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# Modeling Contingency Management in Unmanned Aircraft Systems Traffic Management

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Contingency management in future Unmanned Aerial Vehicles (UAVs) Traffic Management (UTM) requires a variety of distributed and interdependent functions and services—such as flight tracking and conformance monitoring, weather detection and prediction, and ground-based detection and avoidance—that need to be coordinated across multiple roles and organizations. This paper describes a combination of cognitive walkthroughs and computational modeling of work to analyze edge case scenarios and assess resiliency in future UTM operations. We discuss how the walkthrough and modeling inform each other and present early results. The ultimate goal of this work is to identify requirements for robust and resilient system responses in future UTM contingency management.

Unmanned Aircraft System Traffic Management (UTM) is an envisioned concept of operation for lower-altitude airspaces with a mix of unmanned and manned capabilities (National Aeronautics and Space Administration (NASA), 2019). UTM operations rely on effective information sharing and coordination among a number of interdependent roles and organizations, including and facilitated by automated services. To assure efficiency and safety of the operations, the system needs to be robust and resilient against anticipated and unanticipated contingencies.

This paper discusses early work on exploring robustness and resilience in contingency management (CM) in UTM operations. We conducted several cognitive walkthroughs and developed a computational model of CM operations for a variety of edge case scenarios. The approach demonstrates how cognitive walkthroughs and computational work modeling can inform each other and provide early results from a computational experiment testing two different types of CM automation.

## Background

Figure 1 shows a notional architecture for the UTM system (see NASA, 2019 for a detailed description of the architecture). Actors in the system include Remote Pilots in Command (RPIC), UAS Service Suppliers (USS) and/or Supplemental Data Service Providers (SDSS). At the heart of the system is the UTM Operations Center, tasked with supervising the UTM system and managing the airspace. Information sharing is handled through an Unmanned Traffic Information Management System. The UTM system also interfaces with Air Traffic Control (ATC) in the area via the Flight Information Management System (FIMS).

Robustness and resilience describe a system's ability to adapt and maintain performance under anticipated and unanticipated disruptions, respectively. Resilient CM requires fast-paced responses with interaction and coordination across various roles, see the example procedural information flows in Figure 1. Earlier research on coordination and adaptation for resilient behavior used edge case scenarios and cognitive walkthroughs with subject-matter experts (SMEs) to assess the system's response at the boundary of performance envelopes (Bisantz & Roth, 2007; Woods & Balkin, 2018).

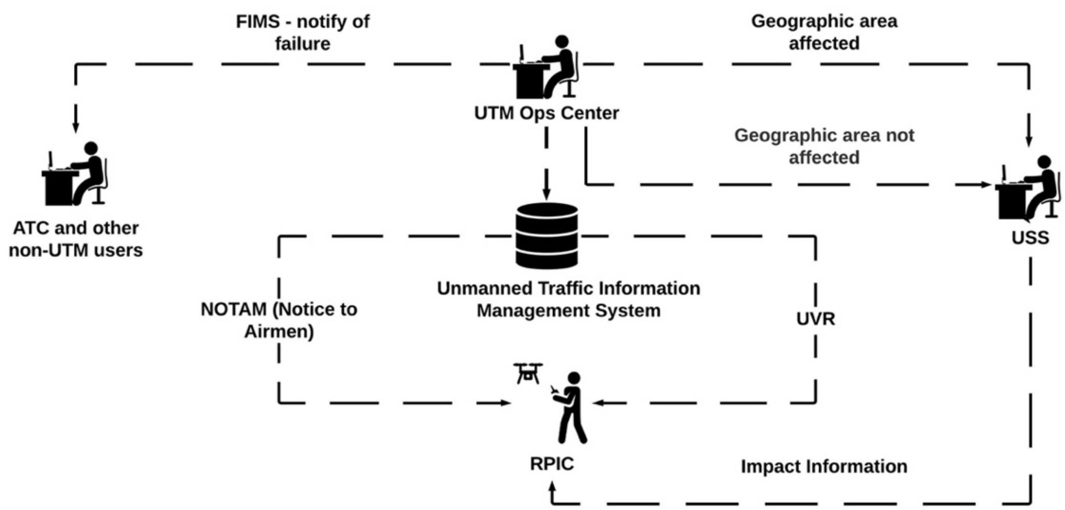


*Figure 1.* Information Flow Diagram for Component Failure Contingency

Modeling of cognitive work can support assessment of robustness and resilience. Work in complex work domains like UTM is driven by constraints and dynamics in the work environment that can be identified and codified (Vicente, 1999). Once codified, models can be simulated to evaluate the dynamics of such work (Pritchett, Bhattacharyya, & IJtsma, 2016; Pritchett, Feigh, Kim, & Kannan, 2014). We argue that for assessing resilience in future UTM operations, knowledge-elicitation and modeling can be part of a formative and iterative cycle in which exploration of system characteristics and responses support identification of design requirements, similar to Vicente (1999) and Woods & Roth (1994). In this paper, we combine cognitive walkthroughs and computational modeling and simulation of edge case scenarios to perform model-based exploration of a UTM system's robustness and resilience.

