

# **Enabling Large-scale Beyond Visual Line of Sight Small Drone Operations**

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## **Background**

This paper describes a system that could enable large-scale, beyond visual line of sight operations of small drones (i.e., 55 lbs. and under). The paper focuses on two key concepts. The first concept is understanding contributing factors to air traffic controller workload and how the current air traffic management (ATM) system operates. Such discussion leads to understanding the factors that may limit scalability of the current airspace operations and why a current approach may not be ideal to enable small drone operations in low-altitude airspace. The second concept is developing a future traffic management system that will scale to accommodate future demand of small drones without being limited by the air traffic controller workload. Therefore, the paper is organized in a manner that presents the current airspace operations paradigm, describes bounds of air traffic controller workload based on aircraft number, discusses lessons learned to improve understanding of contributing factors to air traffic controller workload, and elicits how decision support tools could support air traffic controllers. This paper lays the foundation for why the current paradigm will not be adequate to meet the demand of future small drones. Next, it presents a case as to why a different paradigm is needed to enable large-scale small unmanned aircraft systems (sUAS) or drone operations in the airspace, so they are not limited by workload factors, and provides a description and test results of a new airspace paradigm that safely enables scaled sUAS operations.

## **Current Airspace Operations Paradigm**

In today's ATM system, airspace is divided into small pieces called sectors. Each sector is assigned to one to three air traffic controllers depending on the workload expected in that sector. An air traffic controller performs many functions. These include accepting or transferring control of aircraft to and from the controller's assigned airspace, ensuring that aircraft are on the correct communication frequency for their monitoring airspace, and detecting and resolving conflicts among aircraft. They also maintain the required separation between aircraft and provide important advisories, such as alerts about potential traffic conflicts and weather hazards. The air traffic controller(s) managing a sector are the only party with complete awareness of all aircraft locations in that sector and any constraints that are applicable to that airspace. These constraints could arise from weather, VIP flights, search and rescue missions, etc. As a result, any change (e.g., turn right, turn left, climb or descend, and speed up or slow down) an aircraft pilot prefers to make, must be cleared or approved by the air traffic controller managing that particular airspace (Mogford et al., 1995). This is an example of the *management by control* or *management by permission* paradigm. This approach is essential to ensure that a single authority is responsible for safety of all aircraft and airspace operations, based on complete and accurate information. This is particularly true under meteorological conditions where instrument flight rules are applied for operations instead of metrological conditions where visual flight rules are applied (FAA, 2023).

### **Current Methods to Bound Air Traffic Controller Workload**

In the United States, air traffic control (ATC) is divided into tower, terminal, en route, and oceanic airspace based on location. Typically, towers are located at airports, and tower controllers are responsible for managing aircraft movement near and at taxiways and runways. Terminal airspace refers to airspace where aircraft climb (or depart) and descend (or arrive) immediately near airports. En route airspace covers long-distance flights between airports. Oceanic airspace is over

the Pacific and Atlantic oceans. Different separation standards apply in each of these airspaces based on surveillance accuracy and the level of confidence in knowing exactly where aircraft is located along the flight path. The following discussion of air traffic controller workload will focus on en route airspace operations. Figure 1 depicts a typical air traffic controller station.



**Figure 1: Typical En Route Air Traffic Controller Workstation here**

Given that the air traffic controller is the sole entity who monitors and is aware of the location of all aircraft, it is important that their workload allows adequate time to monitor aircraft from radar and global positioning system feeds and detect and resolve any potential conflicts among aircraft to ensure overall safety of the operation. If they have available time, workload permitting, they also offer efficiency-increasing flight paths requested by pilots. In an en route airspace, the separation minima that must be maintained among aircraft is 5 nm horizontal and 1000 ft vertical. To ensure that an en route air traffic controller's workload is at a reasonable level to maintain safety of operations, each sector sets a threshold of maximum number of aircraft expected to be managed in that sector. That threshold is called the Monitor Alert Parameter (MAP). A MAP value is set to

