Cognitive Task Analysis of Contingency Management in Future Unmanned Aircraft Systems Traffic Management

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Unmanned Aircraft Systems (UAS) Traffic Management (UTM) provides traffic services to low-altitude UASs. Contingency management in UTM involves multiple interdependent roles and organizations that need to coordinate with one another under time pressure and uncertainty. This paper describes the results of a Cognitive Task Analysis (CTA) to explore challenges and identify needs for supporting coordination across various roles during contingency management in future UTM operations. Edge case scenarios were developed to support realistic operations and potential challenges in the system. Subject-matter experts in the aviation industry and research sectors were interviewed using these edge case scenarios. The CTA revealed coordination strategies, work domain characteristics and constraints, information needs, and complicating factors for the cognitive work involved in UTM contingency management. Insights from the study point to future research and development needs for supporting explicit, flexible, and efficient modes of communication between various roles, sufficient control authority support human expertise and custom responses, and mechanisms for increasing predictability and implicit coordination.

I. Introduction

The Federal Aviation Administration (FAA) NextGen Offices Concept of Operations (ConOps) for Unmanned Aircraft Systems (UAS) Traffic Management (UTM) details the need for a UTM ecosystem [1]. UTM establishes the basis for the integration of low-altitude UAS operations. The current Air Traffic Management (ATM) systems do not have the means to efficiently deliver services to low-altitude UAS, which UTM aims to address. UTM is a separate framework from ATM and consists of multiple interacting actors to provide a comprehensive set of traffic services. The National Aeronautics and Space Administration (NASA) and the FAA developed an operational concept and associated architecture with a set of services and actors that cooperatively manage these low-altitude UAS operations [1].

Contingency management is a critical function for the safety of the UTM system. Contingency management helps support operations through planning, coordination strategies involved in procedures and protocols, and pre-programmed systems and/or vehicle responses to anomalies in flight [1]. This 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. As a basis for developing further system design (including automation tools, procedures, and training) and supporting effective coordination and collaboration during contingencies, there is a need to examine requirements and challenges for the cognitive work involved in UTM contingency management.

This paper presents the results of a study to identify and explore challenges and opportunities for robust and resilient contingency management in this envisioned UTM system. As part of this study, a Cognitive Task Analysis was performed to analyze the potential complexity that operators and other actors in the UTM system would need to manage, as a basis for designing and improving supporting tools and/or procedures.

II. Background

Future UTM systems need to be equipped to handle anomalous events that challenge nominal operations. Anomalies are events that are potentially hazardous to the operation and usually create challenges for operators and actors due to the uncertainty that arises as a result of an anomaly [1]. The NASA/FAA ConOps, for example, describe non-conforming UAS as an anomaly.

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The ConOps describe contingency management to support the safety, security, and equity of the airspace [1]. When an anomaly arises, the operator is responsible for notifying the operations that were affected in the airspace. The UAS Service Supplier (USS) can help support the operator through maintaining and establishing communications. The envisioned procedure would include contingency procedures and protocols that are shared with the USS during operation planning processes. The USS would update the network of potentially hazardous conditions. Once the contingency is over, the USS is to provide a notice of recovery and notify the FAA if necessary and provide any data that may be needed to restore nominal operations [1]. Although this notionally describes the patterns of communication and coordination between the operator, USSs, and other stakeholders, more specific procedures, including supporting tools and training, still need to be developed and validated.

Further development of the UTM contingency management functions should build on literature on safety in related complex sociotechnical systems. This research distinguishes between robustness and resilience as desired system properties [2]. Robustness refers to the ability for a system to absorb disruptions that were anticipated, either during the design of the system (e.g., procedures, training) or during the operations but well in advance so that the system's response is part of its envisioned performance envelope. For a robust system, when disturbances arise, they are well-modeled, and the system can respond effectively to absorb the disruption. Resilience refers to the ability to handle and adapt to unanticipated disruptions, i.e., events that were not accounted for and, as such, are not part of the nominal performance envelope of the system. Resilience requires adaptive capacity or real-time adaption to extend the capabilities of the system when unforeseen circumstances arise [2]. The UTM system needs to be both robust and resilient to handle anomalies.

