Development of a Safety Hazards Risk Assessment Tool for Uncrewed Aircraft System Traffic Management during Preflight Planning

Vimmy Gujral[1]
Human Systems Integration
NASA Ames Research Center
Moffett Field, CA, USA
vimmy.gujral@nasa.gov

Paul U. Lee[2]
Human Systems Integration
NASA Ames Research Center
Moffett Field, CA, USA
paul.u.lee@nasa.gov

Gregory Costedoat[3]
San José State University
San Jose, CA, USA
gregory.costedoat@nasa.gov

Jolene Feldman[4]
Human Systems Integration
NASA Ames Research Center
Moffett Field, CA, USA
jolene.m.feldman@nasa.gov

Lilly Spirkovska[5]
Intelligent Systems
NASA Ames Research Center
Moffett Field, CA, USA
lilly.spirkovska@nasa.gov

Charles Walter[6]
ASRC Federal Data Solutions
Beltsville, MD, USA
charles.m.walter@nasa.gov

Abstract— **Tremendous growth in the uncrewed and remotely piloted vehicle market is expected in low-altitude, uncontrolled airspace, resulting in potential decreases in safety without systems that support monitoring, assessing, and mitigating risk. At NASA, the System-Wide Safety (SWS) project has been developing a suite of data-driven tools to predict hazards so that the potential risks that these hazards pose can be mitigated. Services to predict various hazards have been developed, including battery capacity, proximity to static obstacles, population risks, global positioning system signal strength, radio frequency spectrum interference risk, and vertiport congestion. These services can monitor hazards along a flight path and if any risks posed by these hazards exceed a threshold, the uncrewed aircraft system (UAS) fleet manager can be alerted to mitigate the risk by modifying the flight path, changing the scheduled departure or arrival times, and/or diverting the vehicle to an alternate vertiport. These services were originally developed to monitor and assess risks during flight, but they have been adapted to assess hazard risks prior to departure so that a fleet manager can evaluate the potential risks for a fleet of UAS along their planned flight paths. These services have been integrated into a prototype tool called the Supplemental Data Service Provider-Consolidated Dashboard (SDSP-CD), developed at NASA Ames Research Center. The tool consists of a dashboard which provides a comprehensive overview for a number of risks and a map display that shows the details of the hazards along each flight's path. Based on the findings from three previous studies, the SDSP-CD has been updated with new design elements and functions. In this paper, we describe lessons learned from the previous studies, changes made to the interface, and the feedback received during a follow-up usability study. Overall, participants reported that there is a substantial benefit of having a fleet manager use a consolidated dashboard to assess hazards for the vehicles in their fleet and to provide situational awareness to potential risks so that they can be mitigated prior to flight. Once the SDSP-CD matures, it will need to be integrated into flight and mission planning tools. Some initial thoughts on how this integration should be accomplished are shared in this paper. Finally, the functional differences between preflight vs. in-flight risk assessment and the differences in fleet manager vs. UAS pilot roles that may require different information and user interactions are discussed.**

Keywords—preflight risk assessment, system-wide safety, uncrewed aircraft system, fleet management, aviation interface

I. Introduction

The Uncrewed Aircraft Systems (UAS) Traffic Management (UTM) concept is being developed by NASA, the Federal Aviation Administration (FAA), and industry stakeholders to enable safe and efficient UAS operations in low-altitude, uncontrolled airspace [1]. With the expected growth of small UAS traffic in highly populated regions in the full UTM ecosystem, potential safety risks would substantially increase without tools that support monitoring, assessing, and mitigating hazards. Within the UTM framework, Supplemental Data Service Providers (SDSP) are expected to provide services that are essential to planning and executing safe flights.

At NASA, the System-Wide Safety (SWS) project has been developing a suite of data-driven SDSP tools to predict and monitor hazards and mitigate risks by allowing users to change their plans, procedures, or route designs [2-3]. Although these tools were originally developed to monitor and assess risks during flight, they have been adapted to also assess hazards and risks prior to departure. This enables operators to assess potential risks to UAS along their planned flight paths prior to takeoff, when more mitigation options are available. In essence, the pre-departure risk assessment can essentially "buy down" and minimize the risk that UAS pilot may face during flight.

While prognostic data can be essential for proactively reducing the risk of hazards for a particular flight, this information can be complex to understand, driving the need to articulate requirements for designing effective interfaces [4]. Instances of both an over-abundance of information (e.g., display clutter), as well as a lack of information that UAS operators wanted or needed, have been reported [5]. Integration of these tools and displaying the results of each service can provide critical information about changes or predictions regarding a vehicle's performance, system capabilities, or environmental states. One aim of this work is to investigate the interface requirements needed to organize and display predictive risk and hazard information to operators in a clear and comprehensible way. The interface needs to provide operators with information related to situational awareness, hazard information, and the ability to simultaneously manage multiple vehicles.

In previous work, we presented the SDSP-Consolidated Dashboard (SDSP-CD) interface being iteratively developed at NASA Ames Research Center [2,3,6]. We obtained valuable feedback from several usability studies that was incorporated into the most recent version of the SDSP-CD. In this paper, we describe how this version of the SDSP-CD can support fleet managers during preflight planning.

In Section II of this paper, we describe the services provided by the SDSP-CD. In Section III, we describe the interface features and provide rationale for design choices. In Section IV, we discuss lessons learned from previous usability studies of the SDSP-CD and how feedback from those studies informed the present design. In Section V, we propose how the SDSP-CD can be integrated into the workflow of the fleet manager. Finally, in Section VI, we conclude with a summary of findings and suggestions for future work.

