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Ground Risk Informed Operational Planning for Small Unmanned Aerial Systems

William G. Cummings*, Ersin Ancel†, Patricia A. Revolinsky‡, Joanna N. Schmidt§
NASA Langley Research Center, Hampton, VA 23681

Joel 'Sloan' Glover¶
Analytical Mechanics Associates, Hampton, VA 23681

Increasing quantities of small Unmanned Aerial Systems (sUAS) operations present many challenges in terms of safe adoption and integration into existing airspace. The ability to study and quantify the risk to third parties on the ground prior to flight is an important step toward enabling Beyond Visual Line of Sight (BVLOS) operations. The Ground Risk Assessment Service Provider (GRASP) software is a capability developed by NASA to assist with third-party risk quantification and risk-informed flight planning. In this paper, two nominal flight paths intended to represent an infrastructure inspection mission are evaluated using the software to demonstrate its utility. A method is also introduced for adding other NASA-developed capabilities into a single architecture to assess a broader set of operational risks associated with BVLOS operations. These capabilities include a navigation system performance prediction tool, a high fidelity vehicle dynamics model, high resolution wind field data, and other information pertinent to operators. Data produced by these capabilities are combined to enable use of the Performance Based Navigation (PBN) concept borrowed from conventional aviation, providing quantified flight path uncertainty for where the sUAS is likely to be relative to its nominal flight plan. Ground risk is assessed within this region of uncertainty, giving a higher level of confidence in the solution compared to an analysis of only the nominal flight path.

I. Introduction

Emerging operational concepts for small Unmanned Aerial Systems (sUAS) will bring about new capabilities, including rapid delivery of common and life-saving goods, infrastructure inspection, and surveillance. With the benefits of these new operations come new hazards that must be studied and mitigated to ensure public acceptance. Risk to third parties, defined as individuals not directly participating in the operation, is an important component of this analysis. Existing aviation operations have been accepted by the public, but aircraft reliability is typically driven by the need to ensure safety for first parties on board the aircraft. Vehicles without an operator or human passenger on board can be far less reliable and, therefore, less expensive to certify, manufacture, and operate. However, for sUAS operations, the risk to third parties becomes critical and new methods for assessing the associated hazards will be required. The challenge associated with managing risk is particularly difficult when a pilot or operator does not have a visual line of sight to the aircraft and therefore cannot make decisions about the current or future safety of an operation without specialized tools.

This paper characterizes risk to third parties caused by uncontrolled or unpowered descent following a vehicle failure. For this analysis, vehicle failures will be considered as a complete loss of power and therefore no control inputs will be considered during the descent. The result is a ballistic descent towards the ground which may pose risk to any population present at the impact location. To quantify the third-party risk (and other risks), a series of tools designed to be deployed on board the aircraft, on the ground control station (GCS), or on a cloud-based (or otherwise connected) server were developed using a common architecture consistent with the In-Time Aviation Safety Management System (IASMS) vision described by the National Academies [1].

The cloud-based application, named Ground Risk Assessment Service Provider (GRASP), is a relatively mature product that has been in development for the past six years. GRASP, its development, and a description of its current

*Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442, AIAA Member
†Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442, AIAA Member
‡Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442, AIAA Member
§Research Engineer, Aeronautics Systems Analysis Branch, MS 442, AIAA Member
¶Software Engineer, Dynamic Systems & Control Branch, MS 152

interface are presented in Section II. Use cases and an illustration of using GRASP to plan flights in a manner that minimizes risk to persons on the ground are introduced in Section III. A broader concept for using GRASP in concert with other capabilities developed within NASA's IASMS implementation is presented in Section IV. The paper ends with a summary, areas of future work, and the potential impact of this research.

II. Ground Risk Assessment Service Provider (GRASP)

A. Background

NASA Aeronautics Research Mission Directorate's Unmanned Aircraft System (UAS) Traffic Management (UTM) Project established an architecture that aims to enable the integration of new aviation paradigms such as sUAS [2]. The UTM architecture allows communication among UAS operators, UAS Service Suppliers (USS), Air Navigation Service Providers (ANSP), and the public. Within the architecture, the Supplemental Data Service Providers (SDSPs) are envisioned to disseminate essential information like terrain/obstacle data, specialized weather data, surveillance, constraint information, risk monitoring, and others, as highlighted in Fig. 1 (see Ref. [3] for the UTM architecture details and Ref. [4] for the extrapolation of the concept to Urban Air Mobility operations).