Naturalistic and field research in related safety-critical domains highlight the human contribution to enabling resilient performance (see for example NASA's recent study on the human contribution to safety in commercial aviation [3]). UTM contingency management will involve several human roles and actors that need to synchronize their responses, and effective coordination is a necessity. Coordination helps support and share resources and interactions among one another [4]. Coordination further prevents breakdowns by managing dependencies between activities to accomplish goals [5].

Furthermore, communication plays a significant role in coordination. Communication supports team performance through the ability to achieve coordinated actions [6]. Coordinated actions in the UTM system might vary from sharing resources to supporting stakeholders during an anomaly. Research on team cognition in mission critical environments revealed several patterns of effective performance: (1) coordination drives the need for communication, (2) mutual awareness allows for more efficient communication strategies, (3) lower workload is associated with more efficient and lower communication, (4) abilities to preplan missions results in more efficient communication, and (5) more efficient communication among team members results in overall better team performance [6].

Likewise, studies on anomaly response in space shuttle mission control highlight possible challenges to human cognition. Anomaly response is typically associated with high time pressures, multiple interacting goals, high consequences of failure, and multiple tasks that are intertwined with one another [7]. Woods [8] argues that to support operators' responses when an anomaly occurs, designers need to have a thorough understanding of the system's processes and the cognitive work involved in managing these processes. Woods proposes (1) making diverse observations of the work, (2) abstracting patterns across the system, (3) generating models of what makes responding to anomalies difficult, and (4) understanding and making hypotheses on what would be useful based on the affordances related to the demands. Furthermore, in order to respond to anomalies there need to be interventions, contingency evaluation, and activities that rely on re-planning [8].

To support the further development of contingency management functions for UTM, this study performed a Cognitive Task Analysis (CTA) [9] to assess the potential for resilient behaviors by identifying patterns that support anticipation and coordination across multiple roles within the UTM system (similar to steps 1-3 of Woods [8]). CTA is a widely used method for characterizing and supporting cognitive work and can provide two complementary perspectives on the work involved in UTM. One perspective of CTA focuses on the characteristics of the work domain and any cognitive demands that are inherent to the system. The other perspective focuses on how participants may respond to demands that arise in the system. Understanding cognitive work through these two perspectives supports identification and anticipation of performance problems, such as areas of high workload, contributions to error, etc. This can further be used to improve both individual and team performance through new training forms, user interfaces, or aids that support decision-making strategies [9]. CTA further allows the opportunity to understand and support coordination strategies.

III. Methods - Cognitive Task Analysis

The study consists of an iterative approach of Cognitive Task Analysis (CTA) to learn about the challenges associated with this future domain and the work [9]. CTA aims to uncover characteristics of the domain and the envisioned system that would support or challenge robust and/or resilient responses to various classes of contingencies. As a first step to CTA, a document review was performed to understand the envisioned concepts of operation, including the gaps and design questions that are still to be addressed. This resulted in initial diagramming of the architecture and early identification of requirements for information sharing and coordination across the various roles in the system.

Second, to better understand the work involved in future UTM contingency management, knowledge elicitation sessions were conducted with participants who are experts in this field of study. Methods for knowledge elicitation roughly fall into three categories: think-aloud protocols, interviews and/or observations [9]. Due to the nature of UTM being an envisioned ecosystem, observations and think-aloud protocols would be challenging without having high-fidelity simulations. Thus, interviews were conducted with participants from various backgrounds, including aviation safety researchers, air traffic managers, commercial pilots, and research engineers.

The scenarios and questions were all designed to better understand the thought processes behind each action, potential decision-making strategies which the participant may or may not use, and coordination and communication strategies between multiple roles and actors. The interviews included various edge case scenarios, inspired by earlier work on resiliency trade-space studies [10]. The interviews followed a semi-structured approach, i.e., a combination of specific interview questions in a specific order and more free-flowing conversation [9]. The specific questions, designed around the edge case scenarios, ensured that the participants were guided through the scenario and asked the same questions as other participants. In addition, participants were asked for more general input, allowing the participants to take the lead of the conversation and bring up any issues or topics that they deemed relevant to the scenario.