II. Description of the Risk Assessment Services

The SDSP-CD provides six risk assessment services. Five of the services provide information about risks along a specified flight path, whereas one service provides information about risks at arrival vertiports. In this section, we briefly describe the services; for additional details, see our previous work [7,8].

The five flight-route services and their purpose:

1. *GPS signal strength*: Determine if there is adequate GPS coverage along the flight path for accurate 3-dimensional positioning. The number of satellites visible at each point along the flight path determines the severity of risk. GPS risk severity is categorized as "good", "marginal but adequate", and "degraded".
2. *Radio frequency spectrum interference (RFI) risk*: Predicts if there may be excessive radio frequency energy that can disrupt electrical devices (e.g., hindering communication between the flight and ground station, along the flight path). RFI risk severity is categorized in four tiers: "none", "low", "moderate", "excessive". (Note that the initial service developer uses different terminology. We have simplified it here for consistency with the other services.)
3. *Battery energy availability*: Predicts if battery energy will be depleted, to obligatory battery reserve, prior to completing the flight as specified. The service computes the point (expressed in terms of flight time) along the flight path at which the battery reaches the reserve limit, a user-specified parameter. It also computes the point (time) at which the battery reaches end of discharge (EOD). Finally, the service computes the probability of reaching EOD before the end of the mission
4. *Proximity to static obstacles*: Evaluates if the flight path is adequately distant from obstacles. In the current version, the service evaluates the distance from buildings and trees; future versions may expand the variety of obstacles. The user specifies the minimum distance to maintain from each type of obstacle (e.g., 10 ft from buildings and 20 ft from trees). The service computes the safety margin for all points along the flight path. If the flight path comes closer to an obstacle than the user-specified minimum distance, the safety margin is 0%, meaning that the vehicle would fly too close to the obstacle. If it is more than twice as far as the minimum distance, the safety margin is at least 100% of the minimum distance, limited to 100% in the display for simplicity. Finally, if the flight is at least the minimum distance away but less than twice that, the safety margin is computed using the percent error formula and will be between 0% and 100%. The service provides the safety margin for all obstacles and additional data described in the next section.
5. *Population and casualty risks*: Determines if the flight poses ground casualty risk if an unforeseen termination of the flight occurs at any point along its path. The service provides population density predicted along the route and the risk to that population from a crash. Note that high population density along the route does not imply that the risk to that population is high. Rather, the service takes into account the flight's altitude, wind effects on the trajectory of a disabled vehicle, etc., to determine the impact points.

The sixth service that was evaluated was called the *vertiport congestion* service. Because this service had not been integrated in previous versions of the SDSP-CD, and thus the user interface elements have not been documented in our other publications, we describe it in greater detail. In this work, we equate congestion with its symptom of flight delays [8]. The congestion service differs from the other services in that it is not flight path based, but rather vertiport (landing area) based. It considers the risk of excessive delays on flights due to too many other flights competing for the limited resources of the vertiport, namely, parking spots. The constraints for vertiport operations resulted in a range of arrival delays for the preliminary schedule of flights, expressed as (1) number of minutes of delay for a flight and (2) category of average delay for each scheduled time window (e.g., negligible, low, moderate, high), based on pre-specified delay severity thresholds. Potential actions to mitigate vertiport congestion aim to decrease the number of flights competing for limited parking spots and include expediting, delaying, or cancelling flights, or redirecting flights to land at an alternate destination. The landing sequence of any two flights could also be swapped (e.g., a flight with a high-priority mission predicted to be significantly delayed could take the landing slot of a lower-priority flight with no expected delay). The overall congestion would not change, but delays for higher-priority flights could be reduced.

Similar to the other five services, the congestion service was initially developed as an in-flight service for use by an individual remote pilot or an automated pilot [8], but was modified here to be used in preflight planning. With the original in-flight context, the pilot has schedule control over only their own flight; the arrival times of nearby flights are shared only when near the destination; and the predicted arrival times are uncertain, with certainty increasing as the flight nears its destination. Due to the uncertainty and lack of visibility into the overall vertiport schedule, congestion was computed for multiple schedule windows (i.e., range from the destination vertiport, and recomputed as updated information about other flights and the progress of their own flight was obtained). Moreover, supplementary information (i.e., residual delay from one window to the next) was provided to help the pilot decide whether to expend extra energy to expedite their own arrival, conserve energy and delay their arrival, or divert to an alternate nearby vertiport.

The preflight vertiport congestion service was modeled similarly, although with a different context. For preflight planning, the operator can have full visibility and control over the schedule for all flights arriving at the selected vertiport. Additionally, operation uncertainty was not considered. For this application, the service could potentially be simplified by providing only expected delay in minutes (perhaps color-coded for display) for each flight, but the additional features were retained at the moment to get incidental participant feedback toward development of the in-flight service.

III. Consolidated Dashboard Interface for the Risk Assessment Tool

As previously discussed, the SDSP-CD services were originally designed to provide hazard alerts to UAS pilots during flight but were expanded to be used for preflight planning purposes. The SDSP-CD is designed for a *fleet manager*, the person responsible for planning flight paths for a fleet of UAS, analogous to airline dispatchers in commercial aviation. A fleet manager is expected to be aware of all vehicle and environmental conditions for scheduled flights and is responsible for mitigating any potential issues prior to departure. (See for example Part 121 Subpart U regulations [10] for airline dispatcher responsibilities.) Within this context, the tool is envisioned to allow the fleet manager to quickly review and mitigate potential risks. The goal of the SDSP-CD user interface (UI) is to provide a comprehensive overview of the hazards that may be encountered along a vehicle's proposed route using design strategies to intuitively highlight the type of hazard, the severity of the risk it presents, and its location.