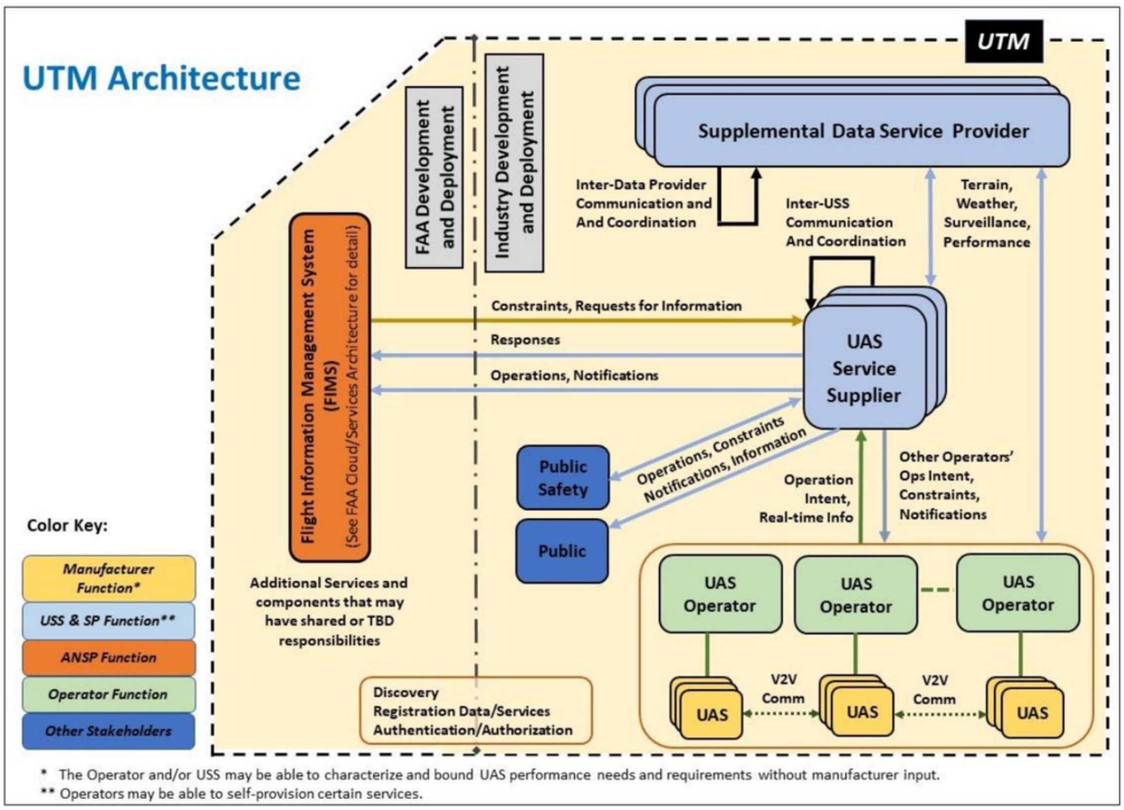


Fig. 1 Notional UTM architecture [3].

Over the past eight years, several projects within NASA's Aeronautics Research Mission Directorate have sponsored the development of GRASP. The development of the precursor to the GRASP application started in 2016 under the UTM Project. The first version of the tool was developed as part of an application-agnostic UAS Risk Assessment Framework (URAF) capability which established a method for assessing the ballistic trajectory of a vehicle with the end result of providing an estimated number of casualties at the impact location [5]. Within the System-Wide Safety (SWS) Project charter, the framework was further modified to establish a pre-flight capability and configured as an SDSP hosted on a public-facing, cloud-based server [6]. Simultaneously, a parallel effort was initiated to create a version that could execute on board (i.e., real-time). The resulting capability, the Real Time Risk Assessment (RTRA) tool, was created using the URAF approach, via the same probability of casualty calculation as GRASP while accounting for active health monitoring of the aircraft systems, which enables the estimation of failure probabilities of these systems using directed acylic graphs (e.g., Bayesian Belief Networks) [7, 8]. More recently, GRASP was further developed under the Air Traffic Management – eXploration (ATM-X) Project with the integration of the operational intent volume concept. Finally, the Combined Operational Risk Assessment tooL (CORAL) architecture was developed to explore the potential to combine GRASP's capabilities with other SWS-developed functions and capabilities, providing a broader, multi-hazard, pre-flight risk management service.

