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Small Unmanned Aircraft System (sUAS) Trajectory Modeling in Support of UAS Traffic Management (UTM)

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Small unmanned aircraft system **(sUAS), as defined by the FAA, refers to a small unmanned aircraft weighing less than 55 pounds on takeoff, and its associated elements that are required for the safe and efficient operation of the small unmanned aircraft in the national airspace system. The unmanned aircraft system (UAS) traffic management (UTM) system is envisioned by NASA to enable civilian low-altitude airspace and UAS operations by providing services such as airspace design, corridors, dynamic geofencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management. Trajectory modeling and prediction methods are foundational capabilities in support of UTM to achieve its goals. This paper presents a framework for the development and validation of trajectory modeling and prediction methods for diverse types of sUASs under nominal environment and under a variety of realistic potential hazards, including adverse environmental conditions, and vehicle and system failures. Results from initial analysis of major components of the framework are also presented. Detailed results from the development and validation will be reported in subsequent papers as the research progresses.**

I. Introduction

For civilian operations in the United States, the term *small unmanned aircraft system* (sUAS) is defined as a system consisting of an unmanned aircraft or unmanned aerial vehicle (UAV) weighing less than 55 lb., and equipment necessary for the safe and efficient operation of that aircraft [5], [10]. Unmanned aircraft of this size have been flown as model aircraft for hobby, recreational, and sports use for many decades. The advancement, increased access by the public, and the reduced cost and size of technologies such as digital communications, digital controls, navigation, and autonomy have enabled fast growing capabilities of sUASs, including model aircraft, that were not imaginable decades ago. However, wide-spread use of sUASs for non-recreational purposes have been limited, particularly for applications requiring operations beyond visual line of sight (BVLOS) from the sUAS operator.

Driven by the potential societal and economic benefits that can be generated from application of sUASs, the Federal Aviation Administration (FAA) recently published the rule of regulation [10], which added the Part 107

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operations to Title 14 of Code of Federal Regulations (14 CFR) [9] that allows routine use of sUASs in the National Airspace System (NAS). Part 107 operations are limited to open airspace at or below 400 ft. above ground level (AGL) or within 400 ft. of a fixed structure, to avoid interference with manned aircraft operations. Additionally, sUAS operations under this rule are restricted within the visual line-of-sight (VLOS) of the remote pilot in command (PIC) or a visual observer in effect communications with the PIC. Although the VLOS restriction may be waived under special conditions, routine BVLOS operations are expected in the future to fully realizing the sUAS benefits. In the simplest form, the sUAS operational space can be summarized as shown in Fig. 1. This figure illustrates the extent of the sUAS operational space—from the long history of model aircraft VLOS hobby and recreational flying to currently authorized VLOS commercial operations, and to future BVLOS commercial operations. In this figure, the green areas represent currently unregulated (model aircraft) and authorized routine operations (non-recreational VLOS). The light blue areas represent future expansion into routine BVLOS operations that have yet to be fully tested.

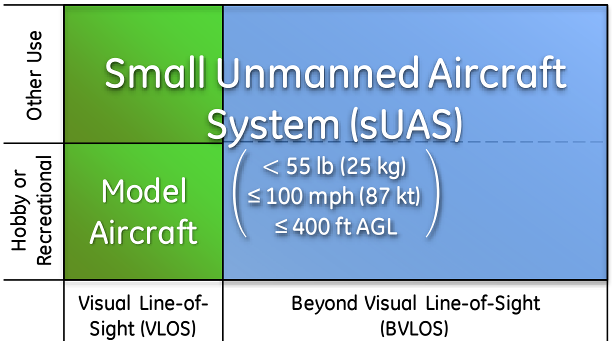


Fig. 1 Small UAS (sUAS) operational space defined.

The unmanned aircraft system (UAS) traffic management (UTM) system is envisioned by the National Aeronautics and Space Administration (NASA) to enable civilian low-altitude airspace and UAS operations, particularly sUAS BVLOS operations, by providing services such as airspace design, corridors, dynamic geofencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management [18]. In the current UTM ecosystem architecture, operational information exchange is envisioned among UAS operators, UAS service providers, supplement data service providers, and the flight information management system (FIMS) that serves as an interface to the air navigation service provider (ANSP) [19]. As seen, trajectory modeling and prediction methods are foundational capabilities in support of UTM to achieve its goals.

Several challenges need to be addressed in developing such capabilities. Small UAS design has been evolving, and vehicles with increasingly diverse design, size, flight envelope, and flight characteristics are expected over time. Vehicles of different configurations, for example: 1) conventional take-off and landing (CTOL) fixed-wing aircraft, 2) vertical flight or powered-lift aircraft, and 3) hybrid configurations with combined CTOL and vertical flight characteristics such as vertical take-off and landing (VTOL) aircraft, have been seen in various sUAS applications. It is important to identify how trajectories of diverse types of sUAS configurations could be planned by the operators and represented UTM. To do this, it is also important to establish effective and efficient means to model diverse types of individual aircraft. Small UAS vehicles are normally evolving at a much faster pace than full-size manned aircraft; many sUASs change their airframe design every couple of years, if not more often. The performance characteristics of many sUASs are not necessarily well documented, and not readily accessible even if they are indeed documented.

Also, to support many of the envisioned UTM services and ensure safety of operations, it is important to understand abnormal trajectories that could be generated under a variety of system failure hazards and environmental conditions. The stack of factors influencing sUAS trajectory are shown in Fig. 2. Key vehicle and system failures should be considered relative to their impact on aircraft trajectories. Examples of such failures include partially losing propulsive power, reduction or loss of control effectors, key sensor failures, key external navigational aid failures, and navigational aid signal blockages, e.g., line-of-sight to Global Positioning System (GPS) satellites blocked by terrain or structure. Because they are light in weight (< 55 lb.), relatively slow (< 87 kt.), and operate at low altitudes (< 400 ft. AGL), sUASs are most likely operating within the atmospheric boundary layer (ABL) and are subjected to varying frequency of changes in environment within the ABL. Traditionally, the aviation community has been mainly focused on weather phenomenon at altitudes. Impact of ABL environmental conditions on aerial vehicles in the scale of sUASs are not well understood, thus it becomes a critical component of the trajectory modeling capabilities.

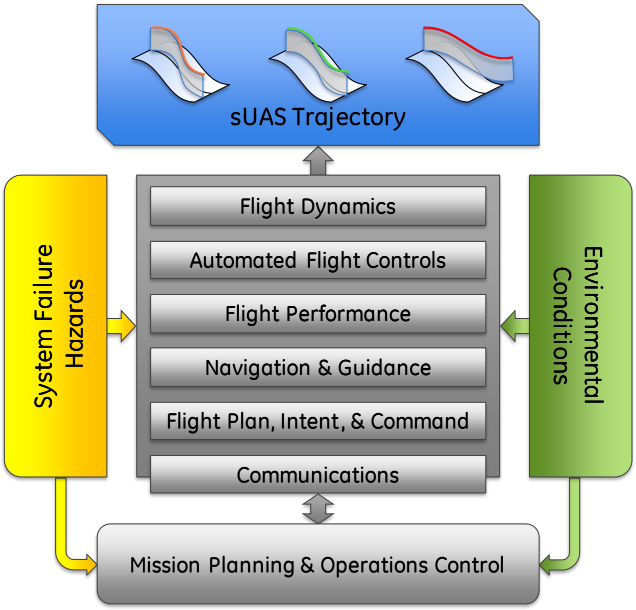


Fig. 2 Stack of factors influencing sUAS trajectory.