The UI consists of two primary components, a dashboard and an interactive map, as shown in Fig. 1, with a close-up of the dashboard also shown in Fig. 2. The dashboard provides a comprehensive, color-coded overview of risk severity posed by the monitored hazards (enumerated in Section II) for the suite of flights being managed, whereas the interactive map contains geographic information and hazard locations.

The dashboard displays the status of each service for each vehicle (with a scrolling window available to accommodate a large fleet), with each row representing a vehicle and each column representing one of the six services. Color-coded alerts indicate the status of each service, with *green* representing that no safety thresholds have been exceeded, *yellow* representing that a safety threshold, although safe in its current state, is approaching threshold, and *red* representing that a safety threshold has been surpassed and represents a heightened level risk. The dashboard has a user settings menu that allows the user to upload vehicle information, select which services they

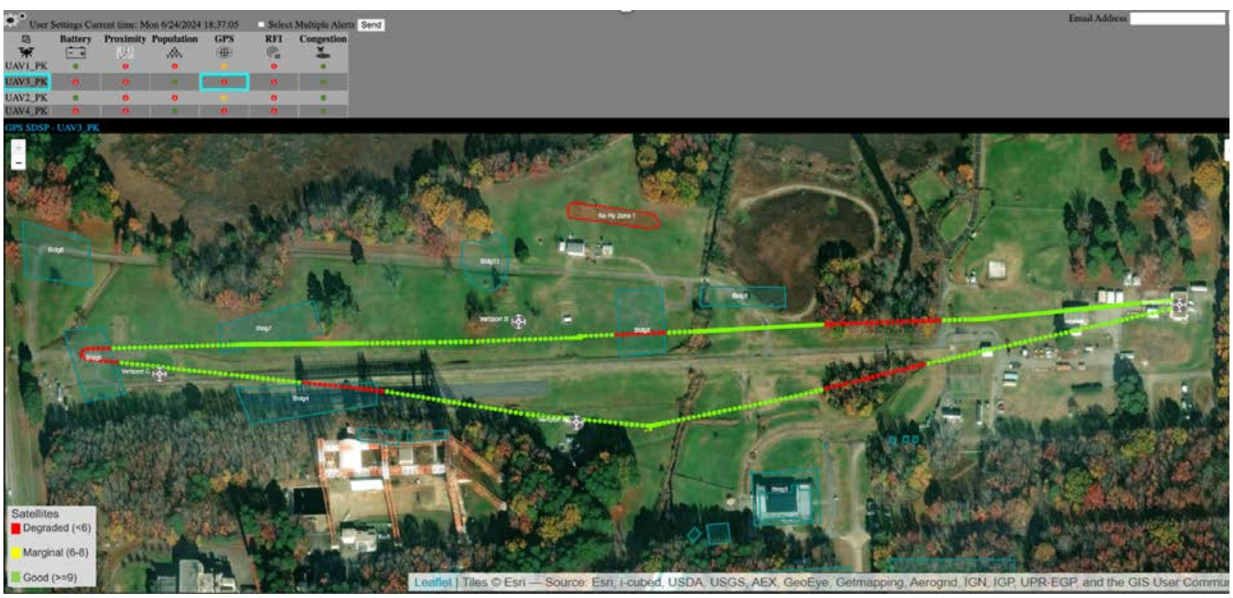

Fig. 1. The SDSP-CD interface (2024 version) (NASA Image). The dashboard is located at the top left corner of the interface, while the map spans the majority of the space below the dashboard. In this screenshot the GPS service is being selected for vehicle "UAV3". The vehicle's route appears on the map as green and red waypoints. The green waypoints represent areas where there is a "good" GPS signal along the route, whereas the red waypoints represent areas where the GPS signal is degraded.

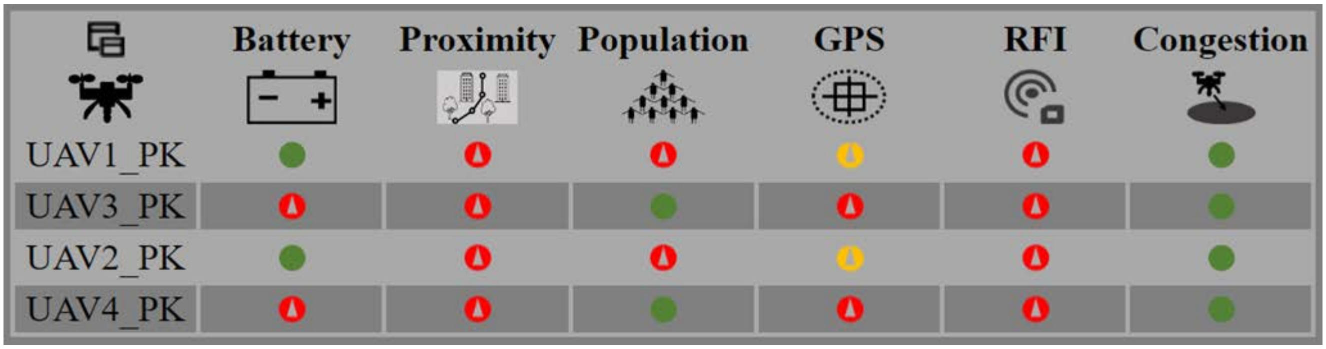

Fig 2. Dashboard on the SDSP-CD interface (2024 version) (NASA Image). Each row represents one vehicle in the user's fleet of UAS. Each column represents the risk level of the available services associated with each vehicle.

want displayed, and set thresholds for safety margins from a predefined safe range for the alerts for different services.