## Edge Case Scenarios & Cognitive Walkthroughs

We conducted cognitive walkthroughs with SMEs to explore how actors in future UTM operations would need to respond and coordinate during CM. A document review was conducted to learn about the envisioned UTM system at hand, including the various types of contingencies that could take place and disrupt the nominal flow of operation. Five classes of contingencies were created that span a range of disruptions to the system's nominal operations, see Table 1.

For each of these classes, we developed narratives with a representative traffic situation and a set of probing questions for the SMEs. The probing questions were targeted at discovering how actors, as part of the bigger UTM system, would adapt and coordinate to respond to disruptions and at testing the validity of the scenarios and envisioned procedures. All interviewees were subject matter experts in the field of aviation who have experience in UAV operations, air traffic management, and/or resilience engineering.

Table 1.
*Contingency classes and descriptions*

| Contingency | Description |
|---|---|
| **Component failure** | Failure of a component or system critical to the operations (e.g., radar, ping station) |
| **Loss of link** | UTM is not receiving telemetry data and/or cannot communicate with a UAV |
| **Weather event** | Weather front moves through area, and/or micro-weather conditions deteriorate |
| **External emergency** | An external event (e.g., fire, police activity) requires unanticipated airspace changes |
| **Unidentified actor** | UAV is not conforming to the expected flight plan or uncontrollable moving objects |

As an example of an edge case scenario, the component failure narrative involved two RPICs, pilots of a commercial flight, one UTM Supervisor, and one USS. The traffic situation consisted of three vehicles flying west of Columbus, Ohio: a high priority UAV flight transporting a liver transplant, a law enforcement UAV surveying a crime scene, and a commercial airline flight landing at the John Glenn Columbus International Airport (CMH). When the traffic is nearing closest-points-of-approach, a radar fails unexpectedly, resulting in a loss of sensing capability for the UTM system and a need for to reconfigure the airspace.

The walkthroughs revealed various complicating factors to CM, such as constraints, goal conflicts, time pressures, and the need to coordination between actors, particularly between the RPICs and UTM supervisor. For example, interviewees noted trade-offs between closing the airspace for all current traffic (requiring rerouting) or allowing existing flights to continue, with the ability to monitor the separation as a determining factor. The findings from the document review and walkthroughs were aggregated into an abstraction hierarchy for the overall UTM system (Vicente, 1999), see Figure 2.

