Security	C2 Loss During Conflict	Operator Alerting
	Remote ID Lookup	USS Latency	Rate of C2 Loss	Duration of Conflict
				Loss of Well Clear

Figure 3. Summary of Measures of Performance, organized by research focus.

The Concept MOPs focus on assessing pilot perspectives on the UTM System, and validating the ability of the system to handle high-density, BVLOS operations. The Architecture MOPs investigate strategic deconfliction of operations, replanning in the presence of dynamic restrictions, security of USS data exchanges, and latency of communications between USSs. The Communications and Navigation MOPs measure the rate of safe landings and various aspects of communications, control, and navigation losses. The Sense and Avoid MOPs focus on the containment of flights within operational volumes, vehicle to vehicle reception, operator alerting of conflicts, the duration of conflicts within UTM, and the frequency of loss of well-clear. There are also MOPs that cross the concept and architecture groups involving contingency responses, priority operations, and remote identification.

The results of each MOP will be published in detail in various venues as they are developed. Some initial results are summarized in Section V.

IV. Test Planning and Execution

The TCL4 flight test built up through several key steps. NASA researchers developed detailed scenarios, test events, and characteristics relevant to NASA's research goals. In this section the overall preparation and execution process is provided, followed by the plans by the NV and TX test sites to deliver on NASA's goals.

A. Planning

The SOW described in Section II was provided to the Test Sites in early Fall 2018. The schedule included therein had several key milestones. A detailed test plan was required as part of the SOW response. The selected Test Sites were then required to iterate on that plan with NASA to produce a second version that would ultimately guide the execution of the tests.

The finalized test plans were then used as the basis for two key activities with all test stakeholders: a tabletop walkthrough of all scenarios and a collaborative simulation. The tabletop exercise clarified the team's understanding of the flow of the flight test and helped identify gaps in terms of data collection, logistics, timelines, etc. The collaborative simulation involved all partners with several vehicles included as hardware-in-the-loop connected to their respective USSs as the test sites and NASA simulating the operations and communications, emulating the day-of-operations activities as well as possible.

The test sites were then required to execute shakedown flights in order to exercise their field deployment plans in their respective urban environments. In parallel with all of these activities, the USSs that were partnered with the test sites underwent software checkout processes [12] to ensure their interoperability and readiness to support the field activities.

B. Nevada

NIAS proposed a test range across two sites in Reno, Nevada and completed Scenarios 1, 2, and 4. Scenarios 1 and 4 occurred in the downtown area (see Figure 4) and Scenario 2 occurred in and around Idlewild Park. Scenarios 3 and 5 were not performed by NIAS, in order to focus efforts on NASA's higher priority requirements and to take advantage of fewer range reconfigurations.

NIAS had 25 partners. Of these partners, 18 participated directly in flight testing as industry and city partners. Five partners were UAS Service Providers (USS) [Uber Elevate, Airmap, AiRXOS (GE Venture), ANRA, and Avision Robotics] and six UAS operators [Uber Elevate, AviSight, Drone America, Switch, Utah State University, and AiRXOS].

Shakedown (practice) testing at Nevada took place May 15-23, 2019 and the official flight Demonstration occurred June 17-28. During the demonstration, NIAS had 144 live flights with a total active operation time of about 18 hours. During a given scenario and run, up to five live UAS flew concurrently. Additionally, more than 500 simulated flights were flown over the course of the demonstration concurrent with the live flights to create higher density UAS operations and to safely execute certain flight interactions.

Figure 4. Downtown Reno test range.

C. Texas

LSUASC proposed a test range across four sites in Corpus Christi, Texas and completed all five scenarios. Scenario 1, 3, 4, 5 occurred in the downtown (see Figure 5) and waterfront sites, Scenario 2 in the Arts and Entertainment district, Scenario 3 also involved operations at Corpus Christi Port and Corpus Christi airport.

LSUASC had 21 partners, 14 of which were industry and city partners. Three UAS operators [Near Earth Autonomy, LSUAC, and the Corpus Christi Fire Department] flew eight live UAS vehicles supported by seven USSs [five of those that participated in Nevada with the addition of One Sky (AGI) and Collins Aerospace].

LSUASC performed a tabletop exercise with NASA in May 2019 to step through the processes and operations. Then, shakedown testing was executed July 25-31, 2019 and the official flight Demonstration took place August 12-23, 2019. During the demonstration, LSUASC had 208 live flights with a total active operation time of about 37 hours. During a given scenario and run, up to seven live UAS flew concurrently. Additionally, more than 400 simulated flights were flown over the course of the demonstration concurrent with the live flights to create higher density UAS operations and to safely execute certain flight interactions.