When an alert is selected on the dashboard, the location and severity of the hazard are highlighted along the flight's route, which is shown on the interactive map (see Fig. 1). The user can then make decisions based on this information. These decisions include altering the route to avoid the potential hazard or keeping the route the same but informing their remote pilots about the risk, among others.

The following describes the information presented on the SDSP-CD interface (2024 version) for each of the six available services:

1. *GPS signal strength*: The service computes GPS coverage for every point along the flight's proposed path. Three coverage categories (good, marginal but adequate, and degraded) are mapped to colors (green, yellow, red, respectively). The flight path is shown on the map as a series of color-coded dots. For example, the path shown for the flight in Fig. 1 is primarily green dots intermixed with sections of red dots, representing that the flight has good (green) coverage for most of the path, but degraded (red) coverage along some sections.

2. *Radio Frequency Interference (RFI)*: Similar to the GPS service, the associated service computes RFI risk for every point along the flight's path. Four interference risk categories (none, low, moderate, excessive) are mapped to colors (gray, green, yellow, red, respectively). Similar to GPS, the flight path is shown on the map as a series of color-coded dots using these four colors.

3. *Battery Reserve*: The battery service is somewhat different from the GPS and RFI services. It computes two values, reaching the reserve-limit and reaching operational depletion, typically set at approximately 30% charge to maintain long-term battery health. On the dashboard, the reserve-limit is mapped to a yellow alert and depletion to a red alert. On the map (see Fig. 3), the display shows where along the path the battery reserve and operational depletion are predicted to be reached, represented by the yellow battery icon and the red battery icon, respectively. The user can also get additional details via an information table that provides the estimated time the user-specified battery reserve limit will be reached, the estimated flight time available, and the probability of completing the mission with adequate battery reserve. Finally, the red "EOD" marker (lower left in Fig. 3) indicates that the vehicle is predicted to land with a battery reserve below threshold.

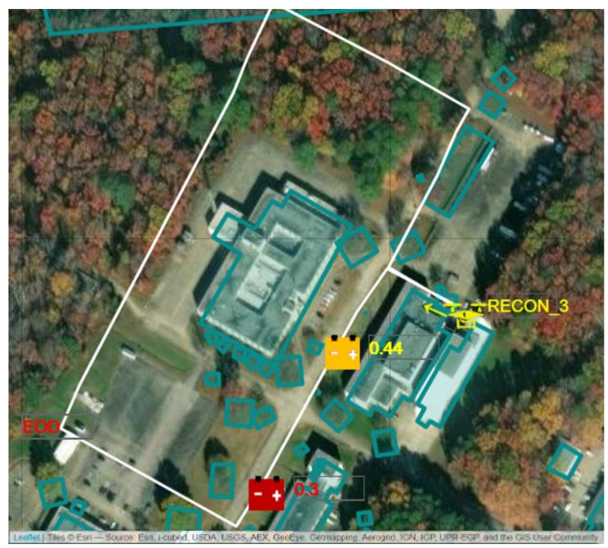

Fig. 3. This example screenshot (NASA Image) shows a proposed route flying clockwise. The yellow battery icon indicates where on the route the battery reserve will approach the threshold set by the user. The red battery icon indicates where the battery will drop below threshold. The "EOD" marker in red indicates that the vehicle would land with a battery reserve below threshold.

4. *Proximity to Obstacles:* The proximity service computes how close the flight path is to static obstacles. Analogous to the GPS and RFI services, parts of the route marked in yellow indicate that the risk is approaching but has not exceeded the threshold (i.e., for the proximity service, the yellow route indicates that the

vehicle route is close to buildings and trees but not over the threshold set by the user). In contrast, the red markings along the route indicate that the vehicle is closer to the obstacle than the threshold. When a vehicle with either a red or yellow alert is selected on the dashboard, the interface provides an information table with detailed proximity information for the vehicle, such as time to hazard, type of hazard (e.g., building or tree), safety margin, shortest distance between the trajectory points and the obstacle, obstacle identifier, whether it is a vertical or lateral threat, and an option to highlight the proximity hazard on the map by highlighting the building or tree.

5. *Population and casualty*: As described in Section II, this service provides the density of population along the route and the risk of casualty in the event of a crash. Unique to this service, a heat map (gradation of color) is overlaid on the interactive map to show areas of high, medium, low, and sparse population density (color-coded red, orange, yellow, gray, respectively) and corresponding impact points (see Fig. 4). As shown in Fig. 4, the population density along most of the route is sparse (gray) and the casualty risk is limited to the area in the upper middle of the route.

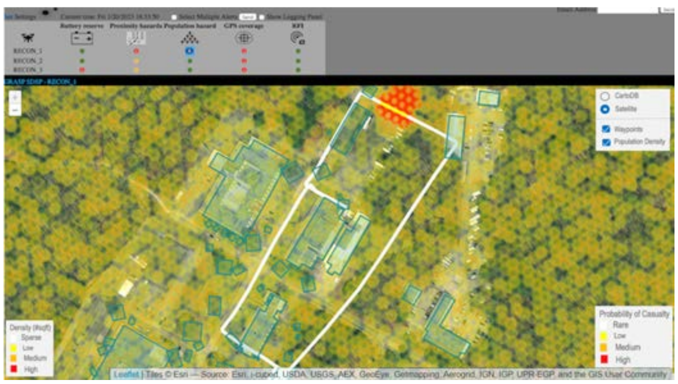

Fig. 4. Image of SDSP-CD User Interface (2023 version) with Population hazard alert selected for the UAS with the callsign "UAV401". Population density and probability of casualty heat map shown (NASA image).