18 ±3 which serves as the maximum allowable aircraft in an en route airspace sector. The origins of MAP values are based on amount of time it takes for an aircraft to transverse through the sector. Functionally, it is used as a trigger value with a look-ahead time of one hour and in some cases up to 2.5 hours. Such forward look allows supervisors and traffic management units to adjust traffic and staffing if desired. Given the safety criticality of their job, it is important to ensure that their instantaneous and predicted workload does not unduly overload them. For his doctoral dissertation, Kopardekar studied if an air traffic controller's instantaneous workload could be assessed by using a non-interfering technique such as speech parameters based on air traffic controllers' communications with pilots. He examined workload impact on speech parameters such as jitter, shimmer, speaking rate, and amplitude. In some cases, he observed a relationship between speaking rate and workload (Kopardekar and Mital, 1997). However, continuous measurement and real-time analysis of speech parameters for all communications seemed impractical for real-time assessment of workload at the time. Perhaps with more modern infrastructure, it could prove useful as valuable measures in studies and post-hoc analysis.

### **Improvements in Air Traffic Controller Workload Characterization**

A fixed aircraft-count-based air traffic controller workload is easy to use, monitor, and interpret. However, several studies have shown that a count-based system does not accurately indicate true workload. For example, 18 aircraft that are lined up and going in the same direction on a route would offer a different workload than fewer aircraft converging or climbing and descending at the same time (Mogford et al., 1995; Kopardekar and Mital, 1997; and Chatterji and Sridhar, 1999 and 2001).

Several researchers from the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and industry were motivated to examine what factors contribute to

the air traffic controller workload and how to assess and predict those factors. A series of dynamic density or complexity measurement studies were conducted, starting with identification of potential factors that would contribute to air traffic controller workload. Researchers identified factors that may contribute to the air traffic controller workload (Kopardekar and Magyarits, 2003, Laudeman et al. 1997).

Mascio et al. (2021), using Eurocontrol model for workload, examined the link between the tower air traffic controller and airport capacity and found that the air traffic controller workload has direct relationship with allowable capability at an airport. Interestingly, similar findings were observed by analysis of Eurocontrol's incident reports and survey. Edwards et al. (2012) found that monitoring, vigilance, situational awareness, and communications were factors that contributed to their workload, and cognitive workload contributed to incidences. Millen et al. (2011), using cognitive workload analysis, identified aircraft near sector boundary as a contributor to workload. Eurocontrol (2016) developed Capacity Analysis (CAPAN) methodology. Using a fast-time simulation, CAPAN calculates sector capacities based on air traffic controller workload. The controller workload was based on flight data management, conflict search, radar monitoring, coordination, and standards radio telephony (which is communications). CAPAN's model included variables such as aircraft (or traffic) count, aircraft density, number of sector entries per flight, number of conflicts, measures of flight level changes, average distance flown per flight, and traffic distribution by aircraft type. Majumdar and Ochieng (2002) found that controllers make trade-offs while monitoring cruise, climbing, and descending aircraft, and these contribute to their workload. Several things that influence the complexity or dynamic density of an air traffic controller's subjective workload are provided in Table 1 (Kopardekar and Magyarits, 2003):

**Table 1: Factors That Contribute to Workload Complexity or Dynamic Density**

1.	Number of aircraft in the sector
2.	Aircraft density (number of aircraft/volume of sector)
3.	Aircraft handled in prior time interval (e.g., last hours)
4.	Number of arrivals
5.	Number of departures
6.	Number of emergencies
7.	Number of special flights
8.	Coordination with other controllers
9.	Traffic mix (arrivals, departures, and overflights)
10.	Staffing
11.	Weather conditions
12.	Equipment status
13.	Number of communications with aircraft
14.	Number of communications with other sectors
15.	Presence of conflicts
16.	Number of path changes
17.	Prevention of conflicts (crossing or overtakes)
18.	Number of hand-offs and printouts
19.	Number of pilot requests
20.	Traffic flow structure
21.	Clustering of aircraft
22.	Control adjustments involved in merging and spacing
23.	Mixture of aircraft types
24.	Climbing and descending aircraft
25.	Number of intersecting flight paths
26.	Number of required procedures
27.	Number of military flights
28.	Airline hub location
29.	Weather and its severity
30.	Aircraft routing
31.	Special use airspace
32.	Sector geometry
33.	Sector size
34.	Requirements for longitudinal or lateral spacing
35.	Radar coverage
36.	Frequency congestion
37.	Number of altitudes used

These workload contributing factors were then used to develop variables that could be measured in real-time and predicted based on aircraft location, their intent, speed, and sector geometry.