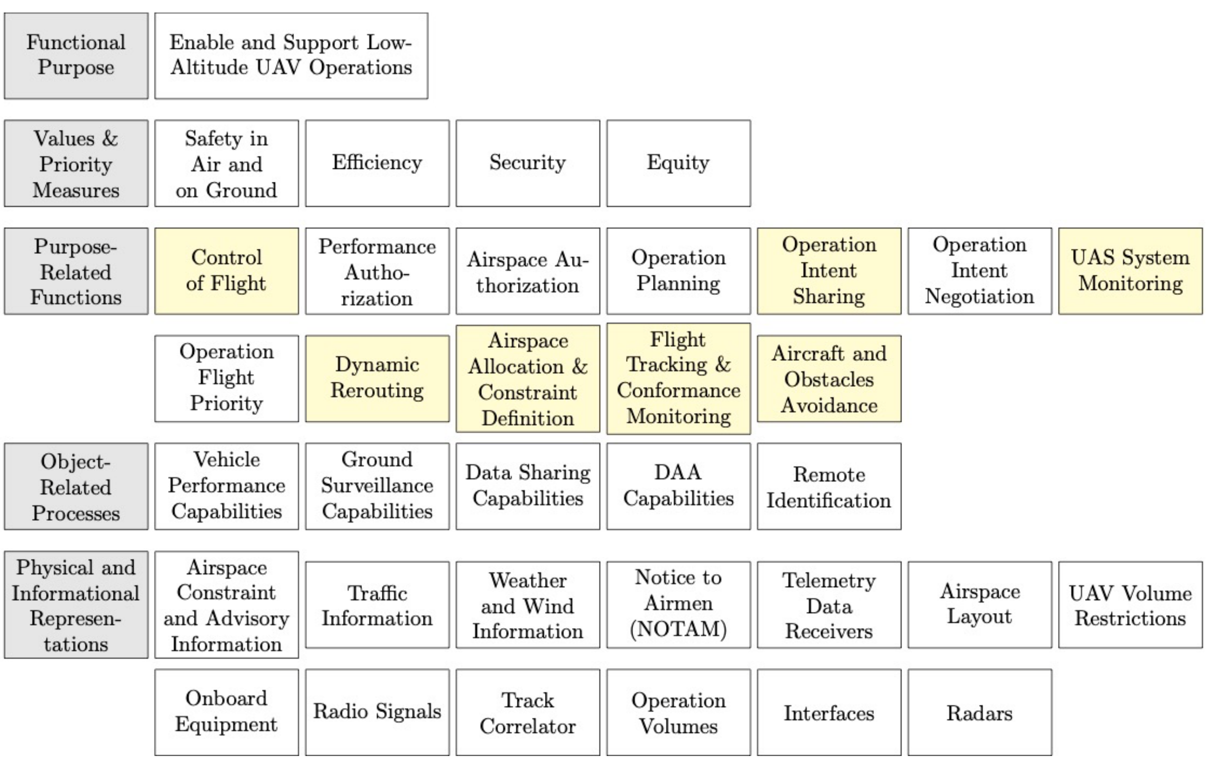


*Figure 2*. Abstraction hierarchy for a UTM system.

## Work Models that Compute

In parallel with the walkthroughs, we developed a computational model of the work involved in UTM CM. Work Models that Compute (WMC) is a computational modeling and simulation framework for analyzing situated work (Pritchett et al., 2014), used before to analyze work allocation in air traffic management and space operations. Through models of resources, actions, and agents, WMC can make quantitative predictions of system performance given different system configurations.

The first two columns of Table 2 show the actions that were modeled in WMC for what were deemed the purpose-related functions most critical to CM, see the highlighting in Figure 2. Furthermore, the flight dynamics of the aircraft are deemed an important driver of the UTM system's dynamics, determining much of the actors' timing of activity to keep pace with disturbances. Thus, the computational work model includes a model of the flight dynamics for a generic UAV, with parameters that can be changed to simulate a variety of vehicle classes (e.g., a small quadrotor UAV or a large package delivery drone).

Results from the cognitive walkthroughs directly informed the modeling, with the system's response captured primarily in the first three and last rows of Table 2. The work model also includes descriptions of the information resources (such as geographic location, altitude, and radar status) that are shared amongst the actors. As an example of how the walkthrough informed the modeling, several SMEs noted their decisions about the impact of the radar failure depended on the vertical separation between aircraft. Thus, the "assess impact" action is modeled to compare the difference in altitudes of the two vehicles, then assigning High, Medium, or Low to the Impact resource that is shared with the other actors in the system.

Table 2.
*Work model actions with two allocations of authority (A) and responsibility (R) (format: A/R)*

| Purpose-Related Function | Work Model Action(s) | Allocation 1 | Allocation 2 |
|---|---|---|---|
| **Airspace Allocation and Constraint Definition** | Generate UVR | Supervisor/Supervisor | Automation/Supervisor |
| **UAS System monitoring** | Assess impact, monitor system integrity | Supervisor/Supervisor | Automation/Supervisor |
| **Operation Intent Sharing** | Communicate via NOTAM | Supervisor/Supervisor | Automation/Supervisor |
| **Flight Tracking and Conformance Monitoring** | Track flight, manage waypoint progress | RPIC/RPIC | RPIC/RPIC |
| **Control of Flight** | Change altitude, change speed, change heading, takeoff, land, direct to waypoint, distance to next waypoint, flight dynamics | UAV/RPIC | UAV/RPIC |
| **Aircraft and Obstacle Avoidance** | Avoid conflict, detect conflict | RPIC/RPIC | RPIC/RPIC |
| **Dynamic Rerouting** | Reroute flight | RPIC/Supervisor | Automation/Supervisor |

A WMC run simulates the detailed interaction between actions and the work environment (as captured in resources), including how activity of actors in the system is interconnected through dynamics and information. WMC provides quantitative data on the dynamics of activity, such how often and when actions are performed, and how often and what information is shared amongst actors. In addition, WMC can be used to evaluate effect of system design choices, such as the allocation of authority and responsibility between human operators and various autonomous capabilities. Here, authority denotes the agent that will be executing an action, and responsibility denotes who is held accountable for the outcome of an action.