The sixth, and most recent service added to the SDSP-CD, *vertiport congestion,* determines whether the arrival and departure flights as scheduled would result in excessive delays to arrivals while they wait for parking spots to become available. Unlike the other five services that rely on information about a single flight to select a mitigation action, resolving congestion requires holistically examining the traffic flows for the congested time period. To support this task, a flight schedule view panel was developed to show not only the selected vehicle with the congestion risk profile, but all of the surrounding vehicles that land in temporal proximity to the selected vehicle.

Fig. 5 shows the flight schedule view for one of the vertiports with the predicted traffic congestion information. The display shows the callsigns, originally proposed estimated time of departure (*Prop ETD*), originally proposed estimated time of arrival (*Prop ETA*), estimated time of arrival based on vertiport congestion (*Cleared ETA*), expected delay (*Delay*), and the severity of the congestion risks (*Congestion*).

Callsign	Prop ETD	Prop ETA	Cleared ETA	Delay	Congestion
UAV5		6:00	6:00	0:00	●
UAV6		7:00	7:00	0:00	●
UAV1		8:00	8:00	0:00	●
UAV7		9:00	12:00	3:00	●
UAV2		10:00	14:00	4:00	●
UAV8		11:00	18:00	7:00	●
UAV9	11:00				
UAV10	13:00				
UAV11	15:00				

Fig 5. Vertiport Congestion information for a given vertiport, with the vehicle callsigns, originally proposed ETD, originally proposed ETA, expected cleared ETA based on the vertiport congestion, expected delay, and the congestion risk severity (NASA Image).

The expected delay and the congestion risks are color-coded to reflect the adversity of the delay on the flight. For example, a less than two minute delay may be insignificant (negligible or low/green), a delay of two to four minutes is undesirable but may be able to be absorbed (moderate/yellow), and because of the small batteries onboard the UAV, a greater delay may have high consequences (high/red). The resulting congestion information in Fig. 5 is based on study-specified constraints for vertiport operations, and is expressed as (1) number of minutes of delay for a flight and (2) category of average delay for each 3-minute schedule window (negligible, low, moderate, high).

A fleet manager would likely want to decrease delays for any flights that have moderate or excessive congestion risk. The congestion service can automatically generate resolution options to support that task, suggesting mitigation actions such as expediting, delaying, cancelling, or redirecting a flight to land at an alternate destination. The landing sequence of any two flights could also be swapped (e.g., a flight with a high-priority mission predicted to be substantially delayed could take the landing slot of a lower-priority flight with no expected delay). The resolution options in the present study were hand generated to test the concept of automated resolutions, which was well received.

Resolution Options for UAV8

(1) Delay UAV1 by 5:00 min and UAV2 by 6:00 min
[--, --, --, --]
(2) Delay UAV8 by 3:00 min
[--, Md 4:00, -- 1:00, -- 2:00]
(3) Delay UAV7 by 5:00 min
[--, Lo 2:00, Md 3:00, Md 3:00]
(4) Swap UAV8 and UAV1
[--, -- 4:00, Hi 7:00, Md 4:00]

Fig 6. Resolution option panel for UAV8. Four options are shown, each with different vehicles and resolution maneuvers, with the corresponding impact of those maneuvers on the overall congestion (NASA Image).

Fig. 6 illustrates an example of the four suggested mitigation options presented to resolve excessive delays for UAV8, a flight that is predicted to arrive at a congested vertiport (see Fig. 5). The options are ordered by the resulting congestion for the schedule, with the option resulting in the lowest overall vertiport congestion first. The display indicates which maneuver to take (e.g. delay, swap), which vehicle to move (UAV8 or other surrounding vehicles), and by how many minutes. The display also shows whether the maneuver resolves the congestion completely or whether some residual delays will persist. This information is shown after each option, shown by dashed lines when the delay is completely eliminated, or indicated as low (Lo), moderate (Md), or high (Hi) if delays will remain for each scheduled time period (3-minute schedule window in this figure) for each option. It also indicates the delay minutes that would carry over into the next time period.

Prior to deciding to redirect a vehicle to an alternate vertiport, it would be helpful to view the congestion levels at the nearest available vertiports so that the fleet manager can confirm that the alternate is not just as congested. In support of this task, the alternate vertiport congestion panel was developed to show the congestion information for multiple vertiports (see Fig. 7).

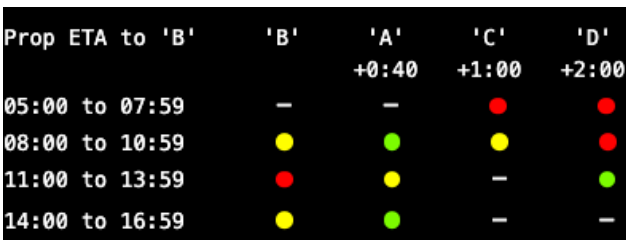

Fig 7. Alternate vertiport congestion information, relative to vertiport B. The congestion levels are shown in green/yellow/red for low/moderate/high congestions; and '-' for no congestion. The congestion levels are shown in 3-minute schedule windows. Vertiport B congestion is shown first, followed by A, C, and D, along with the flight time it would take to fly from vertiport B to the alternate vertiport (time shown in +min:sec) (NASA Image).

Fig. 7 shows the expected congestion category for each 3-minute schedule window for the three nearest vertiports to a selected vertiport, e.g., vertiport 'B'. The expected landing time, shown on the second line in the figure, is adjusted to account for the additional (or lesser) flight time to reach that vertiport from the penultimate waypoint of the flight plan versus from that waypoint to the originally scheduled vertiport. Continuing the example for excessively-delayed UAV8, with a proposed ETA of 11:00, the fleet manager could decide to redirect the flight to vertiport 'C', which is an extra one minute away but is predicted to have negligible congestion, vertiport 'D', which is an extra two minutes away and predicted to have low congestion, or vertiport 'A', which is only 40 seconds away and predicted to have moderate congestion. Beside the extra flight time and predicted congestion, the ultimate decision will depend on operational needs.