A. Scenarios and Experiment Design

Five edge case scenarios were developed, representing stories of how events and complicating factors challenge the envisioned operations. The development of the edge case scenarios was based on the NASA/FAA ConOps operational scenarios, and each focused on different elements of the UTM operations. Furthermore, the edge case scenarios were designed to support the ongoing work at The Ohio Department of Transportation's 33 Smart Mobility Corridor. Each edge case was designed to be (1) realistic in order for participants to immerse themselves in what could potentially happen in the envisioned UTM operation, (2) challenge the system's operations and the operator, to evaluate where there is a potential for goal conflicts and high cognitive demands on the UTM supervisor, and (3) comprehensively assess the system so that the participants can access realistic times and resources (i.e., navigational services, weather services, etc.).

The edge cases included a component failure, an external emergency, a loss of link event, a weather event, and a rogue UAS, each requiring a distributed and coordinated response from multiple actors in the system. Each edge case scenario can be described as:

- The *component failure* was described as a failure of a critical sensor in the system. The developed edge case scenario involved a radar failure at The Ohio State University Airport.
- The *external emergency* was described as a change in priorities within the airspace resulting in an unanticipated UAS volume restriction. This involved a fire starting in the woods near the airspace, as well as ground support being sent in to help.
- The *loss of link* event was described as an operator no longer being able to receive telemetry data and/or is unable to send commands to the UAS as well as maintain control of the UAS. The developed edge case scenario was described as the remote pilot in command (RPIC) alerting the UTM supervisor of potential loss of control over the UAS.
- The *weather event* is described as a weather front moving through the airspace and/or weather conditions deteriorating. In this edge case scenario, ceiling lowered to less than 1,000 feet unexpectedly.
- A *rogue UAS* scenario was described as a UAS that is not conforming to the expected flight plan. The edge case scenario was described as a UAS being external of the UTM ecosystem but has left its designated operational volume. This results in a potential conflict with vehicles in the UTM system.

The probing questions as part of the CTA were aimed at eliciting the knowledge and strategies that expert workers would bring to bear in each of these situations and identify factors that could complicate the system's response. A total of seven interviews were conducted. Each interview followed the same general procedure. The interview began with a brief introduction outlining the goals of the interview. The introduction highlighted the understanding of how an experienced operator would react to contingencies that may arise in the system and evaluate potential contingency management procedures. This was then followed by a verbal consent from the participants noting that there were no risks in participating and the experiment was completely voluntary. Following the general guidelines for the interview, participants were introduced to the role of the UTM supervisor. Participants were told to portray themselves as the UTM supervisor for the duration of the interview. Furthermore, participants were introduced to information on the different technological and procedural resources available to them, such as weather and airspace information.

The interview then transitioned to the scenarios. The scenarios were presented to participants through a slide deck. The slide deck had visuals of potential traffic situations that evolved overtime. Furthermore, there were several junction points where the participants were probed about their responses.

The following example is pulled from the weather scenario. At one of the junction points in this scenario, the UTM supervisor checks the weather and notices marginal ceiling conditions along the route, with unfavorable conditions forecasted after mission completion. Examples of questions that were asked to participants at this junction point were:

1) What information would you be looking for when monitoring the flights and system?
2) Who do you expect to be communicating with?
3) While monitoring the system, what cues would you be looking for?

After the scenario was completed, participants had the opportunity to reflect and share more general thoughts. Examples of the reflection questions were:

1) Do you have any remarks on the realism of the scenario?
2) Do you have remarks on the appropriateness of the responses?

B. Data Analysis Approach

The large amount of qualitative data from the document review and CTA were analyzed to identify major themes related to coordination strategies. Affinity diagrams were used to organize the data and describe the participants' thought processes related to each scenario. Affinity diagramming is a technique that supports analyzing qualitative data. Similar findings or concepts are grouped together during the affinity diagramming process to help identify any major themes or trends [11].

A coding scheme was then created to map the themes to a model of work and associated challenge factors. The model of work describes macrocognitive functions in high-risk scenarios, with domain-agnostic patterns or characteristics that can complicate the performance of each function. This model describes how these functions are not performed only at the individual level (i.e., the micro-level) but are often distributed across multiple interdependent actors and therefore performed jointly by multiple actors at once (hence, this model describes the work at the macro-level) [12]. Analyzing the qualitative interview data with these patterns helps identify areas where further UTM system design and/or specifications or requirements are needed for supporting contingency management.