Various researchers identified 52 variables that could be measured and assessed towards dynamic

density or complexity. A complete list of 52 variables is available in Kopardekar and Magyarits (2003) and Kopardekar et al. (2007). Selected variables are provided in Table 2.

**Table 2: Selected Variables for Measurement and Assessment of Dynamic Density.** Based on factors identified in Table 1.

1.	Aircraft density (1) – number of aircraft divided by occupied airspace volume
2.	Aircraft density (2) – number of aircraft divided by sector volume
3.	Convergence Recognition Index – level of difficulty involved in detecting converging aircraft at shallow angles
4.	Separation Criticality index – proximity of conflicting aircraft with respect to their separation minima
5.	Degrees of freedom index – based on maneuver options in a conflict situation. Each pair in conflict has total 12 maneuver options (e.g., climb, descend, speed up, slow down, turn right, turn left options for each aircraft in conflict)
6.	Coordination task load index – distance of an aircraft from the sector boundary before handoff is completed between sectors
7.	Sector volume
8.	Aircraft count
9.	Number of climbing aircraft
10.	Number of descending aircraft
11.	Horizontal proximity
12.	Vertical proximity
13.	Number of aircraft with various Euclidean distances as related to separation minima
14.	Time to go to conflict
15.	Speed variance

Formulas to calculate each of the 52 variables were developed and are provided in Zinatullin, A., and Lykens, J. (2007). A unified dynamic density model was derived from 52 variables; in addition, individual organizations proposed models (e.g., FAA William J. Hughes Technical Center, NASA, and Metron Aviation) that were built for comparisons.

In the largest study of controller workload assessment, Kopardekar et al. (2007) collected 6480 data points from three air traffic controllers and three supervisors from four en route facilities. These facilities included Atlanta, Cleveland, Denver, and Forth Worth Air Route Traffic Control

Centers (ARTCC). Originally, the plan was to include data from Los Angeles ARTCC; however, the author was mid-flight on September 11, 2001, on the way to Los Angeles. The flight landed in Kansas due to the national emergency, and subsequently, we were not able to collect data from Los Angeles ARTCC. Of the 72 traffic samples provided; each sample was 30 minutes and was replayed using systematic air traffic operations initiative (SATORI). Sixty traffic samples were used to build a multiple linear regression model, and twelve samples were used to test the model. Coefficient of correlation ( $R^2$ ) was used to determine the best fit. The main findings of this study indicated that the unified metric derived from 52 variables performed the best as compared with individual metrics proposed by various organizations, such as FAA William J. Hughes Technical Center (where the author worked at the time), NASA (which had proposed two separate metrics), and Metron Aviation. Additionally, all dynamic density metrics performed better than aircraft count alone. Furthermore, data was analyzed for high- and low-altitude sectors and supervisor and controller ratings separately to account for differences in the sector geometrics as well as roles of supervisor and controllers. The highest  $R^2$  was 0.84 for the unified dynamic density model that was derived from 52 variables. For the same situation, the aircraft-count-based model's  $R^2$  was 0.63. The lowest  $R^2$  was 0.32 for the unified dynamic density model that was derived from 52 variables. For the same situation, the aircraft-count-based model's  $R^2$  was 0.13. This study demonstrated that controller workload is better assessed by using multiple factors rather than aircraft count alone. A total of 23 variables were found to be significant and were considered as part of the multiple regression analysis (Kopardekar and Magyarits, 2003). Given the likelihood of interdependencies of these variables, a factor analysis was conducted. The factor analysis allowed researchers to identify the following potential components, which are provided in Table 3.

**Table 3: Potential Workload Influencers.** Based on analysis of studies where multiple and interdependent variables were found to be significant workload factors.

1.	Overall monitoring
2.	Conflict detection
3.	Transitioning aircraft
4.	Communication and coordination
5.	Aircraft mix
6.	Time to resolve conflict
7.	Vertical separation monitoring
8.	Horizontal separation monitoring – mid- to large-separations
9.	Horizontal separation monitoring – closer to separation minima
10.	Arrivals
11.	Hand-offs
12.	Facility and sector geometry

Kopardekar et al. (2008) used the dynamic density metrics to examine how capacity could change for a simulated sector. They discovered that in many situations the airspace sector capacity could increase. However, in some situations, the sector capacity could be lower as complexity impacts workload. This meant that using dynamic density metrics for real-time management could become challenging. Predictions of dynamic density would be needed in real-time to continuously set capacity thresholds. However, the dynamic density metrics could be useful for redesigning sector layouts and airspace design at each facility so that overall airspace sector workload could be balanced.