Several recent studies have considered the sUAS trajectory modeling problem. To address the need to develop methods that can rapidly integrate and regulate the diverse UAS trajectories entering the airspace, Ishihara, Jung, and Rios presented an algorithm utilizing a kinematic fixed-wing model [15]. The algorithm was simulated with the UAS flying at constant altitude in a uniform wind field to achieve required arrival times. D'Souza et al. developed a generalized six-degree-of-freedom (6DoF) multirotor trajectory model to identify vehicle performance in the presence of wind [7], [8]. The generalized model uses performance parameters that were non-specific to the control system to derive the control solution. This is different from traditional trajectory prediction methods for air traffic management (ATM) application, which introduce many simplifications. In the latest effort [8], a genetic optimization method was used to optimize the control solution. The algorithm was tested to simulate climb to a given altitude with vehicle force and attitude constraints. In solving the safe autonomous flight environment for the notional last 50 ft. (SAFE50) challenge, Krishnakumar et al. used computational fluid dynamics (CFD) to obtain detailed urban wind profiles based on mean wind information from weather services as input [20]. An onboard estimation was employed to estimate the vehicle's aerodynamic drag coefficients, and navigation and control algorithms were employed to generate feasible trajectories for a multirotor aircraft [36].

In support of the broad needs of UTM, the objectives of this research are the development and validation of agile, scalable, and affordable trajectory modeling and prediction methods that are able to support trajectory patterns for diverse airframe configurations, including CTOL, vertical flight, and hybrid VTOL aircraft. The outcome will provide trajectory modeling and validation templates (or processes) that UTM ecosystem participants could use to describe sUAS trajectories under nominal and off-nominal conditions and under a variety of realistic potential hazards, including adverse environmental conditions, and vehicle and system failures.

The remainder of this paper presents the scope of work, research approach, and the framework for the development and validation of sUAS trajectory modeling and prediction methods. Initial analyses for major components of the proposed framework are also described. As this is an ongoing research effort, detailed results from the development and validation of sUAS trajectory modeling will be reported in subsequent papers as the research progresses.

II. Scope of Research

To achieve the research objectives, this effort includes a unique trajectory definition model intended to be a standardized representation for trajectory exchange between diverse systems operated by sUAS stakeholders within the UTM ecosystem to enable sUAS low-altitude operations, grow widespread sUAS applications, and enable effective and efficient measures and operational procedures for ensuring safety. A prototype tool is to be developed to generate trajectories in the format of the definition model, considering a comprehensive stack of contributing factors as shown in Fig. 2. Trajectories may be predicted with containment boundaries and criteria for the type of operations under nominal and off-nominal conditions. Tradeoffs between prediction fidelity, efficiency, and usability are to be carefully considered.

The scope of this project includes the following specific aspects:

1) Perform a literature review to identify and report the current state of the art in sUAS technology, including factors that are thought to contribute to the formation of sUAS trajectories, such as: sUAS flight performance characteristics; flight dynamics; automated flight control systems; navigation and guidance (including GPS-denied navigation); flight plan, intent, and command; communications and impacts of lost-link; mission planning, operations, and autonomous systems; system, subsystem, and sensor failures; effects of environmental disturbances on sUASs (e.g., wind, rain, snow); types of prescribed trajectory patterns for sUASs; and validation methods for aircraft trajectories.
2) Develop an sUAS categorization framework, potentially based on sUAS aerodynamic characteristics, performance, automatic flight control logic, airframe configurations, weight, speed, degree of sUAS flight control autonomy possible, auto-recovery mechanisms, and navigation and guidance capabilities.
3) Identify the types of key sUAS vehicle and system failures and assess their impact on sUAS trajectories. The focus is limited to the ways in which sUAS system failures impact trajectories, not necessarily the impact on NAS safety. The effect of system failures on sUAS trajectories will include the impact of failures such as: ground station failures, radio control (RC) link loss, and autopilot datalink loss; corrupted flight plan, incorrect flight plan interpretation, and navigation errors; GPS failure and unavailable virtual real time kinematic (RTK) reference station; flight-critical sensor failure; autopilot failure (autonomy failure); loss of up to 50% propulsive power; and control surface failures.
4) Define criteria to identify hazardous environmental conditions for sUAS operations within the ABL or below 500 ft. AGL. The goal is to define a set of criteria to identify (and classify) hazardous environmental conditions (e.g., wind, rain, icing, snow, temperature) that may pose problems for safe and efficient sUAS operations based on their category. At the same time, the environmental conditions limits for nominal sUAS operations for each sUAS category will be defined.
5) Develop methods and templates for modeling and predicting sUAS trajectories under nominal and off-nominal (system failures and hazardous environmental) conditions, for a minimum of three sUAS models representing dynamics, performance, and automatic flight control logic of CTOL, vertical flight, and VTOL airframe configurations, respectively. As an over-arching concern, it is important to identify how many types of sUAS trajectories could be planned by the operators and represented in systems such as the UTM system. For the safety of operations, it is important to understand what abnormal trajectories may be generated in response to a variety of system failures and environmental hazards.
6) Develop methods and templates for validating the developed models and trajectory predictions. The template should contain sufficient details so that it could be used by general members of the unmanned aircraft industry could follow the same process to validate their sUAS models.
7) Perform validation of the developed models and trajectory predictions with developed validation methods. The validation should consider analysis of trajectory modeling, prediction fidelity, efficiency, usability, and cost-effectiveness in the development of the trajectory generation methods and templates.

III. Research Approach

To accomplish the work specified in the previous section, the research approach consists of tasks anchored around the stack of factors influencing sUAS trajectory shown in Fig. 2. Methods for modeling the stack of factors and validating the models, along with the prototype implementation, establish the sUAS trajectory modeling and prediction required by the scope of the work. The research approach is divided into major steps including: synthesization of the current state of the art, identification and abstraction of knowledge, analysis and formulation of models, development and functional verification of prototype models and prediction, and finally validation of models and prediction, with each step comprised of one or more method(s) and tasks, as shown in Fig. 3. These steps successively progress from raw knowledge, to organized knowledge, increased knowledge base, application of such knowledge, and finally to validation to deliver concrete results.

The research approach shown in Fig. 3 represents what ultimately should be accomplished. One key consideration in the research approach is that careful tradeoffs must be made among trajectory modeling and prediction fidelity, efficiency, usability, and cost-effectiveness, to ensure that they will be easily adopted by the UTM ecosystem participants. Similarly, careful tradeoffs must be made between the amount of effort allocated to each of the tasks to be carried out within a reasonable timeframe and total resources available. For example, the formulation of safe cases within the analysis and formulation step will be a collaboration with other parallel research efforts beyond the scope of the sUAS trajectory modeling effort. The operation validation task within the validation step will likely be carried out by collecting feedback from UTM ecosystem participants in using the processes and templates from the current research.