The five macrocognitive functions include [4, 13]:

- *Detection* involves noticing an event is taking an unexpected direction and may require explanation and/or conceptualization of the situation.
- *Sensemaking* involves collaborating, collecting, and assembling information to access potential explanations. This can result in the potential to generate or revise a hypothesis.
- *(Re-)planning* involves adaptively responding to changes in objectives that come from other actors. This includes responding to potential obstacles, events, opportunities, or changes to predict future trajectories. New strategies can be created to help achieve one or more goals.
- *Decision-making* involves having one or more options that may constrain the ability to reverse the course of action
- *Coordination* is managing interdependencies across multiple individuals and roles that have goals that are either interacting, overlapping and are common to one another.

An earlier version of the model included execution but for the purpose of this study it was omitted. Execution describes converting a plan into an action, which is already implicitly covered by the other five macrocognitive functions [13].

IV. Results

A. Affinity Diagrams

From the interviews data, similar results and concepts were grouped together through affinity diagramming. An example of the affinity diagram can be seen in Figure 1. The participant's roles/names are blocked out to protect their identity.

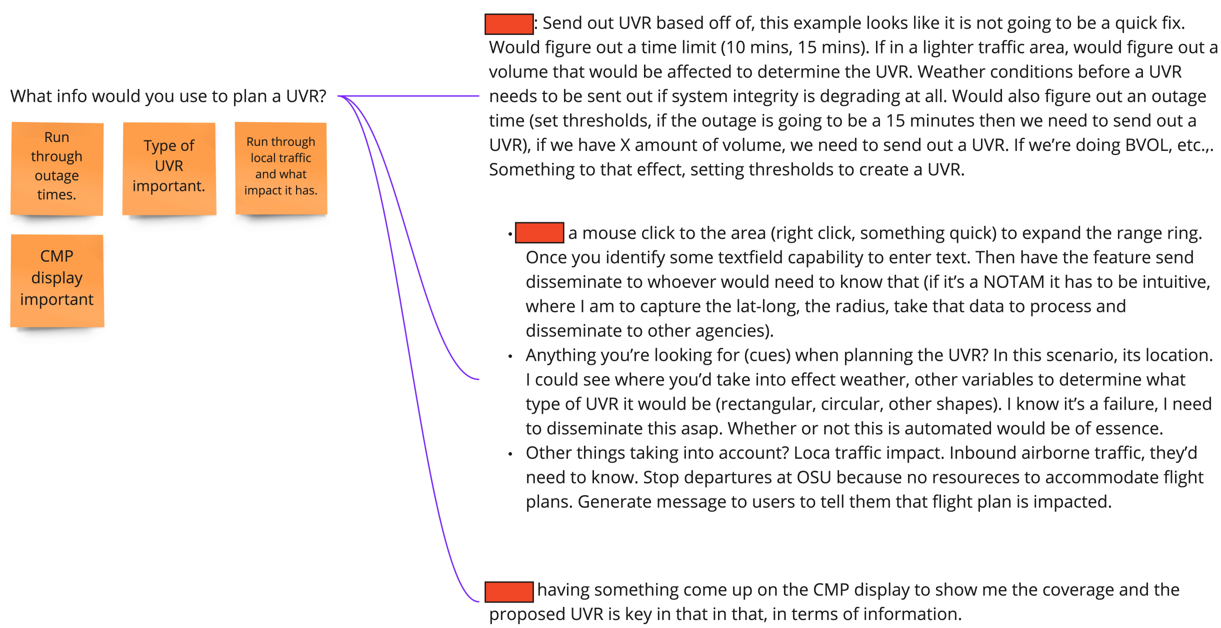

Fig. 1 Affinity diagram to support overall themes and concepts.

This diagram shows part of the qualitative data (transcribed from audio recording) describing multiple participants' thought processes, with several themes/patterns derived from this data. In this example, the participants responded to the component failure scenario. The junction point involves the UTM supervisor observing the failure and determining the best course of action. The participants had the option for the UTM supervisor to generate a UAS Volume Reservation (UVR) in the impacted area. When asked what type of information would be used if a UVR was deployed, the primary response was related to decision-making strategies and supporting coordination tools like display information, outage times, type of UVR deployed, and local traffic information. Generating diagrams like the example in Figure 1 provided an early organization and analysis of the data. The diagramming was subsequently used to develop key patterns that support coordination strategies.