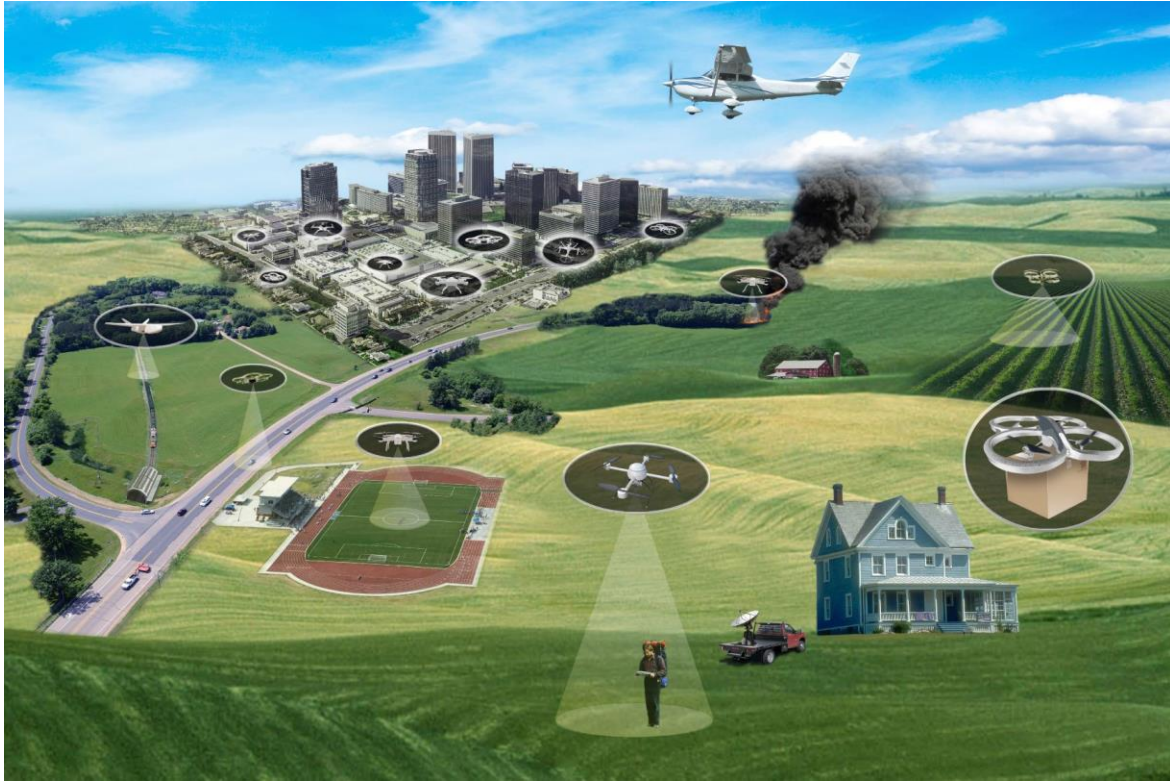
### **Decision Support Tools to Reduce Air Traffic Controller Workload**

The components identified in the studies are important to build and improve decision support tools to reduce the workload factors for air traffic controllers. Furthermore, one can change the sector boundaries dynamically to modify the workload of controllers by shifting some high workload areas to adjacent sector airspace (Klein et al., 2007; and Kopardekar et al., 2007; Bloem and Kopardekar, 2008; Bloem et al., 2009). Sherali and Hill (2011) used mixed-integer programming

to design airspace sectors that better balanced the workload associated with air traffic hand-offs between multiple sectors.

### **Paradigm Change to Enable Scaled Operations**

Immediately after the Iraq war, there was much interest in safely integrating larger drones in the national airspace system. Much research and development activities were undertaken by various organizations across the globe to identify standards related to detect-and-avoid and communications that will enable safe integration and their operations in the airspace. However, there was another phenomenon emerging much more rapidly. The state-of-the-art in computing technology, wireless communications, and software were improving. Such improvements allowed many companies to explore development of smaller drones that will have many useful applications. These applications include cargo deliveries, traffic monitoring, infrastructure surveillance, precision agriculture, aerial photography, wildlife and wildfire monitoring, search and rescue, oil and gas exploration, etc. Figure 2 shows various use cases of small drones or sUAS. The estimated global market for small drones would be \$80 Billion within a few decades (AUVSI, 2013). However, full realization of these economic benefits depends on their safe and scalable integration and ability to safely operate beyond visual line of sight (BVLOS).