To demonstrate, we conducted simulation runs with two types of automated capabilities, see the last two columns of Table 2: Allocation 1 with a UTM supervisor performing the majority of the work manually, and Allocation 2 in which a majority of the CM is automated, with the UTM supervisor monitoring the automated response. In the latter case, the UTM supervisor is still responsible for the outcome. In these instances of mismatching authority and responsibility, WMC automatically engenders a monitoring action for the authorized agent (i.e., UTM supervisor), executed in parallel with the automation's actions (Pritchett et al., 2016).

Figure 3 and 4 show early results from simulation runs. Figure 3 illustrates when each actor is performing an action. Because actions related to control of flight (executed by the UAV) are updated relatively frequently, and the CM actions are of primary concern to this analysis, these actions are omitted from the figure. The figure shows when human actors need to monitor automation agents due to authority-responsibility mismatches (shown as 'teamwork'), clearly indicating that more autonomous capabilities lead to higher monitoring loads. Time pressure was an important concern during the walkthroughs, and data like this can provide estimates for how quickly UTM supervisors and RPICs need to coordinate a response to a radar failure.

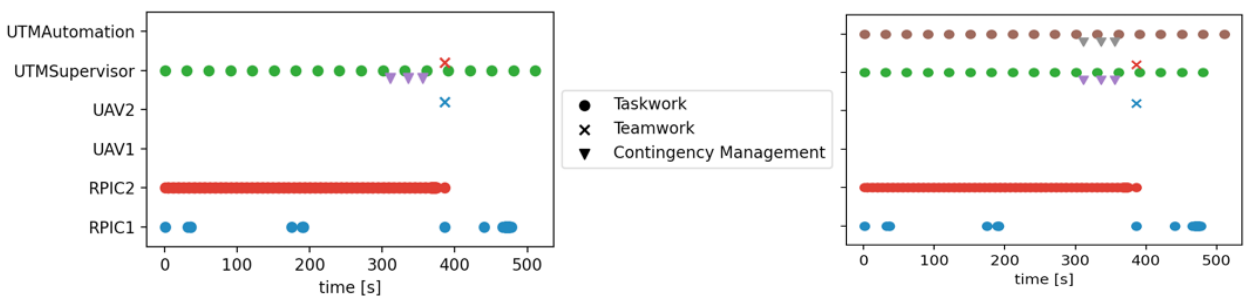


*Figure 3.* Plots for every instance an agent performs an action for allocation 1 (left) and allocation 2 (right).

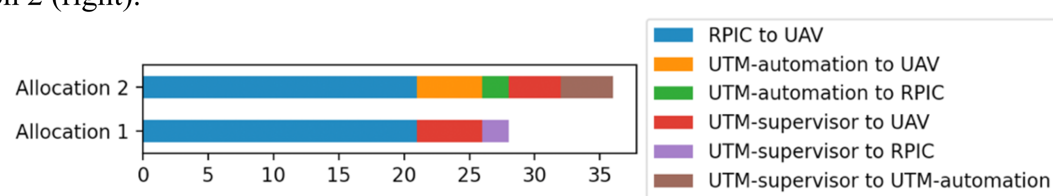


*Figure 4.* Information exchange requirements for various work allocations

Figure 4 shows data on the total number of information exchange requirements for each simulation run, categorized by the agents that are involved in the exchange. Every time an action is carried out, the simulation logs what information is needed and who last updated that information. Allocation 2 shows more information exchange requirements, particularly due to increased requirements for human-automation information exchange. These data provide insight into who needs to communicate with whom and how often, addressing a theme from the walkthroughs related to communication across the various actors in the system.

## Conclusion and Future Work

We used a combination of cognitive walkthroughs and computational modeling and simulation of edge case scenarios to analyze CM in future UTM operations. The scenario development, cognitive walkthrough, and computational modeling occurred in an iterative process and highlighted how insights from interviewing SMEs can be used to inform computational modeling. The walkthroughs provide data and insights for the modeling effort, and the computational models of work afford a thorough analysis of the system's dynamic response. Future work includes more detailed modeling of other classes of contingencies and performing larger-scale analysis using the computational models. Ultimately, with extended modeling capabilities and testing of various system architectural characteristics, the aim is to identify specific requirements for robustness and resilience in the UTM system.

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