B. Key Patterns of Cognitive Work

The data was then analyzed and mapped to the model of macrocognitive functions to identify potential patterns/themes and factors that would make the work of UTM challenging. It further supported examining opportunities for robust and resilient performance. Table 1 highlights eight overall themes that were supported by the patterns from the affinity diagrams. The themes in the first column are organized around the primary set of macrocognitive functions shown in the last column. The coding scheme used in Table 1 was taken from Patterson, Roth and Woods [13].

Table 1 Key patterns from contingencies

Pattern	Description	Macrocognitive Function(s)
Attention Demands	These are situations where information and requests are coming in from multiple sources requiring a rapid shift in attention. During the evaluation of the interviews, participants experienced an attention shift when there was a component failure and had to prioritize replanning current flights before worrying about replanning future flights. It was also noted during the weather event scenario participants felt they had to work with the challenge of deconflicting airspace between multiple operations and focus their attention on the vehicles' altitudes rather than headings and speed.	Detection
Distributed information across individuals and organizations	This refers to information distributed across participants and/or roles requiring recognition of a coherent pattern. During the interviews participants came across this theme when deploying a UAS Volume Reservation (UVR). They needed to account for multiple roles - such as communication with air traffic control (ATC), prioritizing flights, and potential for other traffic restrictions and/or communication.	Detection Sensemaking Coordination
Missing Information	This refers to when information that is needed for an accurate assessment is missing. Throughout the edge case scenarios of the rogue UAS participants noted potentially unknown or old information on the status of trajectory of UAS and how long the UAS has been rogue.	Sensemaking
Data overload	This involves challenges that need to be detected and addressed but are buried in a large amount of potentially relevant information. Participants experienced data overload during the component failure scenario, when dealing with multiple elements and priority decisions on the UTM supervisors' checklists.	Detection
Multiple simultaneous influences	This relates to multiple independent 'influences' that are simultaneously present. It explains the observed evidence. This was seen during the rogue UAS scenario, as participants noted they would need to maintain separation from the rogue UAS and at the same time maintain separation from other UASs in the airspace.	Sensemaking
Workload	This occurs when requirements for multiple cognitive or physical actions need to be accomplished within a specific time limit. Participants experienced this when there was a component failure specifically having to immediately direct their attention to operations impacted in the vicinity, with significant time pressure.	Decision-making Coordination
Misleading information	This is when information may be inaccurate. This includes when information was not updated in a timely matter, the source was inherently unreliable, or inaccurate information was provided due to degraded communication links and revolves around problems in communication or intentional deception. Participants experienced this during the weather scenario. Participants noted that when monitoring the system, they would be primarily relying on performance capabilities that would support them monitoring the system. Specifically, the overall performance of the UAS versus the weather impact on the UAS. With this type of information potentially not updating in a timely manner, participants noted it could result in inaccurate information.	Sensemaking

Stress or fatigue	This relates to emotional incentives that are created to respond in a manner that differs from desired practices. Participants experienced this through personal load and determining whether a task can be delayed - such as later that day or pushed to the next day. For example, during the weather scenario, specifically when asked about their personal goals in generating the UVR. As well as, personal load factors when determining if certain tasks could be delayed until the next day due to the severity of the weather.	Decision-making

C. Characterization and Mapping of Work Domain Constraints

The data from the interviews can be modeled through an abstraction hierarchy, see Figure 2. An abstraction hierarchy describes the system at different levels of abstraction and, at each level, captures characteristics of the work domain that drive or constrain the system's control of a situation, including each of the macrocognitive functions [14]. These levels include physical form and objects in the systems, at the very lowest level of the hierarchy, to the purpose for which the system was designed for, at the highest level. UTM actors, or decision-makers, need to have knowledge of these elements to make effective decisions.