**Figure 2: Various sUAS Use Cases**

### **Origins of Unmanned Aircraft System Traffic Management**

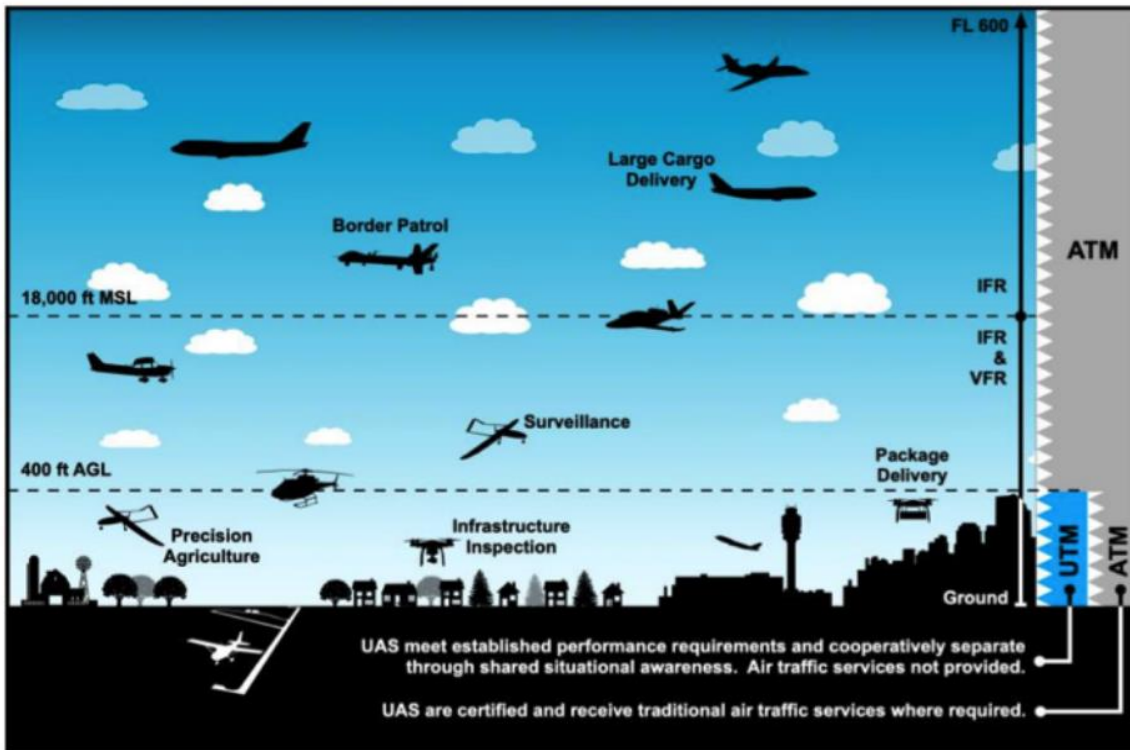
According to the FAA report, in 2023 the number of total airlines pilots are 180,738 whereas the remote pilots who operate drones are now 368,633. The FAA estimates that remote pilots will grow to 472,000 by 2028. In 2015, the total number of airline pilots was 158,559 and officially, there were no drone pilots as the drone pilot certification did not exist then. This statistic shows that the number of drone pilots will continue to increase as drone use cases become more mainstream. In 2023, there were about 45,000 instrument flight rules flights and about 39,000 visual flight rules flights operated per day in the United States (FAA, 2024). FAA forecast also gives a base estimate of 1.82 million small recreational drones for year 2024 which is likely to increase to 1.88 million by 2028. FAA forecast also indicates base estimate of 951,000 commercial small drones in 2024 with a likely increase to 1,122,000 by 2028. The commercial market includes applications related

to construction, energy, agriculture, communications, insurance, photography, real estate, entertainment, and deliveries. The current 2024 delivery market is very small (0.07%); however, once BVLOS operations are allowed, that market is expected to be one of the largest. The main reason for providing this forecast and true potential of small drones is to emphasize that it would be almost impossible to use current ATM paradigm of management by permission or control given that the air traffic controllers workload could limit such growth based on the discussion in the previous section.