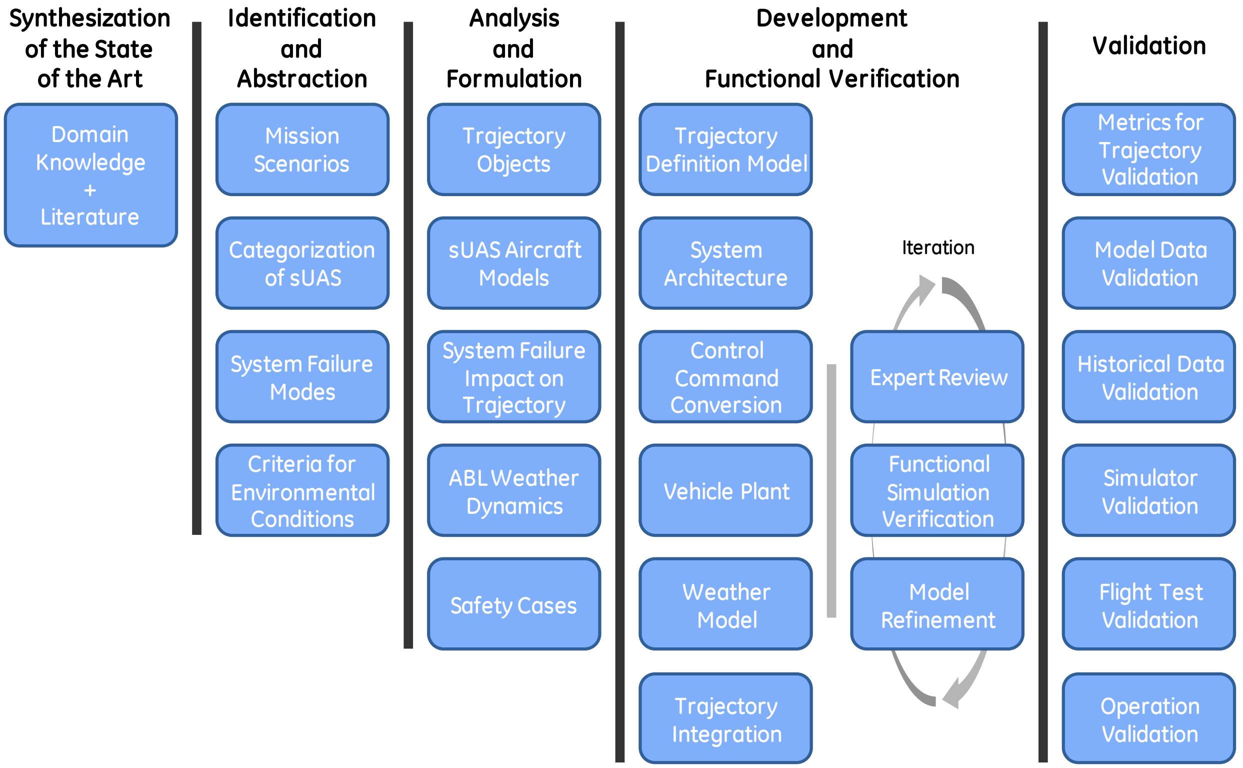


Fig. 3 Research approach, components, and the flow of knowledge from left to right.

In the next few sections, selected topics of the sUAS trajectory modeling research approach are discussed with additional levels of details. As this is ongoing work, additional topics and results from this effort will be reported in subsequent papers as the research progresses. For example, the modeling of the environmental conditions is big enough of a topic on its own, which the research team is actively pursuing.

As an example of subsequent paper topics, the sUAS categorization framework for traffic services will be presented at the 2017 Institute of Electrical and Electronics Engineers (IEEE) and American Institute of Aeronautics and Astronautics (AIAA) 36th Digital Avionics Systems Conference (DASC) [31]. Within the context of UTM, an sUAS categorization framework is established on the foundation of understanding the effects of sUAS design and operational characteristics on the trajectory of the sUAS itself, and the interactions the sUAS may have with other aerial vehicles and people and structures on the ground. Such a categorization framework allows for sUAS operations to be managed efficiently against operating conditions and efficiency and safety objectives, based on distinctive sUAS characteristics recognized following the established framework.

Another example of subsequent paper topics is consideration for off-nominal trajectory computation, which will also be presented at the 2017 DASC [3]. Literature documenting UAS safety has provided multiple pointers for identification, characterization, and prioritization of system failures. Prior work and relevant concepts that may be utilized to develop a framework for sUAS trajectory modeling in the presence of anomalous events are organized and abstracted. These include deterministic and stochastic techniques aimed at computing vehicle trajectories in off-nominal situations. The foundations for these techniques are extended aircraft dynamics models that capture the effects of anomalous events. Three main cases are considered: degraded execution, fail-safe maneuvering, and uncontrolled flight. Finally, a list of requirements for off-nominal trajectory computation serving the specific needs of the UTM system is presented, along with challenges.

IV. Pattern Based Trajectory Definition Model

Trajectory definition models are data structures intended to represent different trajectories to be flown by different sUASs. Commonly accepted trajectory definition models allow for trajectory exchange between different entities involved in the UTM ecosystem. The formulation of trajectory definition models also provides guidance to the selection of specific approaches in the development of the trajectory modeling prototype tool.

For manned aircraft, industry standards such as ARINC Specification 424 [1], Radio Technical Commission for Aeronautics (RTCA) DO-350 [32] Extended Projected Profile (EPP), and International Civil Aviation Organization (ICAO) Flight Plan [12] provide data structures for avionics implementation and trajectory exchange between aircraft operators and the ANSP. The Flight Information Exchange Model (FIXM) [11] is an Extensible Markup Language (XML) schema capturing flight and flow information that is globally standardized in support of the ICAO defined Flight and Flow Information for a Collaborative Environment (FF-ICE). FIXM incorporates ICAO Flight Plan and air traffic service (ATS) message standards, including extensions released by regional ANSP(s), e.g., FIXM extensions released by the FAA. In general, these established standards define a lateral flight path from takeoff to lading, along with altitude (and potentially temporal) constraints or specifications at waypoints on the path. With some adaptation, these standards could potentially be leveraged by the sUAS trajectory definition models for defining trajectories following a conventional three-dimensional (3D) or four-dimensional (4D) linear path.

Within the UTM initiative, geofencing has been used as a means of procedural separation for sUAS from other aircraft and protected areas. Using geofencing, an sUAS operator may reserve a volume of low-altitude airspace for the duration of a flight. The reserved airspace is normally defined by a geographical perimeter and an altitude limit or both minimum and maximum altitudes [16], within which the flight operation will remain. Different buffers may be incorporated into the geo-fence to trigger alerts or actions by humans or automation. In this case, the exact 3D linear track to be followed by the sUAS, either prescribed or ad hoc, is obscured in the geo-fence geometry.

Through an examination of sUAS applications such as weather monitoring, mining survey, infrastructure inspection and monitoring, precision agriculture, public safety, search and rescue, package delivery, aerial photography, news and media, and others, six (6) sUAS trajectory patterns are identified, as shown in the infographic in Fig. 4. Each of the six patterns represents a unique set of trajectory characteristics.

Fig. 4 Abstracted trajectory patterns and the UTM ecosystem.

Track scan represents applications along a fixed linear surface feature or structure, such as a railway or a power line. In this case, the 3D track is essentially fixed. *Point to point* represents applications such as package delivery, where the route between the origin and destination may be flexibly planned or dynamically adjusted, based on various environmental and other conditions. *Three-dimensional (3D) coverage* represents applications such as vertical infrastructure inspection or swarm flying that operate within a limited, defined 3D volume of airspace, but not necessarily having a predefined 3D path. The exact 3D path may have to be dynamically determined due to the nature of the application. *Area coverage* represents applications such as search and rescue that operate over a sizable area, but not necessarily having a predefined lateral routing. The altitudes, however, may be more or less structured. *Area scan* represents applications such as crop dusting or geographic survey where predefined routing is followed to systematically scan an area. Flight altitudes may also be well structured. *Hybrid* trajectory patterns represent applications within which transition between different trajectory patterns occur.

A trajectory definition model based on the six trajectory patterns encompasses the conventional 3D/4D trajectory and the current UTM geo-fence model. Additionally, it offers greater flexibility, scalability, and insights into the sUAS trajectory to support future expanded low-altitude operations. Trajectory objects are also defined to serve as building blocks for the pattern-based sUAS trajectory. These include explicit trajectory objects such as: takeoff/landing sites, waypoints, 3D leg types, and predefined sUAS routes. They also include abstract trajectory objects such as: convex 3D volume, airspace tunnel, area with altitude constraints, and entry/exit points or entry/exit areas to 3D volumes, tunnels, or areas. Abstract trajectory objects encapsulate explicit trajectory details that are either dynamically constructed during the flight mission or are not of interest to entities other than the sUAS operator. Industrial standards for manned aircraft, such as those defined in Refs. [1], [11], [12], and [32], are used as the baseline for explicit trajectory objects, but sUAS-specific objects are also introduced and developed, for example 3D spiral leg types with arbitrary orientation, which may be needed for coordinating high-density sUAS operations. Constraints are also defined to limit legal transitions between trajectory objects.