Likewise, during contingency management, a person typically uses means-end relationships to reason about what is happening and how a contingency might affect the system's performance. A person's reasoning can be described as a 'path' along the abstraction hierarchy. In the UTM ecosystem, the end, or goal, is to support traffic management for low-altitude UAS operations, where the means, or methods, can be the process of maintaining safety in the air and on the ground, through using resources at the lowest levels of the hierarchy, such as traffic information, or radio signals. The direct means-end relationships were omitted from the figure for readability purposes.

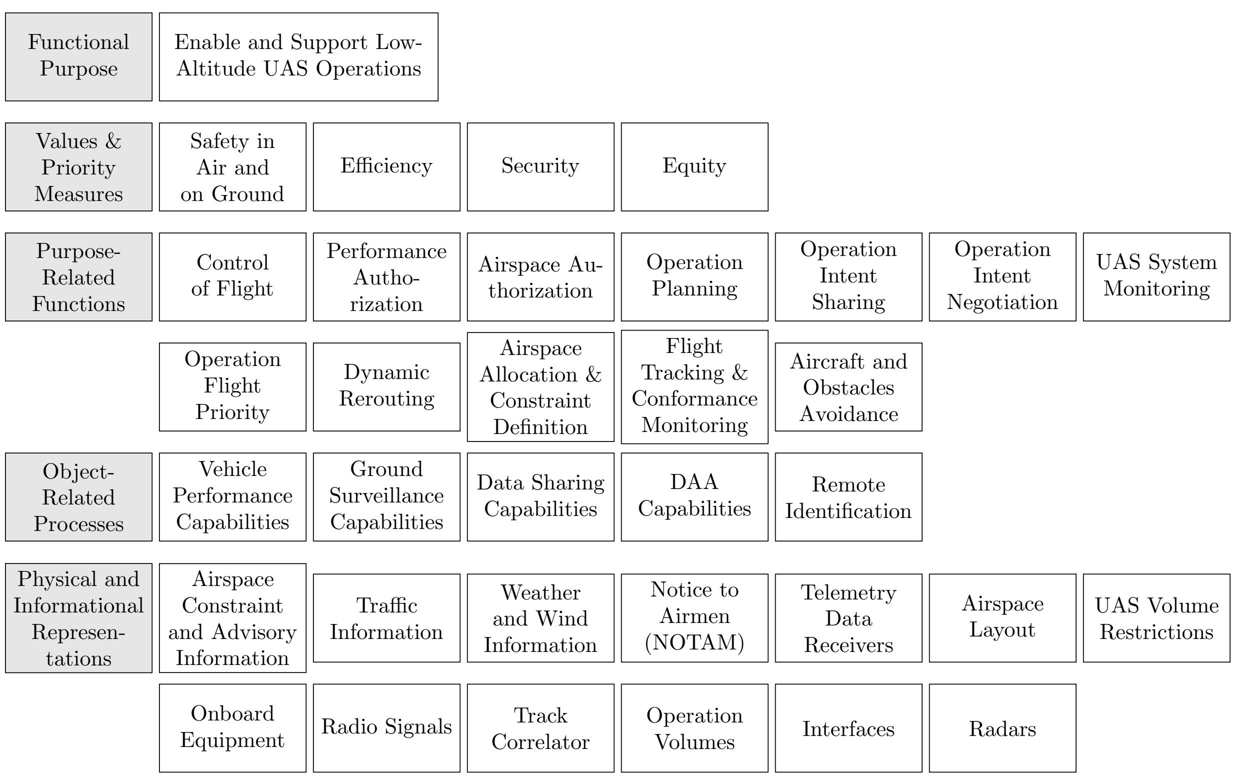

Fig. 2 Abstraction hierarchy of UTM ecosystem.

The abstraction hierarchy allows for further analysis on the means and ends that the work domain requires. Levels of the abstraction hierarchy were derived from the CTA. The *functional purpose* describes the clear objective of supporting low-altitude operations. The *values and priority measures* help achieve the overall goals of UTM. These measures help support the operator's action in maintaining low altitude operations. The following level, *purpose-related function*, decomposes the functions required to be successful from the previous level. The *objective-related processes* support functional capabilities that are necessary to assist the UTM ecosystem. The final level of the abstraction hierarchy, *physical and information-representations* include resources and assistive characteristics that would be useful in the UTM ecosystem.