### **Unmanned Aircraft System Traffic Management Characteristics**

The unmanned aircraft system traffic management (UTM) concept was born in 2013. The author was obsessed over safely accommodating a much higher density of small drones in the airspace as compared with conventional aircraft (which peaked at about 7000 at a time) to unlock true economic potential of emerging small drone technologies (Kopardekar, 2014; Kopardekar et al. 2016; and Kopardekar, 2019). The smaller drones are battery operated, and they are intended to fly at or below 400 feet to keep themselves separated from other airspace operations. The volume of their operations is expected to be magnitude order more than the regular air traffic at their peak. This necessitated a strategy to safely integrate these operations. The question was whether to use a traditional strategy requiring management by control or permission. From prior human factors research on controller workload, that strategy would have limits whereas industry wanted to ensure scalable operations without being limited by human workload. The lessons learned from air traffic human factors research related to workload factors, task analysis, and information processing indicated that the current paradigm needs to be revisited. The heart of the UTM concept is changing the paradigm from management by permission or management by control to management by exception. Therefore, the main tenet of UTM is to provide information to all operators—not just

air traffic controllers—so that management by control or permission can be changed. To provide the same information about small drone operation intent to all small drone operators, UTM needs to be digital. Figure 3 shows the UTM operations below 400 ft and separated from conventional ATM.



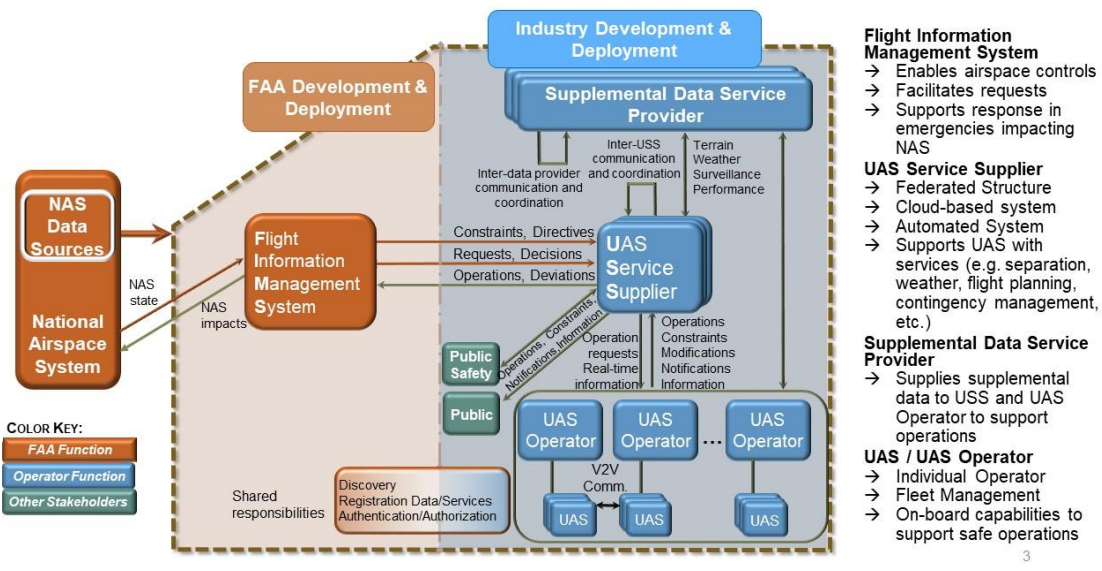
**Figure 3: UTM and ATM Operations**

UTM is a collection of services that are provided to small drone operations. These services are similar to the services ATC provides by monitoring traffic, except UTM services of flight planning, strategic coordination, conformance monitoring, communications, and navigation are provided by third parties instead of air traffic controllers. The third-party service suppliers are called UAS service suppliers (USS). In addition, data related to weather, terrain, and 3D maps are provided by Supplemental Data Service Providers (SDSPs). Furthermore, digital information can be exchanged only if there is a standard protocol which required development of application protocol

interfaces to allow sharing of intent information. And given the multiple types of small drone operators (e.g., occasional picture taking to routine high-volume deliveries), all operators must be supported. Therefore, a third-party services concept was created. In some cases, industry will provide their own services given their volume, business needs, and intellectual property considerations. In other cases, such as real estate or entertainment applications, subscription to third-party services by the USS is possible. In summary, the UTM construct was based on the following key principles:

- Federated (or distributed) system where multiple operations exist within a common framework of interoperability.
- Service-oriented architecture with ability for the third-party services to support operators.
- Fully digital operations where the intent is shared by USS with each other using prescribed and standardized application protocol interfaces.
- Management by exception paradigm where air navigation service providers inform operators and USS what not to do (or where not to go) instead of prescribing what to do every step of the way.
- Regulators maintain approval authority for airspace operations.