IV. Iterative Design, Development, and Evaluation of the Consolidated Dashboard Risk Assessment Tool

The SDSP-CD's development and evolution are firmly rooted in the feedback by subject matter experts detailed in this paper, indicating potential for a consolidated dashboard. It offers a means to assess the potential hazards across multiple vehicles during preflight planning, enhancing situation awareness for fleet managers to proactively mitigate the risks. Here, we outline three prior studies and their roles in shaping the development of the present SDSP-CD.

In these studies, participants assumed the role of a fleet manager and were assigned to optimize the flight paths and schedules to mitigate identified risks while meeting mission criteria. The risk severities were displayed on the dashboard and along the flight path, and the risk could be reduced or resolved by modifying the flight path, rescheduling flights, or changing destinations. Feedback from each study was used to improve and evolve the UI design to support fleet managers. Also, more services were added along the way and evaluated by participants. Overall, these studies emphasize the iterative nature of UI design and the importance of ongoing evaluation and refinement based on user feedback and evolving requirements. The following provides a brief overview of the progression of the UI development and studies.

2021 SDSP-CD UI: This version introduced a two-panel design (shown in Fig 8 and Fig. 9), with the first panel serving as a dashboard presenting four services: battery, proximity, population risk (shown as "GRASP"), and GPS, with indicators reflecting service's health status. As shown in Fig. 8, green indicated safety margins were maintained, while red and yellow alerts indicated potential hazards. Additionally, a neon green square icon next to the service indicated good connectivity (i.e., the service was operational).

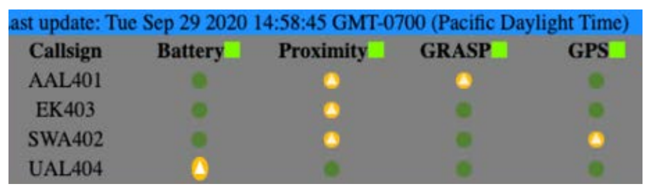

Fig 8. SDSP-CD UI (2021 version) showing dashboard (first panel) (NASA Image)

The second panel, the map display, in this iteration of the UI is shown in Fig. 9. As a usage example, when a proximity alert is selected for a flight (SWA402) on the dashboard, the results from the Proximity to Threat service was shown on the map.

Fig. 9. SDSP-CD User Interface (2021 version) showing map (second panel) showing detail information for the Proximity service, with three caution areas (building and trees) on the flight path for SWA402 (NASA Image).

The map highlights the obstacles that resulted in the yellow dashboard alert, and the alert box cautioned that the predicted flight path is close to the trees in three areas (magenta lines) and a building in one area (cyan line).

This UI design was assessed, primarily focused on the coherence and consistency of services represented on the interface, encompassing elements like color palette, icons, and information organization. The UI was improved and re-assessed in the following year.

2022 SDSP-CD UI: This version featured a consolidated dashboard showing results for proximity alerts selected for more than one vehicle as shown in Fig. 10a and Fig 10b using 'Select Multiple Alert' feature. The feedback from the participants in the previous review [2] contributed to notable improvements in this updated UI version such as consolidated dashboard, user-selectable parameters, adjusted color scales, simplified legends, addition of 'Select Multiple Alert' feature and streamlined navigation, reducing the number of mouse-clicks required to access different views. Moreover, this version also highlighted the event on the flight path when the battery was nearing a threshold level set by experts.

Fig.10a Image of 2022 version SDSP-CD User Interface with proximity alerts selected for the UAS with the call sign "UAV402" and "UAV403" using Select Multiple Alert feature (NASA image).

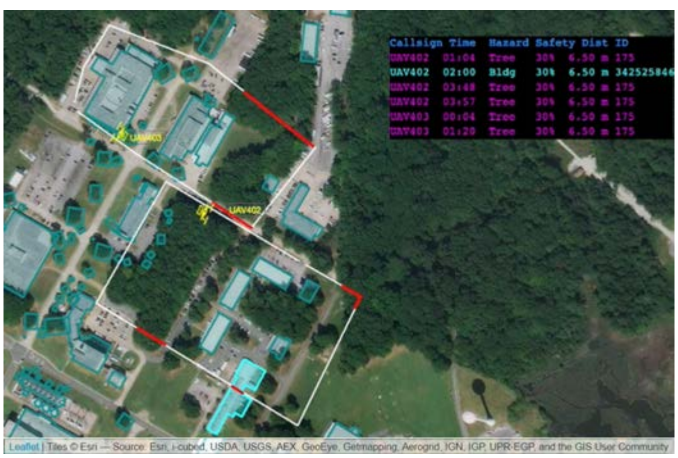

Fig.10b Image of 2022 version SDSP-CD User Interface Map View with proximity alerts selected for the UAS with the call sign "UAV402" and "UAV403" using Select Multiple Alert feature (NASA image).

Note that the reviews done in 2021 and 2022 were remote. These reviews highlighted the importance of adaptability in research methods, particularly in the face of unexpected challenges like COVID-19 restrictions. Being able to pivot to remote interviews and GUI demonstrations allowed the research to continue despite limitations.

2023 SDSP-CD UI: A new service, *Radio Frequency Interference (RFI)* fig 4, assessing the risk of signal disruption, was integrated into the dashboard for this version of SDSP-CD. Previous work evaluating user's feedback on the GUI elements of the SDSP-CD was used for improvements to this interface [2].