D. Information Flow Diagram

Information flow diagram were developed to help evaluate interdependencies and costs of coordination from the work domain. The information flow shows the distribution of responsibilities and roles between multiple agents in the system [15]. Figure 3 shows the information flow for the UTM ecosystem when a contingency arises. Multiple agents and actors are involved showing the distribution of work and their coordination flow. The information flow diagram envisions the communication of both the UTM system and external parties that are outside of the system. The external parties are depicted with dotted lines, as they are still in constant coordination with the UTM system.

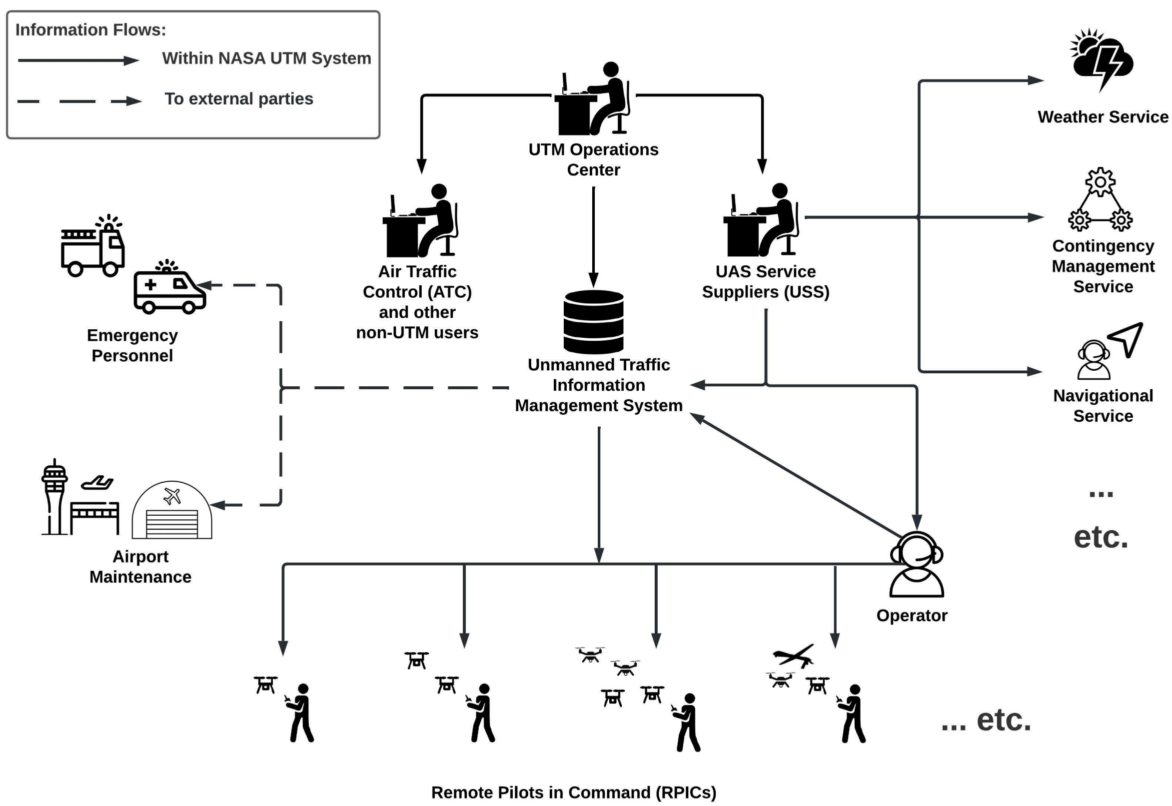

Fig. 3 Information Flow Diagram of the UTM ecosystem.

E. Visualization of Coordination Requirements

The information flow was further derived to highlight the RPIC and UTM supervisor's decision-making strategies through a visualization of coordination requirements. The RPIC and the UTM supervisor were analyzed in more detail during the interviews. These two roles were found in need of the most coordination during a contingency. The interviews helped analyze how much coordination might take place from a temporal perspective and how information needs to be shared. The coordination strategies were then derived so that they could be translated into a decision support system tool.

Figure 4 details the RPIC and UTM supervisor's decision-making and coordination strategies. This was based on a control task analysis. The control task analysis supports the contextual activities that are derived from the abstraction hierarchy and information flow diagram. Furthermore, it can help us understand more specific work functions and refine our understanding of the UTM ecosystem [15].