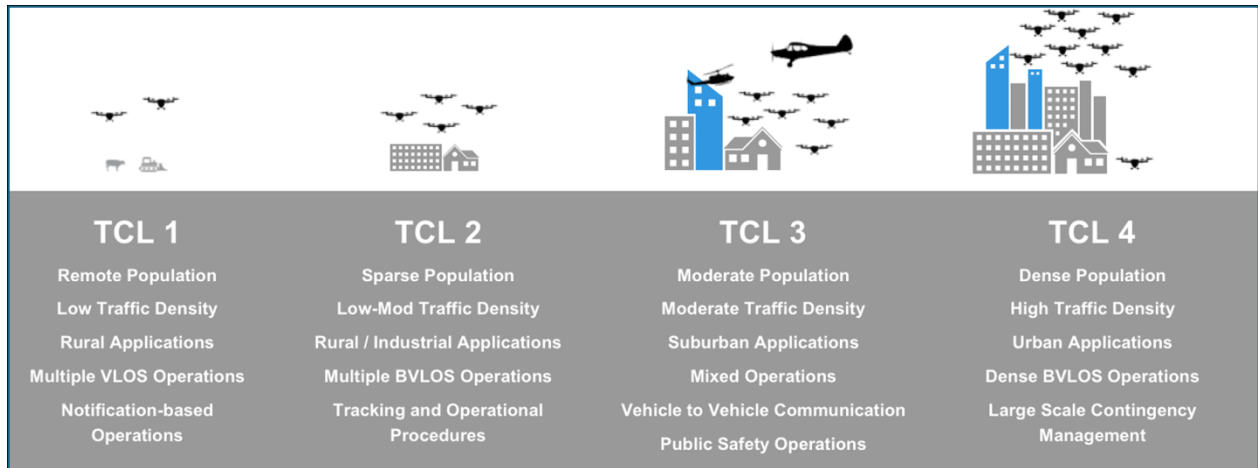
Figure 4 depicts the main architecture that supports the UTM-based operations. It shows the various information exchanges and roles of third-party service suppliers (i.e., USS), UAS operator, SDSPs, and the FAA system. One important aspect is clarity of which systems and roles (and associated costs) are borne by the industry and which are owned by the FAA (or any air navigation service provider in other parts of the world). The UTM architecture allows accelerated transformation by leveraging industry investments and competitive third-party services without dependence on government investment only.



**Figure 4: UTM Architecture**

NAS: National Airspace System, FAA: Federal Aviation Administration, V2V: Vehicle to Vehicle, USS: UAS Service Supplier

In order to examine this complex architecture for its feasibility and benefits, NASA used a build-a-little-test-a-little approach. The United Nation’s International Civil Aviation Organization (ICAO) has adopted the UTM construct and published the UTM framework to harmonize its use across the globe (ICAO, 2020). Figure 5 shows the stages of demonstrating the UTM architecture and systems—from low-risk environment to complex city environment. Four technology capability levels (TCL) of increasing functionality were used to operate from a low density, remote, low-risk operation to a high density, BVLOS, higher-risk operation. The first three TCL tests were conducted at all six FAA test sites (New York, Nevada, Texas, North Dakota, Alaska, and Virginia) and the last TCL test was conducted at Reno, Nevada and Corpus Christi, Texas.



**Figure 5: Risk-based Technology Capability Level Demonstration Approach**

TCL: Technology Capability Level, VLOS: Visual Line of Sight, BVLOS: Beyond Visual Line of Sight

Europe has also adopted the UTM construct using a term called “U-Space.” The European Commission initiated a network of U-Space stakeholders in 2021 to continue the U-Space demonstrations launched in 2018. Single European Sky Air Traffic Management Research (SESAR) Joint Undertaking published a fourth edition of the U-Space Concept of Operations in 2023 that describe services needed to enable the small UAS operations using third-party service suppliers (SESAR JU, 2023).