Building on prior research, an in-person usability study at NASA Ames Research Center compared two pre-flight planning interfaces: SDSP-CD and HATIS (human automation team interface system) for sUAS missions to evaluate participant performance focusing on user interaction, task efficiency and cognitive load.

The SDSP-CD provided a comprehensive vehicle view, while HATIS required sequential selection, increasing navigation and cognitive demands. Participants found in HATIS the need for sequential selection and excessive clicking frustrating, despite valuing the option to alter flight paths. However, both interfaces were acknowledged for their potential to alleviate operator workload.

2024 SDSP-CD UI: Another new service, *Vertiport Congestion*, was integrated into the latest SDSP-CD, as shown in Fig. 1 and described in Section III. Previous work evaluating user's feedback on the GUI elements of the SDSP-CD was used to improve this interface [2]. This latest UI was evaluated by sixteen UAS pilot participants [7]. Their feedback is expected to be integrated into the next UI development for improvement. Some of the insights gathered from this latest evaluation are discussed in the following section.

V. Integration of Risk Assessment in the Workflow of future UAS Fleet Managers

During the SDSP-CD evaluations, participants stated that a use of hazard risk assessment dashboard was an effective way to identify and mitigate potential hazards analytically during the preflight planning phase. They also indicated that existing preflight planning tools in both crewed and uncrewed aviation have yet to integrate risk assessment capabilities that exist in SDSP-CD into the preflight planning tools. Rather, available tools provide disparate and piecemeal information that the fleet manager or pilot must mentally integrate and assess. Further, the participants expressed that for the SDSP-CD or other analogous preflight risk assessment tool to be effective, an integration framework is needed to merge the risk assessment with flight and mission planning tasks. Thus, there are potentially three distinct risk assessment tasks during mission, preflight, and in-flight phases of operations. The risk assessment tasks could be integrated into the fleet manager's tasks during the mission and preflight planning and into the UAS pilot's tasks during the in-flight operations. Fig. 11 summarizes the integrated workflow of the risk assessment in these three phases.

The following subsections provide additional details about how a risk assessment tool could support the three phases. We then describe several differences between UI requirements for preflight vs. in-flight tools, and finally, provide initial thoughts on how integrated risk assessment can be merged with existing fleet manager and pilot mission and flight planning tools.

A. *Mission Planning Risk Assessment*

Integration of risk assessment capabilities in mission planning would aid the initial flight planning development efforts. Typically, when UAS fleets are deployed for a particular mission (e.g. site surveillance), the mission planner surveys the targeted sites for environmental factors. The mission planning is typically done well in advance of the actual flight. In this phase,

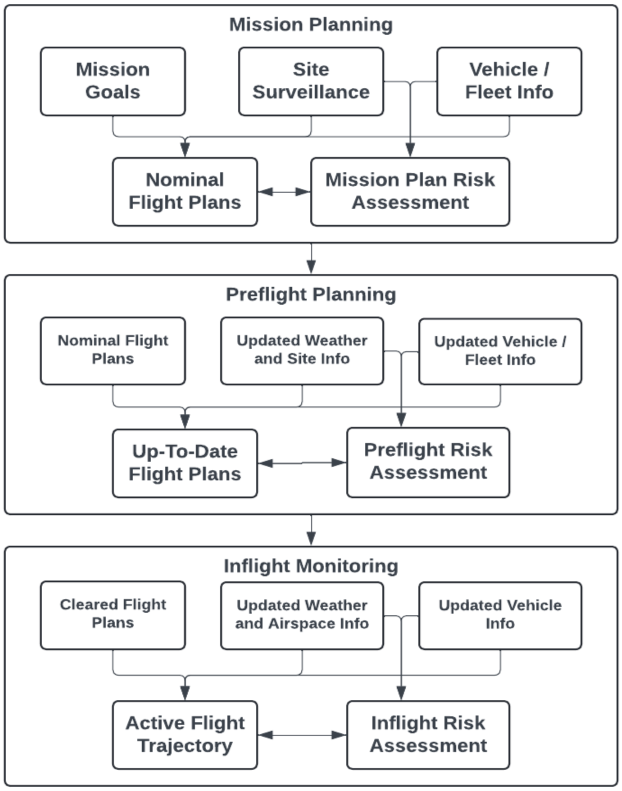

Fig. 11. Integration Risk Assessment for Fleet Manager and UAS Pilot during Mission, Preflight, and In-flight Operations

the mission goals, vehicle characteristics, and environmental factors, such as physical obstacles, terrain, airspace restrictions, and typical weather factors could be considered for developing nominal flight plans. Currently, mission planners gather risk-related information from various sources and mentally integrate this data to derive flight plans. A risk assessment tool such as SDSP-CD could reduce the cognitive load on mission planners by automatically checking potential risks against known constraints and obstacles. They can then design the flight paths to minimize those risks.

B. Preflight Planning Risk Assessment

After formulating the initial mission plan, a fleet manager may review and adjust the flight plans of individual flights on the day of the flight. Dynamic environmental factors like wind forecasts, airspace constraints, and physical obstacle locations may change daily, and therefore they should be continually updated and monitored, as any change in vehicle conditions or schedules could affect safety along flight paths. During the preflight planning phase, the hazard risks should be reassessed to identify any changes to the risks based on up-to-date information. Identified risks empowers the fleet manager to modify flight paths, ground flights, or alert pilots to potential issues for in-flight resolution with additional monitoring.