B. GRASP Interface

As previously discussed, the GRASP service helps to mitigate the risk of third-party casualties should the vehicle experience loss-of-control or a critical system failure (e.g., power loss). Since its inception, the GRASP web server has been hosted on numerous platforms, both NASA-internal and public-facing formats. The current implementation is hosted using Google Cloud Platform (GCP) and is administered by an internal NASA team that manages system access, system security, and maintenance. GRASP offers both a graphical user interface (GUI) and a programmatic access through a RESTful interface [6]. Using either interface, the client accesses the service and provides operational information that GRASP then uses to (1) simulate execution of the flight plan, (2) estimate the potential impact points for the aircraft at every 10-meter interval, and (3) calculate the probability of casualty for each interval. Figure 2 shows the required data fields within the GUI, which include flight date and time, aircraft characteristics (weight, drag coefficient, diameter, and type), and the waypoint file contents (which include information on the location, altitudes, and velocities of the planned flight)[*]. Besides client-provided data, the GRASP software relies on publicly available and commercially acquired data sources to compute casualty probability values. For select localities, historical[†], 10-meter resolution, hourly population density data were procured from the Airsage company[‡]. Additionally, current and forecasted weather data procured from a commercial weather company (TruWeather Solutions[‡]) were employed to include the wind effects while estimating the vehicle impact point. Finally, publicly available building footprint databases are used for computing sheltering effects.

Upon the upload and subsequent execution of the code, results are provided in two formats; they can be downloaded/saved in JSON format (top-right corner in Fig. 2) or they can be displayed using the embedded, interactive map application (bottom-right corner in Fig. 2). The map view allows clients to visualize a) color-coded probability of casualty values along the flight path, b) the predicted impact points for each 10-meter interval, c) population density heat map and associated values, d) 24-hour population density visualizer controlled via a slider bar, and e) aircraft and wind data specifics as provided by the client. Examples of the use of the GRASP service in operational planning are given in Section III.

III. Ground Risk Reduction through Informed Operational Planning

GRASP can be used in two primary ways to inform an operator as they plan for the start of operations. Both analyses are strategic in nature, occurring before the vehicle leaves the ground. The first use is statistical analysis of the intended area of operations. An analysis of this type will compile information about the general safety trends associated with specific flight paths across a variety of dates and times. The information can be used to design standard flight path routing so that flights pose comparatively lower ground risk. If the operator expects to repeatedly fly a similar profile, these reduced risk paths may be used as part of a safety case to obtain operational approval from the regulator. Common findings enabled by GRASP may include the identification of busy roadways, parks, and pedestrian areas. Examination and evaluation of the geometric and temporal trends of populated areas can help minimize risk exposure via selection of orthogonal road or highway crossings and identification of areas to avoid during daily or weekly time windows.

The second type of operation planning with GRASP occurs immediately prior to the time of departure and uses the exact date and time of the operation to assess the risk posed by the specific operation. The analysis focused on a particular date can alert the operator to unique population patterns, such as those associated with holidays or events. Performing this analysis may be included as a step to filing operational intent as part of a pre-flight checklist within a future UTM operational concept. The existing implementation of GRASP uses historical data to perform this analysis. However, a model that leverages machine learning to more accurately predict population density for a combination of dates, weather conditions, and holidays or other events would enhance performance of the pre-flight use case for GRASP.

[*]The commonly used Mission Planner Ground Control Station (GCS) software waypoint file format was adopted to communicate the aircraft trajectory data, see https://ardupilot.org/planner/index.html for more information.

[†]Ongoing research, aimed at developing a population density model that estimates expected population values, is currently underway.

[‡]This is not an endorsement by the National Aeronautics and Space Administration (NASA).