The pattern-based trajectory definition model is further illustrated in Fig. 5. In the figure, two 4D trajectory (4DT) constructs are shown. The conventional 4DT construct is used for defining trajectories following a 3D/4D path, using only explicit trajectory objects. The conventional 4DT construct is sufficient to support track scan and point to point trajectory patterns. This is similar to the trajectory definition models used in manned aircraft operations, and it is traffic flow management (TFM) friendly in that the 3D location of the aircraft at any given time may be described by the trajectory. Flights sharing the same meter fix or route may be coordinated so that proper spacing may be established between aircraft. Properties such as time and performance-based navigation (PBN) specifications may be attached to trajectory objects to represent a PBN 4D trajectory.

The unconventional 4DT construct extends the conventional 4DT construct by including abstract trajectory objects in order to support the other four trajectory patterns: 3D coverage, area coverage, area scan, and hybrid trajectory. One key difference between the unconventional 4DT construct and existing geo-fence airspace reservation concept is that access to a volume of airspace included in the unconventional 4DT is not exclusive. For example, the cylindrical mission area (with top and bottom altitude constraints) in Fig. 5 is not necessarily exclusively used by the own aircraft. With acceptable sense and avoid (SAA) capability (either established visually or electronically), multiple vehicles may access the same volume of airspace at the same time, without having to prescribe the exact 4D location for individual vehicles. Additionally, like a linear leg segment, a 3D volume object is also directional.

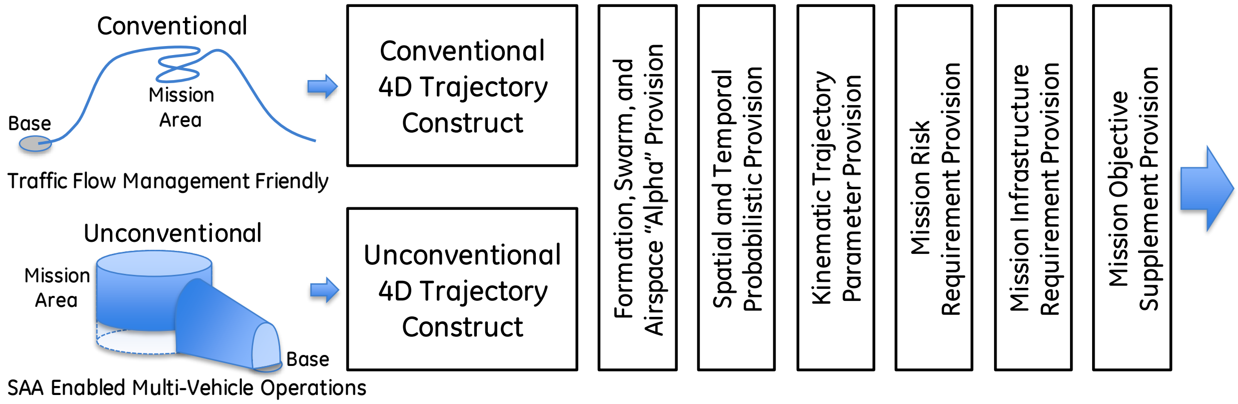


Fig. 5 Pattern-based trajectory definition model.

To enhance the flexibility, scalability, and insights into the sUAS trajectory, the pattern-based trajectory definition model includes several supplement provisions. Small UAS categorization information [31], such as speed classes and equipage information may be included in the trajectory. Specifically, the pattern-based trajectory definition model includes the following provisions:

- Formation, Swarm, and Airspace “Alpha” Value Provision: This provision provides information on how densely 3D volumes are occupied by the current flight. It is an indication of the possibility of shared access. For example, a 3D volume included in the trajectory of a large swarm of hundreds of vehicles should probably be exclusively accessed by the current flight.
- Spatial and Temporal Probabilistic Provision: Unlike in the current geo-fence concept, 3D volumes in the pattern-based trajectory definition model are directional. Spatial and temporal progression information of the flight may be provided using this provision, probabilistically, if so desired. Such information may serve as an indication of the possibility of shared access.
- Kinematic Trajectory Parameter Provision: Kinematic information such as the progression direction and speed information may be provided using this provision to allow the client to receive the trajectory to estimate the rough order location of the sUAS at some time in the future.
- Mission Risk Requirement Provision: This provision may be used to provide mission risk exposure, for example rural area operations, flight over people. This gives the consumer insights into the mission risk requirements without having to decode and interpret specific trajectory objects included in the trajectory.
- Mission Infrastructure Requirement Provision: This provision allows the information on required infrastructural support for command and control, or that for payload, to be provided. Such information is useful for service providers to collaborate with sUAS operators in real time, should infrastructure performance degradation or bandwidth congestion become a concern.
- Mission Objective Supplement Provision: This provision provides information on mission objectives. For example, a flight may be conducted to inspect the condition of a given powerline or a power substation. Such information is useful for airspace situation awareness, and offers flexibility for other aircraft to determine if shared access to a specific airspace resource is possible.

In formulating the trajectory definition model, tradeoffs among trajectory granularity, data exchange efficiency, and usability are carefully considered. Additionally, the pattern-based trajectory definition model may also be used to represent sUAS trajectories under off-nominal conditions, such as hazardous environmental conditions and/or key vehicle and system failures. These off-nominal conditions may include one or a combination of degraded nominal trajectories, recovery or emergency trajectories, uncontrolled failure trajectories, and trajectory containment boundaries. The pattern-based trajectory definition model allows for special trajectories that cannot be accommodated by traditional trajectory definition models.

V. Prototype Tool System Architecture

A prototype tool is being developed to integrate modeling methods and templates developed under this research effort so that their functions may be simulated and verified, and their effectiveness may be validated. The prototype tool will decompose a given sUAS flight mission scenario into trajectory objects that can be modeled, and will subsequently integrate modeled trajectory objects into predicted trajectories represented using the trajectory definition model. The prototype tool will be able to model diverse types of sUAS airframe configurations, including implementation for three sUAS models representing dynamics, performance, and automatic flight control logic of a CTOL, a vertical flight, and a VTOL airframe configuration, respectively. The prototype tool includes models of ABL weather dynamics for winds, temperature, density, and (potentially) precipitation for the mission to be simulated. The prototype tool is expected to model and predict sUAS trajectories under both nominal and off-nominal (system failures and hazardous environmental) conditions.

To incorporate the required features, an open system architecture is established. A high-level view of the system architecture is shown in Fig. 6. Each of the square blocks represents a system component, which can either be swapped, reconfigured, or re-initialized with different parameters. This is particularly important for UTM ecosystem partners to incorporate their own in-house models into the system. System components include those to support the conventional trajectory segment construction process (the upper group in Fig. 6), those to support unconventional trajectory segment construction process (the lower group in Fig. 6), and those to provide common capabilities and system integration functionalities (the middle row in Fig. 6).