Mission planning and preflight planning may be done by the same person and the delineation of the tasks between the two phases may be blurred. The main difference between the phases may be the information requirements. Participants' feedback during the SDSP-CD evaluations suggests that it may be challenging to input the wide range of mission specific data required for mission planning into a risk assessment tool, whereas doing so for preflight planning may be more feasible, as preflight planning seems to require a relatively common set of flight information across different missions that can be more easily integrated into a tool.

C. In-Flight Risk Assessment

Once the UAS vehicle is airborne, a third layer of risk assessment may be added. A tool that monitors the live flight track and calculates the in-flight risks against the known obstacles, terrain, weather, and vehicle status may alert the UAS pilots of potential risks that have been detected. The alerts can be reviewed by the UAS pilot to assess if the risks pose real safety threat in their estimation, and if so, they can take mitigation steps to maintain safety.

D. UI Requirement Differences between Preflight vs. In-Flight Risk Assessment Tools

During the development of SDSP-CD tool for preflight risk assessment, questions have been raised whether preflight risk assessment tool for a fleet manager could be the same as the in-flight risk assessment tool for a UAS pilot. There are many similarities in how the services function in both phases of flight such that a common tool user interface may serve both purposes.

However, the risks posed in each phase of flight, as well as the human operators' role in their mitigation actions are fundamentally different between preflight fleet managers vs. in-flight UAS pilots. During preflight planning, a fleet manager has significantly lower time pressure to determine the mitigation actions for identified potential risks since the flight has not taken off yet and the risks have yet to materialize. During preflight, there are greater number of available mitigation options, such as grounding the flights or canceling them altogether if the flight condition cannot be resolved. However, the fleet manager has to also keep in mind that the identified potential risks may not occur at all due to large uncertainty of the actual flight paths and conditions once the flight departs. Therefore, they may need to weigh the cost vs. benefit of taking the risk mitigation actions proactively that may not actually occur if left alone.

Given the greater and nuanced decision space and the reduced time pressure for preflight planning, the fleet manager needs a tool that provides more vehicle, mission, and environmental information than a tool intended for a UAS pilot. The participants in our studies, performing the fleet manager's role, requested detailed information on the weather and winds, terrain, vehicle status, vertiport status, and other information on the airspace constraints, mission goals, etc. to support the fleet manager's role.

In contrast, once airborne, the flight and environmental conditions that may be encountered become more certain, and the likelihood that detected risks will transpire becomes much higher. Given the likelihood of the safety risks and the time pressure to mitigate the risks in time, UAS pilots may need more focused and targeted information to manage the situation. Their mitigation actions are also limited, such as heading or altitude changes to avoid obstacles, or conduct a precautionary or emergency landing if the vehicle cannot continue the flight.

Therefore the information should be organized for them to make such decisions quickly.

The differences in the roles of fleet managers vs. UAS pilots, as well as the different risk profiles between preflight vs. in-flight, suggest that both types of tool interfaces should be developed in parallel to identify the information and interaction requirements for the risk assessment tools in both phases of flight.

E. Initial Thoughts on Integrating Risk Assessment with Flight Planning

Feedback from the participants who evaluated the SDSP-CD tool to perform the fleet manager's role have suggested how the tool could be integrated into the mission and preflight planning workflow. Risk assessment is an integral part of mission / flight planning, and therefore the risk assessment tool needs to be integrated into a flight planning tool.

Participants from crewed aviation have suggested the ForeFlight [11] tool that allows extensive mission and preflight planning capabilities as a type of tool that the SDSP-CD could integrate to assess the potential risks during the flight planning and re-planning tasks. Participants with extensive UAS experience have mentioned other similar mission / flight planning tools that could benefit from risk assessment capabilities such as those in the SDSP-CD. There was wide agreement that the ability to create, assess, and iteratively refine flight plans until potential risks are adequately mitigated would be useful in ensuring safer aviation operations. To efficiently accomplish this, environmental and vehicle databases, a flight planning tool, and a risk tool should be integrated.

For the actual interface and the UI interactions, participants liked the key features that the SDSP-CD provided. They found that a simple risk dashboard that shows the alerts is highly intuitive and a useful way to display the risk information. They also liked the visualizing additional risk related information on the map display, but they also wanted more mission and flight information than could easily fit into the map display. Some suggested adding text-based windows to provide details. A more comprehensive analysis of the usability findings has been documented [7].

VI. Summary and Next Steps

The System-Wide Safety (SWS) project at NASA has been developing a suite of data-driven tools to predict various hazards including battery energy availability, proximity to static obstacles, population risk, global positioning system (GPS) signal strength, radio frequency spectrum interference (RFI) risk, and vertiport congestion. These services have been adapted to assess hazard risks prior to departure so that a fleet manager can assess the potential risks for a suite of UAS vehicles along their planned flight paths. These services have been integrated into a prototype tool called the SDSP-CD, which consists of a dashboard that provides a consistent and comprehensive user interface for multiple hazards and a map display that shows the details of the hazards along the flight paths. The overall feedback from a series of usability studies suggests that there are substantial benefits to using the SDSP-CD to assess potential hazards for multiple vehicles on a single dashboard, to provide situational awareness to any potential risks, and to enable the fleet manager to mitigate the risks prior to flight.

Based on the feedback, the logical next steps would be to integrate the SDSP-CD into flight and mission planning tools. A full integration would allow the SDSP-CD to access the mission, flight, and vehicle information that the tool needs for risk assessment, and the fleet manager would be able to modify the flight paths away from the identified hazards before rerunning the risk models to see if the new paths resolved the issues. Such an integrated tool has the potential to ensure greater safety in future UAS operations with high traffic complexity by relying less on the human operators to assess hazards and more on automation to analytically calculate these risks.

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