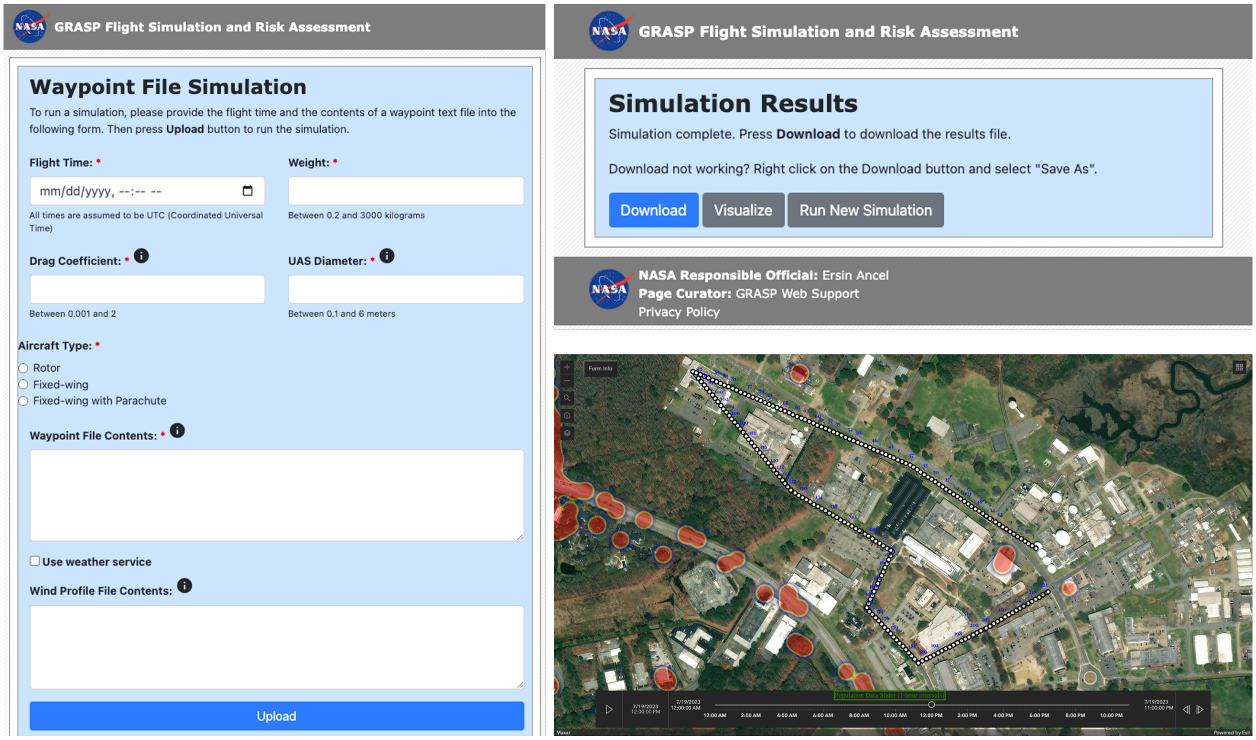


Fig. 2 GRASP interface and sample output.

In addition to the two ways GRASP can be used in planning operations, a third use of GRASP is as part of a trade study not associated with any particular flight or operation, such as determining the impacts of various vehicle types/reliabilities, weather conditions, or operational intent volume sizing strategies. These studies may be used early in the pre-operational planning process as operators or manufacturers choose vehicles or components to achieve a safety goal required to conduct operations in a particular area.

To illustrate using GRASP for operational design, trial runs were performed with the intent to inform ground risk for notional operations in the San Francisco area. The example operation features a sUAS used by the Department of Transportation (DOT) to perform an infrastructure inspection on the Golden Gate Bridge. Importantly for this analysis, the sUAS is assumed to be launched and recovered at a DOT building on the east side of downtown San Francisco. This assumption means the vehicle must traverse the populated area in between its base and the bridge where it performs the infrastructure inspection. Three variables were included in the evaluation to test the ability of the tool to capture a breadth of information. These variables were season, time of day, and vehicle weight. The dates for the two seasons were chosen to compare the same day of the week, in this case two Saturdays selected to maximize the pedestrian traffic for illustration purposes. Baseline trajectories featuring direct routes from origin to destination were also compared with routes improved by iterating after the first GRASP analysis. Table 1 shows the values that were used for the evaluation.

Table 1 Evaluation variables for illustrative flights

Variable	Value 1	Value 2
Season	Winter: Feb 4 2023	Summer: July 8 2023
Time of Day	Daytime (15:00)	Nighttime (02:00)
Flight Profile	Baseline	Adjusted

The mission profile used for this illustration includes a climb to 400 ft above ground level (AGL) before transiting the urban environment and descending to 100 ft AGL to perform the inspection. The same profile is used for the return leg to the launch site. The direct track, including segmentation for GRASP analysis, is shown in Fig. 3. The heat map illustrates the historical number of people in the area (blue - less populated; red - more populated), but it does not show the sheltering effects that are also considered by the risk estimate calculations.

Fig. 3 Golden Gate Bridge inspection - baseline path.