Figure 5. Downtown Corpus Christi test range.

D. TCL4 Fleet and Equipment

Across the two test sites, there were 8 unique multicopters used (DJI M600, M200, M210, and Mavic; Air Robot AR200; Drone America Nav X; 3DR Solo; and Tarot X6) in the flight demonstration. Also, there were a variety of on-board and ground equipment and infrastructure on the UASs and at the sites such as radars, detect and avoid and obstacle avoidance technologies, communication and navigation technologies, parachute technology, and weather stations, that were used to support testing. UAS Command and Control (C2) communications equipment was in two variants, one that used the Industrial, Scientific, and Medical (ISM) frequency spectrum and another using Long Term Evolution (LTE) spectrum. GPS was the main navigation technology for participating sUAS.

E. Operational Incidents

While the vast majority of operations and vehicles performed as expected, there were a few occasions in which unexpected issues were observed. There were wiring issues with one of the UAS models resulting in the damage to two vehicles during hard landings. This necessitated the grounding of that model for some time during the testing window to address the issue. Radio frequency environmental issues caused damage to two vehicles while operating in the urban environment. The likely cause for the first was GPS multipathing[7], while the second exhibited command and control interference. These two incidents occurred on the same range on different days. Another model vehicle experienced multiple instances of control interference, but without an unplanned landing or vehicle damage. One vehicle was also moderately damaged due to an unexpected parachute activation, landing hard, but clear of people or property on the ground.

While the root causes of these incidents, and their eventual solutions, are distinct (wiring issues, RF environment problems, payload malfunction), there are general lessons to learn that are likely more valuable than solving the individual problems. Some of these are touched upon in the Lessons Learned subsection below. At a high level, it will be important to share information about off-nominal situations, including crashes, in an operational environment such that the entire UTM community can benefit from what is experienced by individual operations, operators, and manufacturers.

Manned incursions by medical helicopters into the test range occured in both Nevada and Texas. These incursions interrupted UAS operations and were handled procedurally by range safety personnel as such events were considered in the safety case for both ranges. UAS involved in TCL4 were always able to stay clear of the manned operations. These manned incursions happened in spite of test coordination with the helicopter dispatch. This highlights a known need within future UTM operational environments for appropriate integration with traditional aviation. That potential integration can take many forms, but is not discussed further in this document.

E. NASA Data Collection

Data collection and analysis were critical to the success of TCL4. USSs submitted data collected from the operations that they supported as well as data from the test sites as required by a Data Management Plan (DMP) [13, 14].

V. Findings

A. MOPs

In this section, some of the key results, and an example of the result, are summarized. Each MOP that is intended for external reporting is detailed in other publications. The following subsections group the MOPs by the publication in which they are more fully reported; for in-depth analysis and visualization of the results, please see the referenced publication.

USS Network Performance

The communication performance of the USSs is summarized by three MOPs fully reported in a NASA Technical Memorandum [13]. For example, network latency between USSs was the focus of UTM-MOP-13. The results for this MOP showed that latency is not a likely impediment to nominal operation of a future, operational UTM system, with the 95th percentile latency across all USS-USS messages being 532ms (see Figure 6). Results did indicate that performance requirements need to be developed on a per endpoint basis, as the processing required for the various USS endpoints can vary significantly. UTM-MOP-16 successfully demonstrated high density operations (at least 10 operations within 0.2nmi^2) with no observed negative network effects. To maintain this level of quality, USSs would have to horizontally scale their resources based on the geographical extents under their management, which is a reasonable expectation for modern web services.

[7] GPS multipath occurs when the radio signals from the GPS satellite(s) are received after traveling a variety of distances due to reflecting off of nearby objects, like buildings. This introduces uncertainty in the GPS calculations determining position.