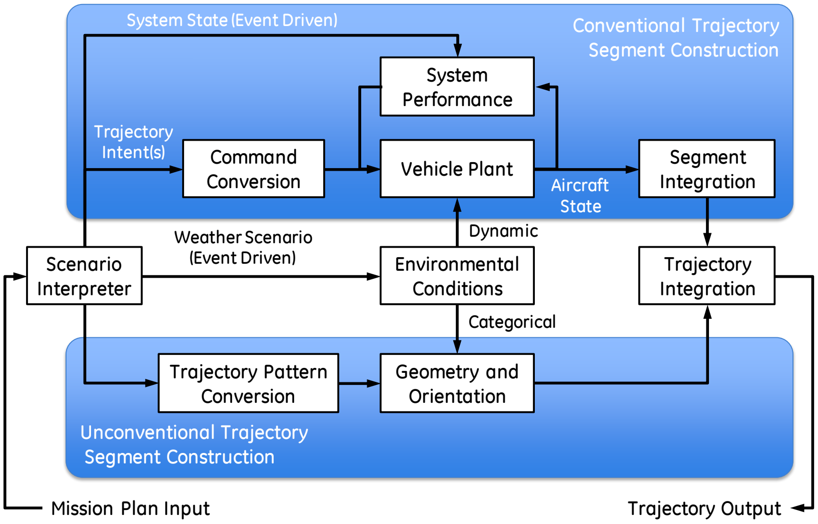


Fig. 6 Prototype sUAS trajectory modeling tool system architecture.

The system takes mission plan as the input. A mission plan can generally be represented by one of the trajectory patterns, along with the weather scenario and the system state. The scenario interpreter passes the weather scenario to the environmental model component to generate environmental conditions, and parses the trajectory pattern into conventional trajectory intent segments and unconventional trajectory intent segments to be modeled by their corresponding trajectory segment construction processes, respectively. Results from these two trajectory construction processes are then integrated into trajectories represented using the definition model.

As the name indicates, the conventional trajectory segment construction process is similar to existing manned aircraft trajectory modeling processes. The purpose is to construct 4D linear trajectory segments for given trajectory intents and the system state. The trajectory intent is translated by the command conversion component into vehicle guidance commands. At the core of the conventional trajectory segment construction process is the vehicle plant represented by a 6DoF dynamics model. A unique feature of the conventional trajectory segment construction process is the ability to simulate different levels of system performance, such as the performance of navigation systems and flight controls. System performance refers to both nominal performance, and off-nominal performance under the impact of system hazards. Dynamic environmental conditions, including both spatial and temporal properties, are fed to the simulation to calculate aircraft state at each time step. Aircraft state from simulation is then integrated into 4D trajectory segments by the segment integration. It is worth mentioning that the conventional trajectory segment construction process is not only used to support the modeling of conventional trajectories, but is also used to support the modeling of unconventional trajectories. For example, it can be used to support the determination of containment boundaries for an unconventional trajectory by simulating 4D linear trajectory segments that represent recovery maneuvers from points inside the 3D airspace volume mission area.

The purpose of the unconventional trajectory segment construction process is to construct 3D volume trajectory segments. This process mainly comprises kinematic operations and constructive geometry operations. It determines the geometry, orientation, and temporal progression of the trajectory segment. Orientation refers to how a volume of 3D airspace is to be traversed by the own aircraft. For example, an area scan segment may have a defined entry point and exit point, and a general direction how the scan is to be accomplished. Temporal progression refers to the time and speed for the trajectory segment to be traversed. Orientation and temporal progression are important properties to support shared access of the same airspace volume by multiple aircraft. They allow for service providers or other sUAS operators to predict the traffic level or density for a given airspace volume from the shared trajectory information. Unlike the conventional trajectory segment construction process, modeling of a vehicle plant is generally not required. Categorical environmental conditions, generally not dynamically simulated, are fed to the kinematic operations to calculate the temporal progress of the vehicle within the trajectory segment. If required, auxiliary conventional trajectory segments may be formulated by the scenario interpreter to obtain more detailed and more accurate determination of properties for the current unconventional trajectory segment. Such properties may include the temporal progression and trajectory containment boundaries, among others. Alternatively, auxiliary conventional trajectory segments may be formulated in advance to obtain probabilistic properties for fast and efficient inline modeling of unconventional trajectory segments.

As the final step of the trajectory modeling process, in trajectory integration, results from the trajectory segment modeling are combined into resulting trajectories. This is not always simple. For example, even in case of a simple trajectory segment sequence, for a given mission plan, certain trajectory segments in earlier phases of the flight may be dependent on those in later phases of the flight; a proper iterative process may be needed. For unconventional trajectory, modeling results from *auxiliary* conventional trajectory segments, if required, need to be integrated into the corresponding *unconventional* trajectory segments to complete those unconventional trajectory segments before they can be properly assembled into a final trajectory. Some of the supplemental trajectory provisions may also be filled by the trajectory integration component, particularly the spatial and temporal probabilistic provision, and the kinematic trajectory parameter provision.

VI. Small UAS Aircraft Modeling

Small UAS aircraft modeling addresses the technical approach for modeling the vehicle plant and the incorporation of different levels of system performance into the prototype simulation tool. The technical approach includes two main aspects. The first aspect is the parameterization of the aircraft performance model (APM), which includes the aerodynamic performance, engine performance, and mass and moment of inertia properties of the airframe. The second aspect is the modeling of vehicle dynamics and flight controls, which includes the equations of motion, different levels of flight controls, and state estimation.

A. Small UAS Aircraft Performance Model

Parameterization of shareable sUAS APM is a critical element of trajectory modeling. Such models allow for a trajectory to be checked, re-predicted, or re-interpreted by systems other than its originator. However, one major challenge does exist in this area. Vehicle manufacturers may not always be willing to share high-fidelity APM data. In some cases, sUAS manufacturers might not have the established high-fidelity APM themselves, mainly due to the cost associated with preparing such models and the compressed vehicle type upgrade cycles, sometimes a couple of cycles per year. Because sUASs are not expected to be subject to the same level of scrutiny in vehicle certification processes as most of the manned aircraft categories, their system configurations are much more flexible, and their vehicle and system modification are much more frequent. This means it is highly likely that the performance of a particular sUAS in the field will deviate from the manufacturer's specification, even if high-fidelity APM does exist in the manufacturer's possession. The formulation of the sUAS aircraft model parameterization must balance the fidelity, usability, computational complexity, and data availability.

Based on extensive aircraft modeling experience gained through the development of the Tool for Analysis of Separation and Throughput (TASAT) [29], [30], and the application of the Base of Aircraft Data Version 3 (BADA 3) [25]-[27] developed by the EUROCONTROL Experimental Centre (EEC) in internally funded trajectory-based operations (TBO) studies, the research team believes that a model parameterization with a granularity comparable to the BADA 3 APM would be sufficient for sUAS trajectory modeling purposes within the context of UTM. The TASAT APM is a mix of parametric models and tabulated data to capture highly nonlinear behaviors over a wide range of operating conditions. The accuracy of the TASAT APM has been validated by comparing simulated trajectories and trajectories recorded during flight tests, first at Louisville International Airport (KSDF), involving UPS's Boeing 757-200 and Boeing 737-300 cargo airplanes [30], and later at Hartsfield–Jackson Atlanta International Airport (KATL), involving additional passenger airplanes such as Boeing 737-800 from Delta Air Lines [4]. TASAT APM is a high-fidelity model derived from aircraft manufacturers' performance engineering data. BADA 3 APM is a relatively simple model comprising parameterized performance equations, basic performance parameters for each modeled aircraft type given in an Operations Performance File (OPF), and procedural performance parameters given in an Airlines Procedures File (APF) and a Performance Table File (PTF). BADA 3 has been widely used by many ATM tools and operational automation systems. Its format has been used to create APM for larger UASs [2], [38], including several aircraft within the sUAS weight class (see [38]). Efforts using BADA 3 achieved some level of success, particularly for fixed-wing aircraft. NASA's Center TRACON Automation System (CTAS) APM [34], [35] has a granularity that is similar or slightly lower than that in the TASAT APM. The main differences between the TASAT APM and the BADA 3 APM include Mach number compression effects and Reynolds number effects on aerodynamic drag, and engine performance over wide range of operating conditions. Given that an sUAS is expected to be operated below 400 ft. AGL and 86 kt., those effects can be simplified, although they might not be completely ignored. For example, an assumed flight altitude of 200 ft. AGL in Miami, Florida is quite different from 200 ft. AGL in Denver, Colorado in terms of pressure altitude or density altitude. The same principle could be applied to the engine model.