At a level of zoom appropriate to show the full duration of this flight, the dynamically scaled heat map utility only confirms that the city is a densely populated area. However, zooming in to the flight plan reveals a more granular data representation that can be used to make decisions about the routing. The area enlarged in the inset of Fig. 3 shows a populated area of Golden Gate Park. GRASP has predicted that the probability of casualty due to a failure in this location is elevated, as shown by the green and yellow markers on the flight plan. The colored markers have been enlarged for ease of visibility in this paper. These elevated risk points are associated with the arc of impact locations of matching color. Flight path modifications were made based on the results of the first GRASP Analysis. The area around Golden Gate Park was observed to include several areas of elevated ground risk, so the flight plan was modified to avoid the area and instead stay above buildings until reaching the coast, then continuing the flight over water (Fig. 4). The return leg was adjusted only slightly to remain over more forested areas. Due to the sheltering effect of the buildings along the route, the risk to third parties on the ground is decreased.

Ground risk for the duration of the flight is presented in the form of cumulative probability of casualty given failure. Cumulative probability is calculated by summing the probability of casualty associated with each discrete point along the analyzed flight path. The data for daytime baseline, nighttime baseline, and daytime adjusted flights are displayed in Fig. 5. In all of these cases, the vehicle is a rotorcraft with a weight of 25 kg, drag coefficient of 0.40, and radius of 1 m.

First, note that for the baseline flight path the accumulated ground risk is lower at night compared to the day. This is not surprising as the number of people expected to be in unsheltered areas at 02:00 is lower than at 15:00. This effect is more notable in the winter as the risk remains off the bottom of the chart until almost the end of the flight. Second, note the reduction in accumulated risk on the ‘adjusted’ flight trajectory. The path chosen to intentionally reduce ground risk was successful in this goal as can be seen by the reduced risk throughout the duration of the flight. Note particularly that while flying over water, the cumulative risk does not increase at all. This is a useful, albeit intuitive, finding and shows the quantified benefit of operating intentionally in an area unlikely to be populated. The adjusted flight track in the winter scenario did not reduce the ground risk as substantially as in the summer case. This highlights the need for the tailoring of flight paths to specific dates or times of year since population density trends are not constant.

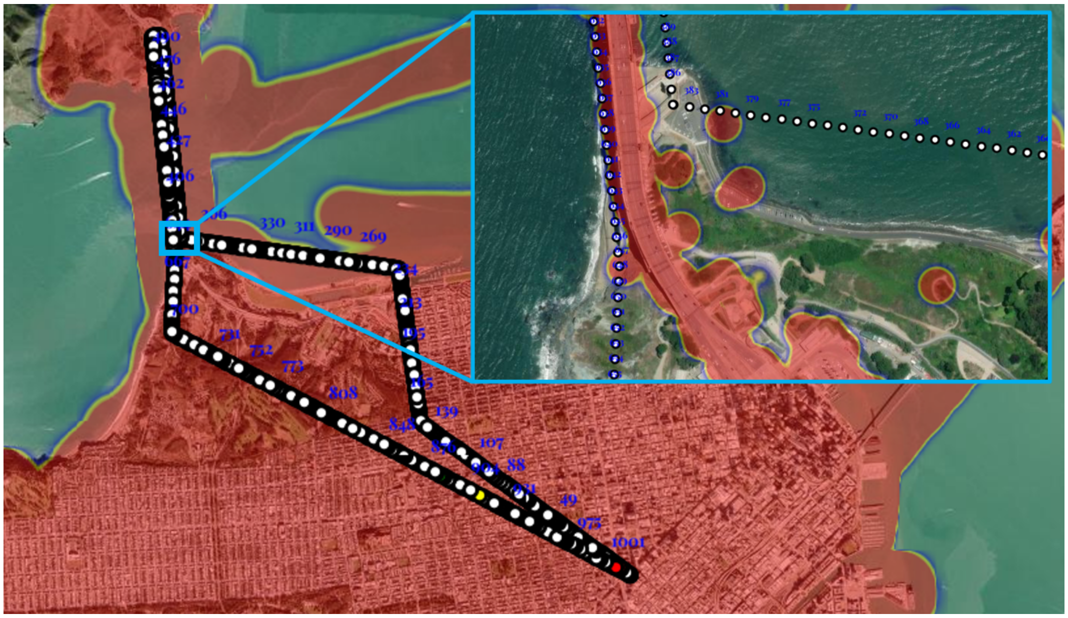
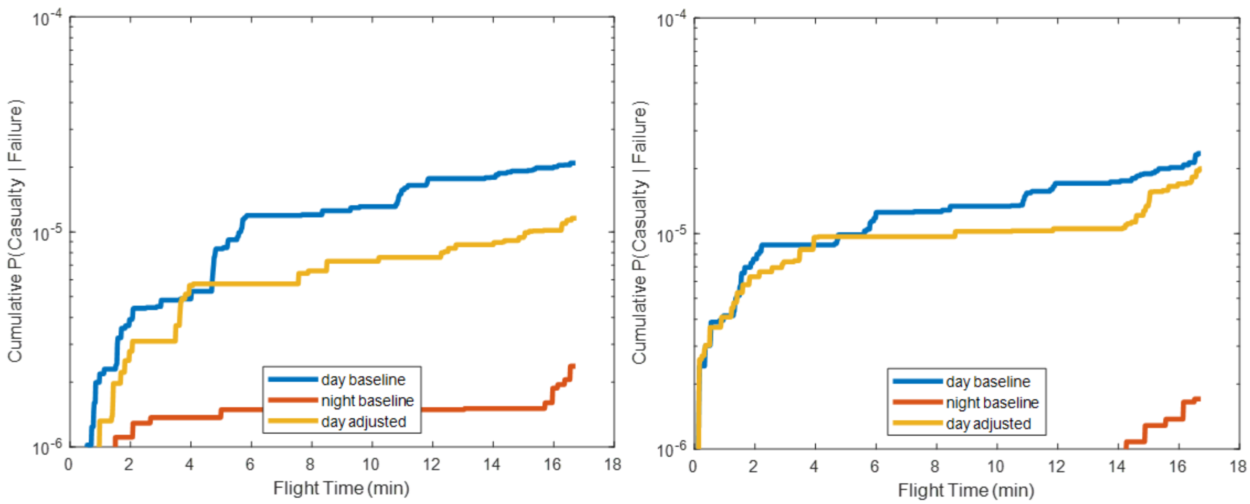