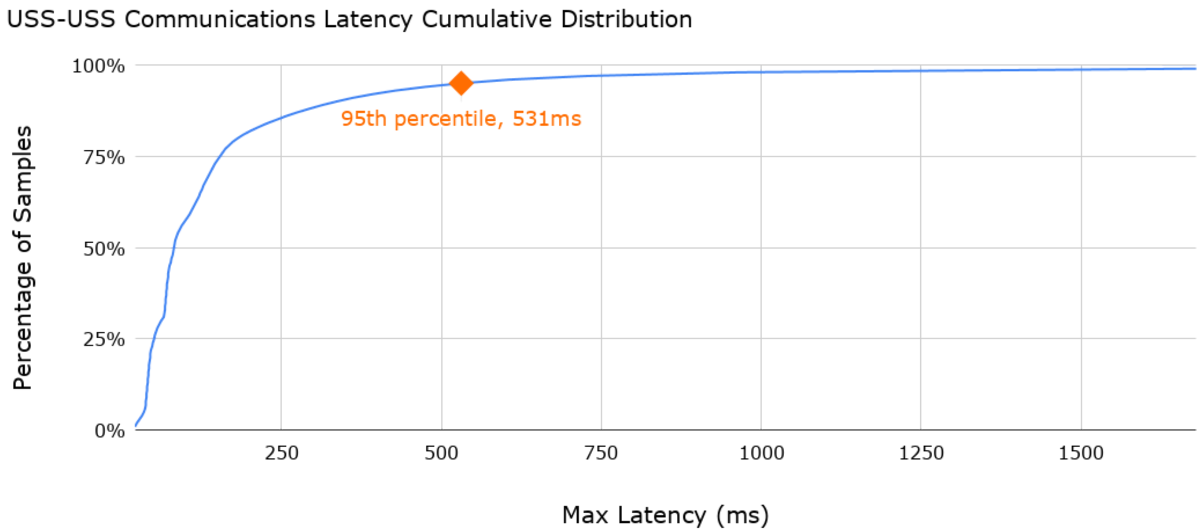

Figure 6. UTM-MOP-13 results for latency of USS-USS data exchanges.

Strategic Deconfliction

The performance related to the strategic deconfliction of UTM operations was measured in three MOPs and are fully reported in a NASA Technical Memorandum [15]. UTM-MOP-01 measured the overall strategic deconfliction rate and showed that USSs were able to use UTM protocols to strategically deconflict operations by meeting the overall minimum success criterion of more than 95% of nominal operations strategically deconflicted.

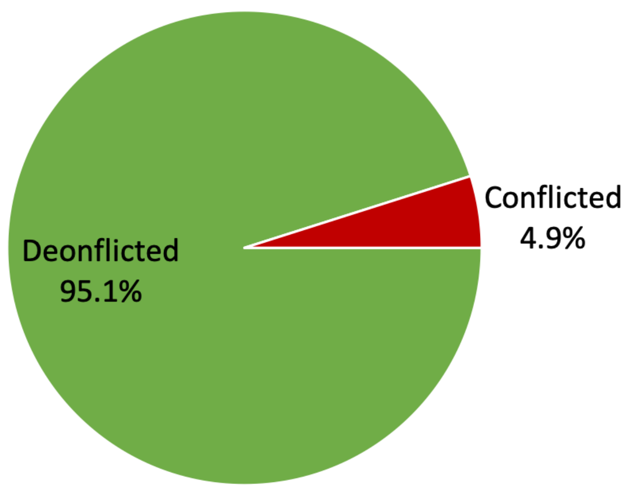

Figure 7. Strategic deconfliction results over 327 operations.

Communications and Navigation

The performance related to the communications and navigation of operations within TCL4 was measured in four MOPs reported in a NASA Technical Memorandum [16]; the results are briefly summarized here. Two of these MOPs rely on a TCL4 definition for a conflict. UA-to-UA conflicts were defined as being within 700ft horizontally and 200ft vertically of each other. Note that this does not imply or state any standard or accepted definition of well-clear for sUAS, but provides a reasonable set of values for testing purposes. Also note that operations may be strategically deconflicted and still be in "conflict" via this definition.

Rate of safe landing was measured in UTM-MOP-05. Of the 219 landings used in this analysis, 117 (~53%) occurred within 3m of a planned landing location or within an identified polygon, such as a contingency landing polygon, 26 (~12%) were outside of 3m but within 5m of a planned landing location, and 35 (~16%) were outside of 5m but within 10m of a planned landing location. The remaining operations also landed safely, but did so inconsistently with their operations plans, indicating a need to ensure intent is appropriately updated and shared in UTM. Figure 8 illustrates these values.