Quantitative and qualitative data was collected during the TCL tests. The TCL tests demonstrated feasibility of the UAS operations over the highly populated areas supported by the UTM. Qualitative data such as questionnaires and debrief summaries indicated that operators found UTM system functionality useful for common situation awareness and enabled separation with other operators and operations (Martin et al., 2020 and Martin et al., 2020). Figure 6 shows four small drones (circled in yellow) operating over the city of Reno.



**Figure 6: Small Drone Operating in Reno as Part of TCL 4 Tests**

Two pilot projects were undertaken by the FAA. UTM Field Test was conducted in Virginia by the FAA and industry, and initial BVLOS operations have recently been conducted in the Dallas vicinity involving multiple industry operators. At the time of writing this paper, the final BVLOS rule was pending.

### **Summary**

The main lessons learned from human factors related air traffic controller workload studies were valuable insights into the factors that contribute to ATC workload. Therefore, when the opportunity to design a concept for small drone operations materialized, it was critical not to overload the human ATM-related workload. Instead, a different paradigm to enable the future scale of drone operations was conceived. After several flight tests, NASA demonstrated that a paradigm-based nonmanagement-by-exception is feasible with all digital operations supported by the federated construct. UTM has been globally harmonized through United Nation's International Civil Aviation Organization (ICAO) and Global UTM Association (GUTMA). Several countries, including the United States and Europe, continue to develop operational rules to enable BVLOS operations that will be supported by the UTM construct. Valuable human factors studies of the past

air traffic controller workload assessments influenced a whole new paradigm that is instrumental for enabling small drones, advanced air mobility, and many other future airspace operations.

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### **My Memories of Prof. Martin Helander**

I am very grateful to late Prof. Martin Helander for his guidance during my master's degree. He was my academic advisor, and his graciousness has influenced me forever. I also had an opportunity to serve as his teaching assistant for an undergraduate human factors course. His kind and caring nature toward students was very motivating. He always took time to understand their challenges and offered reassurance. It is my honor to write this chapter for the Helander's Compendium of Human Factors and Ergonomics.

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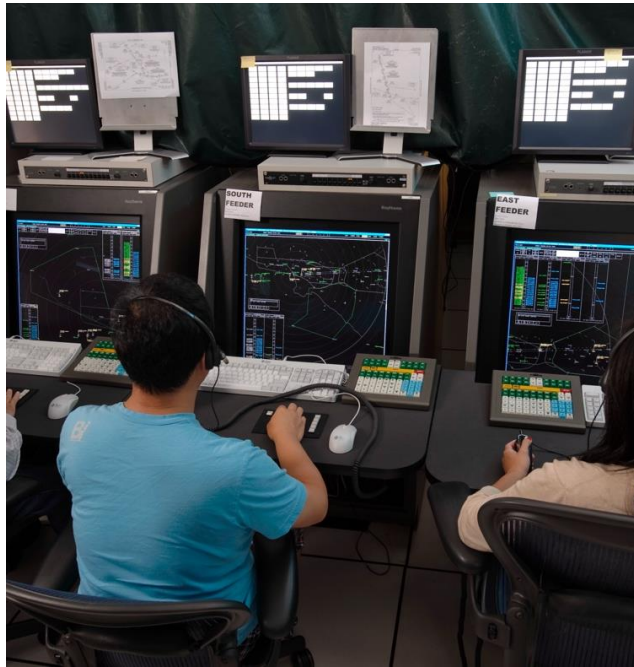
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## Speaker Biography



Dr. Parimal Kopardekar serves as the Director of NASA Aeronautics Research Institute, and as the Mission Integration Manager of Advanced Air Mobility. He is a fellow of the American Institute of Aeronautics and Astronautics (AIAA) and Royal Aeronautical Society. He holds two patents and has published more than 50 articles. He is a recipient of the AIAA Hap Arnold Award; Samuel J. Heyman Service to America Medal for Promising Innovation (called Oscar's of Public Service); and NASA awards such as Invention of the Year; Exceptional Technology Achievement Medal; and Outstanding Leadership Medal. He also serves as an adjunct faculty at Colorado State University Global and Northeastern University.



**Figure 1: Typical En Route Air Traffic Controller Workstation**