Fig. 4 Golden Gate Bridge inspection - adjusted path.



(a) Summer **(b) Winter**

Fig. 5 Golden Gate bridge inspection - cumulative probability of casualty.

IV. Combined Operational Risk Assessment tooL (CORAL)

CORAL is a concept architecture that combines several hazards associated with the operation of UAS and expands upon the approach used for GRASP. Each of these risks is comprised of several elements, including, but not limited to, aircraft health management, flight performance, weather, and mission and path planning. To properly assess these risks, and to integrate with future UTM concepts, an operational intent volume concept was chosen similar to that proposed by Jung et al. [9]. This tool's implementation of the operational intent volume concept uses the lateral flight path uncertainty of the vehicle to inform the width of the operational volume blocks. Since there is limited historical flight data available, this factor is calculated using the Performance Based Navigation (PBN) concept from legacy aviation operations. In this concept, Total System Error (TSE) is considered as the sum of Flight Technical Error (FTE), Navigation System Error (NSE), and Path Definition Error (PDE). Estimation of each of these errors can be performed using a number of tools currently in development. Each of the individual services and how they are combined to form the CORAL architecture are shown in Fig. 6.

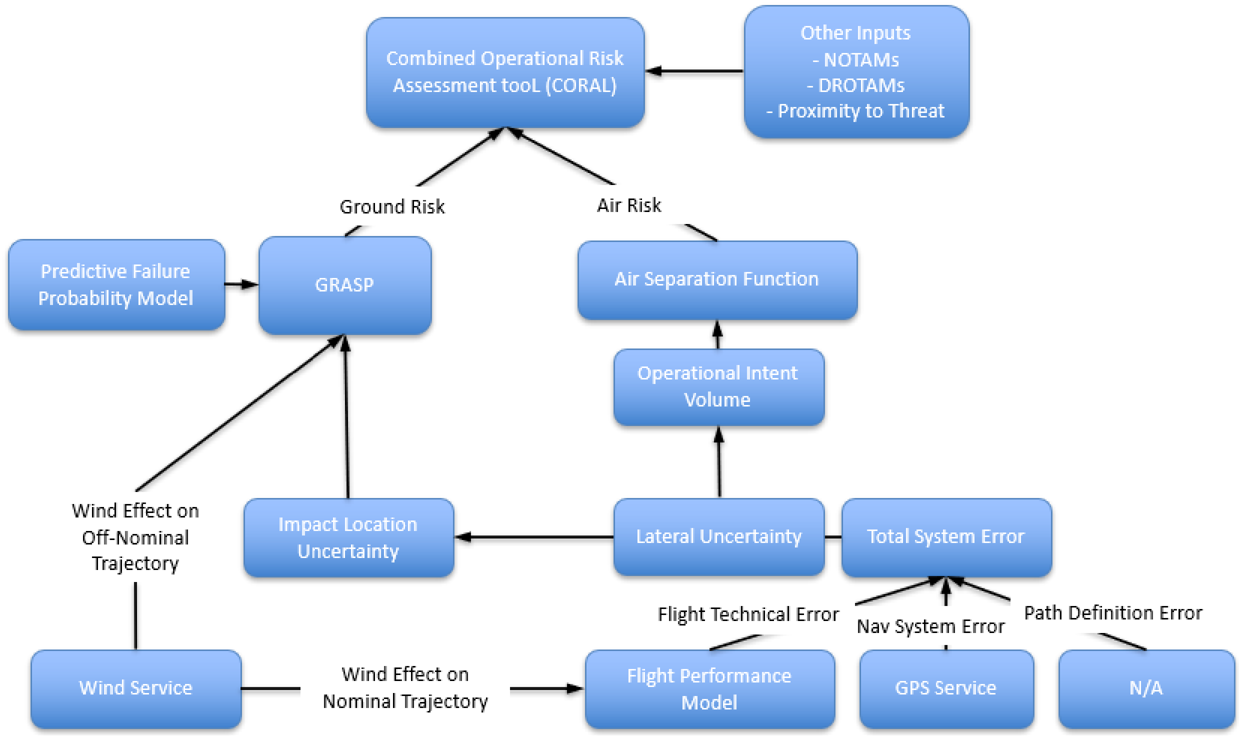


Fig. 6 CORAL architecture.

The diagram in Fig. 6 shows how some of the NASA-developed services could be leveraged within a CORAL architecture. In the bottom right, the TSE box displays connections with each of the services that provide sources of error. PDE is shown as N/A only because it is not addressed in this paper; it will be addressed in the future. NSE can be derived from information provided by a NASA-developed service called NavQ, which determines, for example, the number of GPS satellites visible at each point along the flight path at the proposed flight time [10]. Using this data, the Horizontal Dilution of Precision (HDOP) can be calculated, which is then used to predict the NSE along the flight plan. Other navigation systems and associated sources of error may exist for these vehicles but are considered out of scope for this paper. FTE is derived from a six Degree-of-Freedom (6DoF) vehicle dynamics model that includes nominal and some off-nominal vehicle cases. High resolution wind forecast data is also used as an input to the flight performance model. As with GRASP, this wind service is sourced from an external provider and contains data for wind at altitudes stratified between surface level and 400 ft, ensuring relevancy for sUAS application. These data are also used to determine the impact location given failure at any point in the flight plan.

The lateral uncertainty generated from TSE is used to determine the width of the operational intent volumes constructed for air-to-air separation. The volume width is also used as uncertainty bounds for the calculation of ground risk within GRASP. Using the same volume geometry for ground risk assessment and air separation assessment is important because it allows operators to utilize the full bounds of their operational intent while maintaining a risk-informed profile. This is valuable when vehicles must deviate from their nominal path due to unforeseeable factors such as micro-weather, bird activity, or an encounter with a non-cooperative vehicle. In all of these cases, an operator may react in a more informed way if they have timely access to an assessment of the ground risk associated with the airspace around their path.

In the proposed CORAL concept, additional information presented to the operator includes NOTices to Air Missions (NOTAMs), Drone NOTAMs specific to sUAS operations(DROTAMs), and the results from a tool called Proximity to Threat (PtT) [11] that evaluates the flight path for intersection with any ground obstacles (e.g., buildings). The combination of all of this information into a single capability enhances situational awareness and enables the operator to make informed decisions about their operation. For a full list of services that are being developed by the SWS Project, see Moore et al. [12].

Fig. 7 Operational intent volume visualization using the GRASP GUI.