However, there are several limitations in BADA 3 APM. It does not include battery/electric motor engines. This may be addressed with two options: 1) map battery/electric engine performance parameters to existing BADA 3 engine thrust and fuel flow (power drain) parameters; and 2) replace existing BADA 3 engine thrust and fuel flow parameters with battery/electric engine thrust and power drain parameters. The first option will be compatible with the BADA 3 OPF format, but the second option will be more accurate and easier for obtaining parameter values for a given aircraft model type. In either case, a new set of thrust and power drain equations needs to be developed for battery/electric motor engines.

In BADA 3, all aircraft types are modeled as CTOL fixed-wing aircraft. Helicopters are assigned to a generic helicopter that is represented by the Piper PA-28-161 piston fixed-wing aircraft. The only VTOL aircraft, Bell Boeing V-22 Osprey, is represented by a twin turboprop fixed-wing passenger aircraft, namely the Bombardier Dash 8-300 (changed to Saab SF 340B in BADA Revision 3.13.1 [27]). Given the proliferation of multirotor sUASs and the potential growth of VTOL sUASs for applications requiring longer range, and the significantly different flight characteristics of such airframe configurations from CTOL fixed-wing aircraft, they must be introduced into the sUAS APM. Depending on the airframe configuration, new performance parameters must be introduced to either complement existing BADA 3 parameters or to replace some of the existing parameters. New performance equations will also need to be formulated.

In addition to the simplicity and the ability to relatively accurately model low-speed and low-altitude performance, a model parameterization comparable to BADA 3 APM also has the benefit of easier adoption by UTM ecosystem partners due to the large user base of BADA 3 APM in the ATM community. Design specifics of the sUAS APM will be determined based on simulation and validation results from the prototype sUAS trajectory modeling tool being developed.

B. Vehicle Dynamics and Flight Controls Model

Modeling vehicle dynamics and flight controls is important for accounting for effects of environmental conditions such as wind, turbulence, temperature, and air density, and for quantifying impacts of system performance and hazards. Most trajectory modeling tools in the ARM arena, including BADA [27] and CTAS [34], [35], employ a point mass to model the motion of fixed-wing aircraft in the airspace. Many assumptions must be made to arrive at a simple and efficient model. In the case of BADA, the principle of total energy control [21] is applied to derive the equation of motion (EOM) in the longitudinal direction. Different energy share factors are assumed for climb and descent operations to simplify the calculations. CTAS considers climb and descent navigation control laws to arrive at equations for modeling the trajectory in the vertical and lateral plane. It assumes small flight path angle, small sideslip angle, and zero flight plan angle rate. TASAT [29] uses a highly efficient pseudo 6DoF model to accurately simulate aircraft trajectory response to winds and wind uncertainty. Engine response and rotational motion are modeled as second order feedback systems. No small angle assumptions are made in TASAT. To achieve balance between accuracy and efficiency, the model is formulated for different types of trajectory segments. The formulation for each type of the trajectory segments captures a specific set of characteristics and assumptions. BADA, CTAS, and TASAT are all limited to fixed-wing aircraft only.

A comprehensive survey of rotary-wing sUAS control systems is provided in Ref. [17]. One example is the dynamics model and controller developed for the Stanford Rotorcraft for Multi-Agent Control (STARMAC) fleet of quadrotor aircraft [13], [14]. More recently, to study sUAS trajectory in the presence of wind, D'Souza modeled multirotor vehicles as a point mass with a simplified set of EOM and a gain scheduled proportional-integral-derivative controller (PID) controller [8]. A genetic optimization method was used to optimize the controller.

Although aerial vehicle dynamics vary from airframe configuration to configuration, they are all derived from Newton's second law. In the body fixed frame with its origin at the vehicle center of gravity (CG), the basic ROM has the following form, assuming the vehicle body is perfectly rigid

$$\begin{cases} X - mg\sin\theta = m(\dot{u} + qw - rv) \\ Y - mg\cos\theta\sin\phi = m(\dot{v} + ru - pw) \\ Z - mg\cos\theta\cos\phi = m(\dot{w} + pv - qu) \\ L = I_x\dot{p} - \left(I_y - I_z\right)qr \\ M = I_y\dot{q} - (I_z - I_x)rp \\ N = I_z\dot{r} - \left(I_x - I_y\right)pq \end{cases} \tag{1}$$

where, u, v, and w are linear velocity components, and p, q, and r are angular velocity components, in the x, y, and z direction, respectively. They are major state variables in the perspective of flight control, along with inputs to the flight control system: X, Y, Z (linear external force components) and L, M, Z (torque components) that are applied to the vehicle body. Lastly, m is vehicle mass, I_x, I_y, and I_z are moments of inertia components, and g is the gravitational acceleration.

From the flight controls' point of view, Eq. (1) may be linearized around a certain equilibrium point of state as

$$\dot{\mathrm{X}} = \mathbf{A}\mathrm{X} + \mathbf{B}\mathrm{U} \tag{2}$$

where X denotes the state variable vector, U denotes the system input vector, and $\mathbf{A}$ and $\mathbf{B}$ are corresponding matrices representing contributions of state variables and inputs to the system dynamics, respectively. The state variable vector X does not necessarily have to contain all the states, because the overall system dynamics could be split into multiple partial dynamic equations (for example, longitudinal and lateral ones for conventional aircraft). In addition, state variables that are regarded as important ones are different depending on the vehicle types. And this is also the case for the system input vector U, because the source of external forces that contributes to vehicle flight really depends on each of vehicle type and configuration.

For conventional fixed-wing aircraft, matrix $\mathbf{A}$ in linearized EOM Eq. (2) consists of nondimensionalized entries to avoid calculation issues, for example to prevent singularity in matrix calculation. The linearized EOM are usually separated into longitudinal and lateral ones, Input for conventional fixed-wing aircraft consists of throttle ΔT, and control surface deflections normally include elevator δ_e, aileron δ_a, and rudder δ_r

$$\mathrm{U} = [\Delta T \quad \delta_e \quad \delta_a \quad \delta_r]^T \tag{3}$$

For conventional helicopters, i.e., rotorcraft with cyclic pitch control, the simplified EOM is virtually identical to that for fixed-wing aircraft, but they have totally different input. Its sources of lift, thrust, and controls are mainly from the thrust of the main rotor(s) and the tail rotor (for single rotor helicopters). At a high level, there are four inputs: two for the thrust and collective controls of the main rotor(s) and the tail rotor (u_{col}, u_{ped}), and the other two for the control of the inclination of the tip-path-plane (TPP) in longitudinal direction and lateral direction (u_{lon}, u_{lat})

$$\mathrm{U} = [u_{col} \quad u_{ped} \quad u_{lon} \quad u_{lat}]^T \tag{4}$$

Helicopter dynamics are very complex. Significant simplification must be made for it to be practical to be applied in trajectory modeling. Input in Eq. (4) represents, at a minimum, the effects of engine throttle control, rotor collective pitch and cyclic pitch control, and main rotor blade flapping and lead-lagging motion.