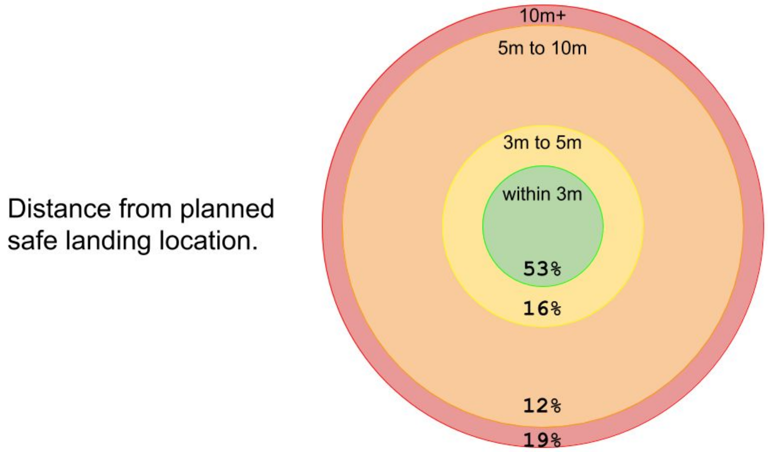

Figure 8. Rate of safe landing (UTM-MOP-05) in TCL4.

Rate of loss of navigation during conflict was measured in UTM-MOP-06. For this MOP, both operations in conflict needed to have navigation data in order to be considered. A loss of navigation was determined by either a provided Navigation Accuracy Category Position (NACp) or a calculated position dilution of precision (PDOP) relative to an applicable threshold. The majority of operations in conflict which provided either NACp or PDOP indicated a loss of navigation capability resulting in 14205 seconds where at least one operation had a navigation loss out of a total conflict duration of 15523 seconds, a rate of about 92%. This was poorer than targeted for the flight test, but illustrates the difficulty of GPS reliance in an urban environment, especially during conflict situations.

For UTM-MOP-19, most operations with reported data maintained command and control links throughout their operation (128 out of 140). The 12 operations that experienced a loss of C2 accounted for 1807 seconds of lost airborne C2 time, which was about 1.8% of the airborne time over 140 operations. For UTM-MOP-09 both operations in conflict needed to have C2 data in order to be considered. Of the operations identified in MOP-19 which experienced a loss of C2, only 1 was in conflict, resulting in 28 seconds of C2 loss out of a total conflict duration of 12553 seconds, which translates to a less than 1% rate. UTM-MOP-09 was defined with a minimum success criterion of < 4%, thus the operations met expectations for this MOP.

Human Factors

UTM-MOP-15 was entitled "Crew Assessment of UTM Information Properties" and was focused on gathering data related to user interactions with UTM components. A full report on this MOP is provided in two separate NASA Technical Memoranda [17][18]. Crew interactions with the UTM System are mediated through the displays provided by USSs, so impressions can vary. UTM information was reported by flight crews to be useful for building their awareness of the flight situations, and data collected from flight crews indicated that UTM provided information that contributed to users' ability to operate safely and effectively within the UTM environment. UTM system-to-user communications were possibly better than users were aware of, since data exchanged between system components of UTM are not always displayed to the user, depending on the USS user interface implementations. Although crews had good situation awareness of their ownship, they requested additional UTM information when the information they had access to was not sufficiently usable, salient, intuitive or complete on their current displays. Information management on UTM, especially of alerts, was reported to be a distracting activity to some crews and may benefit from filtering capabilities. As expected during flight tests in a complex environment, observers noted a fair amount of crew cross checking of UTM information with alternate information sources, suggesting that crews' confidence and trust in UTM information were still being established.

B. Related NASA UTM Project Research

The TCL4 flight activities spawned a great deal of research beyond the core MOPs. Work supported by the UTM Project and related to TCL4 has been published on navigation performance characterization[19], which provides data related to sUAS operation in urban environments. In addition, the reporting of off-nominal operations [20][21] has been further developed and tested in multiple flight tests, with recommendations for incorporation into an operational environment. Vehicle-to-vehicle system design [22] and path planning with obstacle avoidance [23] were also studied with point-design solutions to ensure alignment with the UTM concept and lay the groundwork for future requirements development. NASA UTM research related and contemporaneous to TCL4 includes the development of mission task elements for sUAS [24], ground risk assessment [25][26], sense-and-avoid characterization [27], and sUAS vehicle cybersecurity [28].

C. Lessons Learned

There were many lessons learned from this demonstration. NASA has cataloged several lessons for various purposes and audiences. These and other lessons have been transferred in various ways to industry (via standards development meetings, workshops, etc.), to the FAA (via the NASA-FAA Research Transition Team activities), and internally at NASA (to other Projects and to NASA Centers).