The flight path in Fig. 7 shows an example of an operation over the Fisherman's Wharf, a popular pedestrian area in San Francisco. In this evaluation, operational intent volumes were generated. These are depicted as rectangles in the figure, each colored according to the highest ground risk that occurs in that volume. The impact point at which this highest value was assessed is also highlighted so that the operator can locate the problem and adjust the flight plan accordingly. It is apparent from this visualization that the operation over the Fisherman's Wharf exposes third parties to risk in the case of a critical system failure on the vehicle (e.g., power loss). By combining the view of the flight plan and problematic, exposed ground population on the same map, the operator/remote pilot can choose to take action by adjusting the intended flight plan. Ongoing development of CORAL will focus on integration of the aforementioned SFCs, enhancement of methods used to shape operational intent volumes, and links to future UTM systems.

V. Summary and Conclusions

This paper describes the evolution of GRASP and provides an updated description of its interface. An example application of GRASP to a sUAS infrastructure inspection mission illustrates the current capabilities of the tool. The application of GRASP to the example scenarios showed how a user could successfully plan an operation to reduce ground risk along the planned route. Differences in the selected seasonal and operational variables were evident in the tool outputs, but greater resolution is recommended for dense urban environments such as San Francisco. Greater resolution could be enhanced through the creation of a machine learning model trained on population data that enables the tool to generate results for a given day of the week, weather condition, and special event combination. An improved method to determine and analyze the sheltering effects of buildings could also improve the accuracy of the tool.

The paper also introduces a concept to combine a variety of additional services and capabilities to create a combined operational risk assessment tool for sUAS operations. An initial implementation of this concept was shown. Future work will expand on the initial implementation to fully explore the CORAL concept. To fully realize the benefits of such a tool and facilitate the emergence of BVLOS operations, future work should leverage the capabilities of this architecture to generate optimized routes that minimize ground risk in the context of uncertainty. Additionally, future work should include more information about the uncertainty associated with individual analyses so that potential operators and regulators can fully understand and make more-informed decisions regarding the risks associated with these operations.

Acknowledgments

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References

[1] National Academies of Sciences, Engineering, and Medicine, *In-Time Aviation Safety Management: Challenges and Research for an Evolving Aviation System*, National Academies Press, 2018. doi:10.17226/24962

[2] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," AIAA Paper 2016-3292, June 2016. doi:10.2514/6.2016-3292

[3] Federal Aviation Administration, "Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v2.0," 2020.

[4] Federal Aviation Administration, "Urban Air Mobility (UAM) Concept of Operations v2.0," 2020.

[5] Ancel, E., Capristan, F. M., Foster, J. V., and Condotta, R. C., "Real-time Risk Assessment Framework for Unmanned Aircraft System (UAS) Traffic Management (UTM)," AIAA Paper 2017-3273, June 2017. doi:10.2514/6.2017-3273

[6] Ancel, E., Helsel, T., and Heinich, C. M., "Ground Risk Assessment Service Provider (GRASP) Development Effort as a Supplemental Data Service Provider (SDSP) for Urban Unmanned Aircraft System (UAS) Operations," *38th Digital Avionics Systems Conference (DASC)*, IEEE/AIAA, San Diego, CA, 2019, pp. 1-8. doi:10.1109/DASC43569.2019.9081659

[7] Ancel, E., Capristan, F. M., Foster, J. V., and Condotta, R. C., "In-Time Non-Participant Casualty Risk Assessment to Support Onboard Decision Making for Autonomous Unmanned Aircraft," AIAA Paper 2019-3053, June 2019. doi:10.2514/6.2019-3053

[8] Ancel, E., et al., "Design and Testing of an Approach to Automated In-Flight Safety Risk Management for sUAS Operations," AIAA Paper 2022-3459, June 2022. doi:10.2514/6.2022-3459

[9] Jung, J., et al., "Applying Required Navigation Performance Concept for Traffic Management of Small Unmanned Aircraft Systems," International Council of the Aeronautical Sciences, Sep. 2016.

[10] Moore, A.J., et al., "Volume Raycasting of GNSS Signals through Ground Structure Lidar for UAV Navigational Guidance and Safety Estimation," AIAA Paper 2022-2218, Jan. 2022. doi:10.2514/6.2022-2218

[11] Spirkovska, L., Roychoudhury, I., and Quach, C. C., "Computing Proximity to Threat Along Uncertain Trajectory to Support Urban Air Mobility," NASA TM-20240000892, 2024.

[12] Moore, A. J., and et. al., "Testing of Advanced Capabilities to Enable In-time Safety Management and Assurance for Future Flight Operations," NASA TM-20230018665, 2023.