In the context of sUASs, *multirotor* typically refers to vehicles with multiple rotors that are mostly fixed-pitch. In this case, the only control inputs are thrust vector T_i and the corresponding torque vector M_i from individual rotors installed at r_i

$$\mathrm{U} = [\mathrm{F} \quad \mathrm{M}]^T$$

where

$$\mathrm{F} = \sum_{i=1}^{m} \mathrm{T}_i\,, \quad \mathrm{M} = \sum_{i=1}^{m} (\mathrm{M}_i + \mathrm{r}_i \times \mathrm{T}_i) \tag{5}$$

VTOL fixed-wing aircraft have been a subject of extensive research and development since 1950s for the combined benefits of VTOL and the range and endurance efficiency of a fixed-wing aircraft. A wealth of literature exists for VTOL configurations. The main new challenge for VTOL aircraft is the transition between full vertical flight (helicopter or multirotor mode) and full forward flight (fixed-wing mode). During this process, both types of control input will contribute to the flight. For other unconventional airframe configurations, such as a flying insect [6], Eq. (2) still applies, but there is one important difference from the ones that are already introduced: discreteness of its dynamics. The dynamics need to be discrete in harmony with the quasi-periodic control input and thus requires considering time varying matrix $\mathbf{A}$.

Being able to model different levels of navigation, guidance, and auto flight controls capabilities and performance is a key aspect for sUAS trajectory modeling. Significant system capability and performance variations exist among different aircraft types. For the same aircraft, system capability and performance may change or degrade due to changes in operating environment and/or system failure hazards. These variations or changes may be achieved by swapping simulation components such as different auto flight control modules, automatically tuning control gains to match a different level of system performance, or including different levels of navigation and state estimation errors and uncertainties in the simulation.

VII. Small UAS Trajectory Modeling Validation

In general, the validation process must first measure the performance of the trajectory from the modeling process, and then identify the specific sources of any resulting errors, thus facilitating an improvement. To measure the accuracy of a trajectory predictor in support of any systematic validation framework, four main processing areas should be considered:

- Parsing and checking the trajectory prediction from the modeling process

- Parsing and checking the reference trajectory data of an aircraft
- Comparing the predicted and the actual trajectory by sampling and measuring based on the definitions of the validation metrics
- Analyzing the results and identifying sources of any resulting errors for improvement

The validation process could be iterative if any improvement needs have been identified during the previous validation iteration. In the following subsections, validation data sources, validation metrics, and potential tools that may be used to obtain those data and metrics are discussed.

A. Validation Data Sources

Lack of validation data sources has been cited as the main challenge in recent UAS trajectory modeling efforts [2], [33]. To address this challenge, the approach must consider multiple data sources.

Aircraft performance data, often given as tabulated vertical flight profiles under zero wind conditions, may be available to conventional trajectory modeling for ATM automation that focuses on civil transport aircraft. Multiple vertical profiles may be provided as a function of aircraft weight, climb speed schedule, and temperature deviations from International Standard Atmosphere (ISA). This type of data can be used to validate the vertical performance of the trajectory model under controlled conditions, but it is hardly available for most sUAS aircraft.

Simulation data may be obtained from fast-time, hardware-in-the-loop, and/or human-in-the-loop flight simulators. Depending on the fidelity of the flight simulator, the vertical flight profile and the lateral flight profile of the trajectory predictor can both be validated under a broader range of controlled conditions, e.g., impact of turns on the vertical flight profile under wider atmospheric conditions in the simulation environment.

Flight test data is collected from actual flight operations. Conventional trajectory modeling efforts often take advantage of the abundance of surveillance data. Such data are very limited for sUASs due to the lack of an operational surveillance system. The high cost of flight testing for conventional manned aircraft results in a data set that is constrained by a small set of operation cases. However, the relatively low cost of sUAS operations may allow for extensive flight tests to be conducted. Flight test data is subject to uncontrolled atmospheric disturbance, sensor noise, and onboard processing delays; greater variation may be presented within the data. However, validation against flight test data would help evaluate the robustness of the trajectory model.

B. Validation Metrics

Reference [23] provided the basic metrics definition for assessing trajectory prediction performance. Ref. [28] presents a comprehensive implementation for measuring the accuracy of a trajectory prediction in support of a validation methodology. Metrics that could potentially be used in validating sUAS trajectory models are summarized in this section.

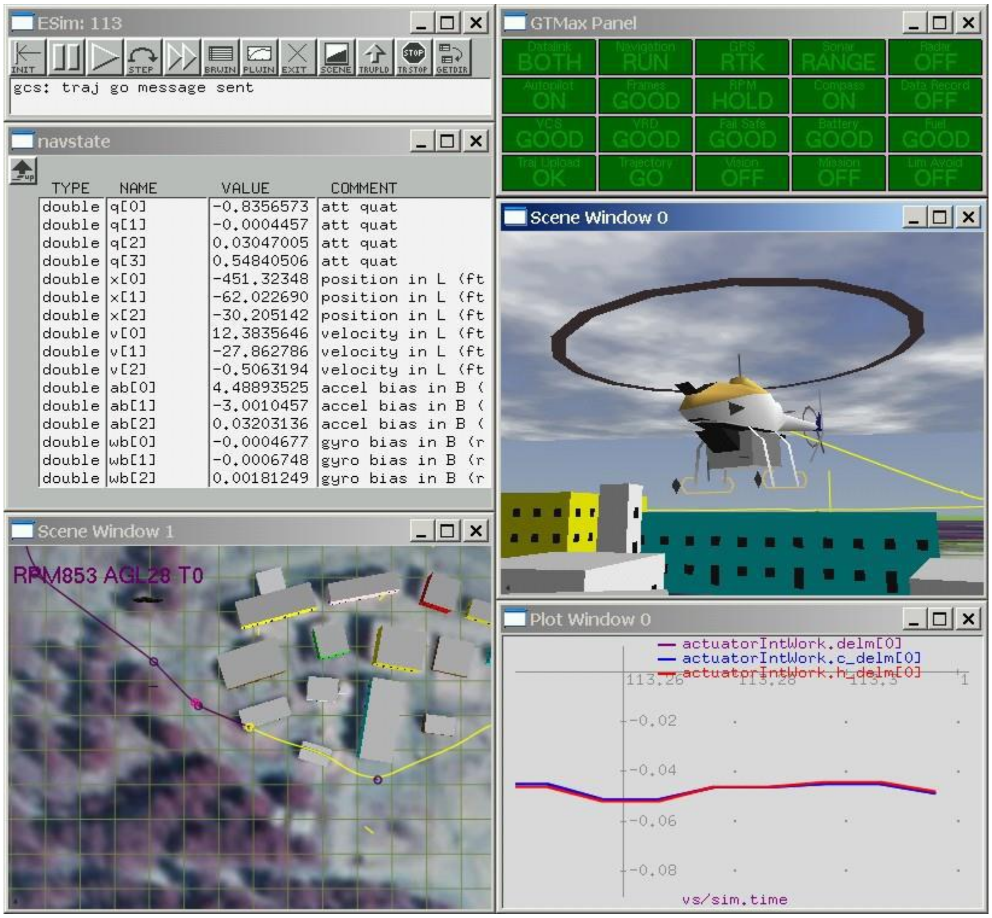
Since the quality of the input data to the trajectory predictor can have significant impact on the trajectory prediction, metrics regarding the input data should be captured to eliminate input errors and assure that the validation process is designed to evaluate trajectory model performance versus the effect of input data. Input data that may be required to obtain trajectory model include 1) aircraft performance model data, 2) meteorological conditions, 3) lateral intent, 4) vertical or speed indent, and 5) initial aircraft state. Basic metrics regarding those input data source may include 1) vector wind error, 2) speed intent error, 3) difference in the input route lateral path and the route actually flown, 4) lateral route error, 5) input weight error, and 6) initial condition position error.