TCL4 had several high-level objectives which could be summarized into three major categories. Objective 1 (O1) was to identify technological gaps to enable UTM. Objective 2 (O2) was to demonstrate and illustrate the viability of the UTM concept through live flight tests in an urban environment. Finally, Objective 3 (O3) was to inform standardization of UTM that will occur through future rulemaking and standards developing organizations. Three columns in Table 3 indicate how the lessons learned supported the high-level objectives (O1-O3)

Table 3. Summary of key lessons learned in TCL4.

Lesson Title	Description	O1	O2	O3
Altitude reference	The lack of standardization in referencing altitudes across components in the sUAS domain is a significant hurdle that NASA and others have noted previously. For USS-USS data exchanges, WGS84 measured in feet has been used by NASA for a few years. However, USSs and other stakeholders often make translations of altitude measurements from other sources with other reference frames, units, or approaches that are not always fully understood by all the users of those data. This potentially causes false or missed conflicts between operations when USSs attempt to compare altitudes with each other for deconfliction or conformance purposes. This is a significant issue that industry must address for safe integration and operationalization of UTM.	✓		✓
Discovery worked	When the architecture of UTM evolved between TCL1 and TCL3 to a fully federated system, NASA recognized the need for a system for the key federated components (USSs) to discover each other for communications. NASA engaged with industry partners via technical outreach activities to force the discussion on a discovery system. NASA's initial approach to prove		✓	✓

	the concept was improved upon by industry and successfully tested in TCL3 and TCL4. This transfer from government research to industry innovation on a component of the UTM ecosystem is a key example of how the system should continue to evolve, with industry taking a larger and larger role in the specification of the operational system based on insights gained through collaborative testing.			
Off-nominal situation handling	A critical path in off-nominal situations handling was identified (e.g. a human director of flight operations coordinating UAS and USS in response to off-nominal situation) and automation is suggested to remove that critical path [20]. An approach involving each USS providing a semi-standardized interface to collect off-nominal situations reports was identified as the best approach. Continued collection of off-nominal reports and sending them to the Aviation Safety Reporting System was suggested so that evaluation and analysis can continue in order to understand off-nominal situations and reduce their occurrence [19].	✓		✓
Degraded C2 and navigation performance in urban environment	Given the obstacles in the urban environment, reliance on GPS for navigation and the known characteristics of communications between the pilot and ground infrastructure, it was expected that there would be degraded performance of UA navigation and C2 links. It was valuable to obtain measurements of dozens of flights using multiple UAS platforms to document these performance issues.	✓		✓
Gathering consensus	Early and often partner engagement pays off. This was planned as a feature of the UTM Project from the beginning and it bore fruit through collaborative testing. The efforts of the industry partners provided them key insights into the UTM Concept that could not be easily gained in any other way. Those partners, in turn, have taken the concept into the standardization process and have become global experts and ambassadors of the UTM concept as understood by NASA and the FAA.		✓	
Value of flying in the NAS	Early in the development of UTM at NASA, the Project had a choice of flight testing in restricted airspace or in the National Airspace System (NAS). The value of flying in the NAS was assumed to outweigh the increased effort to execute the flight tests. This assumption was realized throughout all flight tests, including (and especially) in TCL4. It was vital to gather public acceptance and understand community concerns. It was valuable to go through the approval processes with the FAA to learn the limitations and opportunities to improve that process for NASA and the FAA. It was beneficial to work through safety cases that took into consideration pop-up operations that were not involved in the testing, experience incursions by non-participating operations, and to then consider how that might affect or drive the concept.		✓	✓

USS negotiation development	The most complex protocol tested in TCL4 was USS-USS Negotiation. Given project schedule limitations, the protocol was not defined to a level that allowed for USSs to properly implement for full testing in TCL4. However, even with a limited implementation, the value of negotiations was evident. Further refinement of negotiations will be important in all phases of UTM development and operationalization.	✓		✓

VI. Conclusion

TCL4 testing accomplished NASA's general objectives and several auxiliary objectives. We accelerated partner development of the seven participating USSs, tested in an urban environment, tested the state of the art of many existing commercial technologies, and established the need for improvements or new technologies. The test sites, partners, and NASA gained a better understanding of the FAA process necessary for authorizations, waivers, and vehicle safety approvals as well as city approvals required for UAS operation in urban environments and were able to provide that experience back to the FAA.

As a capstone activity for the NASA UTM Project, TCL4 highlighted how far the concept and implementation of UTM has come since its inception at NASA Ames over six years ago. Industry and other government agencies are poised to take the lessons and experience gained through collaborative flight testing and move toward operationalization of UTM. This is generally the primary goal of all NASA aeronautics research, thus indicating a measure of success for the overall UTM effort at NASA.

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