Output metrics are obtained by taking measurements of the output of the trajectory predictor and comparing the measurements with the reference data. Basic output metrics may include 1) altitude error and 2) horizontal error, which may be decomposed into cross-track and along-track components.

Control performance is an important factor that directly influences trajectory output metrics, even for the same input. Control performance metrics can roughly be classified into two categories: 1) tracking and 2) disturbance rejection. Tracking performance can be measured by transient and steady-state errors. Considering both transient and steady-state errors, a single performance index for tracking capability may be obtained as a cost function of square of errors, to be minimized over the entire time domain. Usually, disturbance is modeled as an additional input to the system along with system input from the controller. The goal of disturbance rejection is to reduce the steady-state error caused by the disturbance signal. This error can also be incorporated into the cost function defining the overall control performance index.

C. Georgia Tech UAV Simulation Tool (GUST)

Among available simulation tools that may be used for trajectory validation, the Georgia Tech UAV Simulation Tool (GUST) [37] is of particular interest because of its availability to the research team. GUST is a set of C/C++ software that supports pure software, hardware-in-the-loop, and research flight test operations. To date, eight different aircraft types have seen extensive simulation within the GUST environment, as it has matured over the past 12 years into an effective research platform. GUST includes models of the sensors, aircraft, and aircraft interfaces – down to the level of binary serial data (i.e., packets) with time delays. It enables injection of model error and environmental disturbances. It includes a flexible scene generation capability (see Fig. 7) and reconfigurable data communication routines, enabling a large number of possible hardware-in-the-loop simulation configurations.



```
gcs: traj go message sent
```

TYPE	NAME	VALUE	COMMENT
double	q[0]	-0.8356573	att quat
double	q[1]	-0.0004457	att quat
double	q[2]	0.03047005	att quat
double	q[3]	0.54840506	att quat
double	x[0]	-451.32348	position in L (ft
double	x[1]	-62.022690	position in L (ft
double	x[2]	-30.205142	position in L (ft
double	v[0]	12.3835646	velocity in L (ft
double	v[1]	-27.862786	velocity in L (ft
double	v[2]	-0.5063194	velocity in L (ft
double	ab[0]	4.48893525	accel bias in B (
double	ab[1]	-3.0010457	accel bias in B (
double	ab[2]	0.03203136	accel bias in B (
double	wb[0]	-0.0004677	gyro bias in B (r
double	wb[1]	-0.0006748	gyro bias in B (r
double	wb[2]	0.00181249	gyro bias in B (r

Datalink BOTH	Navigation RUN	GPS RTK	Sonar RANGE	Radar OFF
Autopilot ON	Frames GOOD	RPM HOLD	Compass ON	Data Record OFF
VCS GOOD	VRD GOOD	Fail Safe GOOD	Battery GOOD	Fuel GOOD
Traj Upload OK	Trajectory GO	Vision OFF	Mission OFF	Lim Avoid OFF

Fig. 7 Simulation scene generation capability provided by GUST.

The simulator tools normally run on high-end personal computers or laptops with the Windows or Linux operating system. The sensor models include errors, mounting location and orientation, time delays, and digital interfaces. The scene generator includes a 3D graphics window (see Fig. 7) showing the aircraft and the terrain, and has additional functionality to aid in data visualization for use in the Georgia Tech Ground Control Station.

D. Open Source and Commercial off the Shelf (COTS) Flight Test Platforms

One of the open source sUAS navigation, flight control, and autopilot projects is MatrixPilot, which is supported by a community founded by William Permerlani [22], a former GE research engineer. MatrixPilot can be used to control fixed-wing airplanes. In the waypoint mode, MatrixPilot can be used to control the aircraft to follow a prescribed 3D flight path. In the fly-by-wire mode, MatrixPilot can be used to control the aircraft to maintain flight intent commands. In the pass-through mode, the aircraft can be controlled by the pilot remotely.

MatrixPilot has been extensively tested on several fixed-wing airframes. In particular, it has been extensively tested on the popular and commercial-off-the-shelf (COTS) Multiplex Easy Star II RC trainer [24]. Hardware-in-the-loop simulation with the SparkFun MatrixPliot UAV Development Board (UDB) and the X-Plane desktop flight simulator [39] have been developed for testing navigation algorithms, command languages, telemetry, wind estimation, etc. without risking crashing the airplane in the field. A plugin has been developed for the X-Plane to synthesize and provide sensor data back to the UDB. The same plugin can be used in software-in-the-loop simulation with the MatrixPilot software running on a virtual UDB hosted by the same desktop computer that runs the X-Plane flight simulator.

An algorithm has been developed to estimate the wind vector in real time. The algorithm combines sensor data from the GPS receiver and inertial measurement unit (IMU) measurements, with onboard aircraft state estimation to arrive at an estimated wind vector without using a pitot tube. MatrixPilot also supports outputting telemetry data in different formats. This enables real-time monitoring of the airplane on the ground, or offline analysis from data recorded on board the airplane. Supporting tools have been developed to export the data in csv format and to visualize data in Google Earth, as shown in Fig. 8. This figure shows the flight track in blue, the aircraft attitude by 3D models of the aircraft, and estimated wind vector as yellow board arrows.

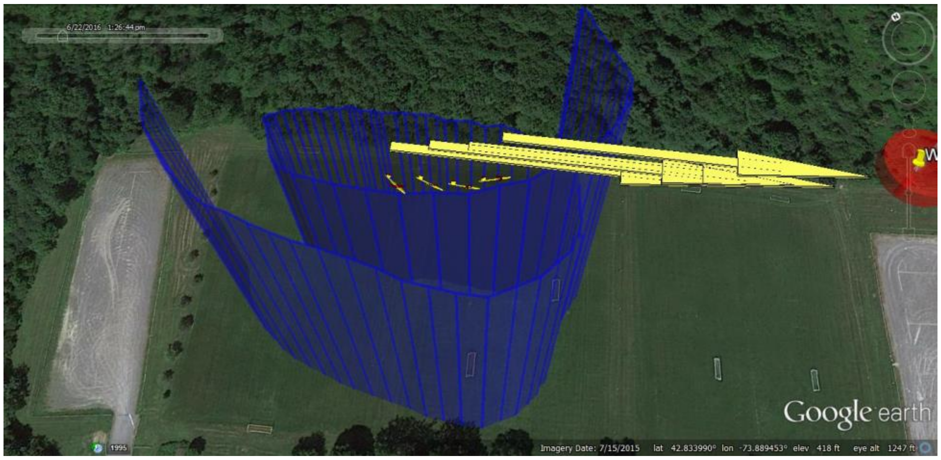


Fig. 8 Google Earth visualization of recorded flight data and estimated wind vector.

Open source and COTS flight test platforms, such as the MatrixPilot powered Multiplex Easy Star II, offers an alternative low-cost system for flight test validation. The great flexibility offered by such a system would allow certain components, such as flight controls and wind models, to be verified with flight test data. More complex test scenarios could also be quickly experimented with such a system before the test is refined for formal test with more sophisticated flight test platforms.

VIII. Summary

This paper presents a framework for the development and validation of trajectory modeling and prediction methods for diverse types of sUASs under a nominal environment and under a variety of realistic potential hazards, including adverse environmental conditions and vehicle and system failures. The paper also presents additional details on several components being developed under this framework. These include the pattern-based trajectory definition model, the prototype tool system architecture, aircraft modeling approaches, and trajectory validation approaches. As this is an ongoing effort, other components being developed under the proposed framework will be presented in subsequent papers as the research progresses. These include an sUAS categorization framework for traffic services, considerations for off-nominal trajectory computation, and the modeling of the environmental conditions within the atmospheric boundary layer. The final results are expected later in 2018.

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