In order to represent the cognitive demands and operational phases, the previous results were combined into a coordination requirement visualization, depicted in Figure 4.

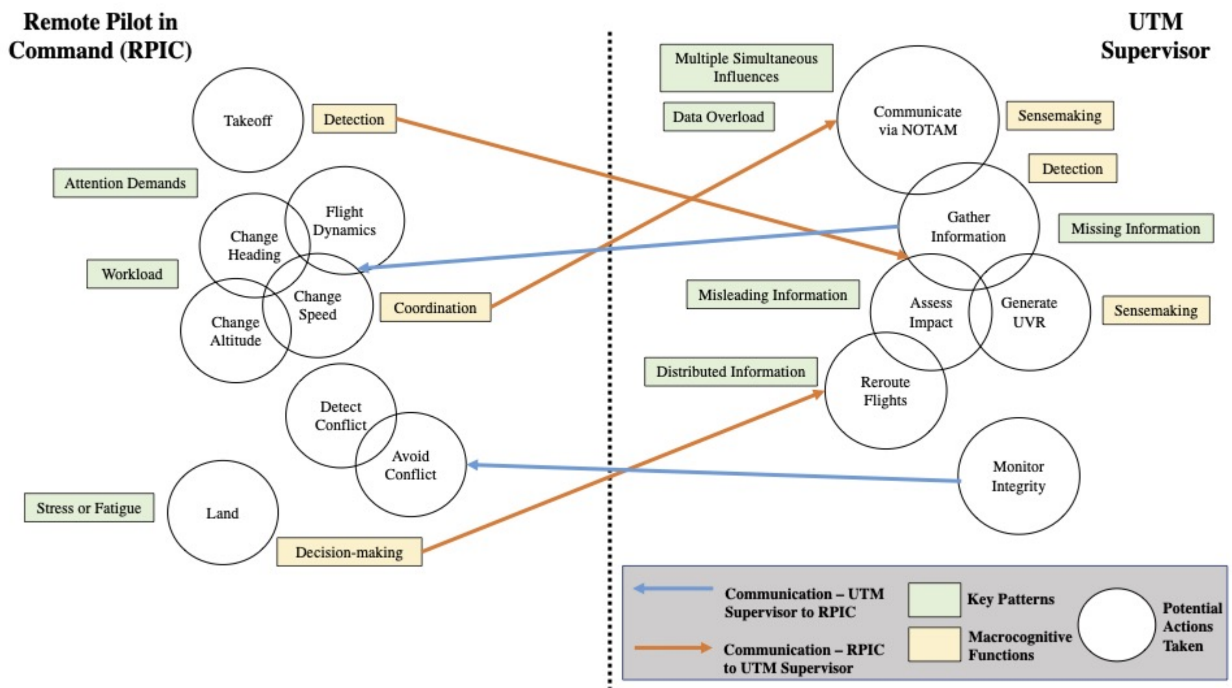

Fig. 4 Visualization to represent decision-making and coordination strategies.

This visualization shows a non-linear representation of coordination and action decision aspects that may be involved when anomalies arise. The circles in Figure 4 represent actions determined from the interviews that may need to be taken when there is an anomaly. Demands on the system and strategies taken are continuously changing and are never in a coherent order. The green rectangles represent the key patterns of cognitive work that were discussed earlier in Table 1. These patterns were then compared to actions that the participants felt they would take. The yellow rectangles represent the macrocognitive functions that were organized around the eight themes. The orange arrows depict the communication roles from the RPIC that would be needed to support the UTM supervisor. The blue arrows show the communication roles from the UTM supervisor that would be needed to support the RPIC. From the suggested actions, the key themes, the macrocognitive functions, and the arrows, a series of coordination requirements can be identified.

V. Discussion

The cognitive task analysis revealed several directions for future research to create a robust and resilient UTM system. This section discusses three main insights derived from the CTA results.

Insight 1: UTM needs support for communication modes that are explicit, flexible, and efficient

The first insight is the need for supporting communication that is explicit, flexible, and efficient. UTM involves information that is distributed across various actors and organizations, including control authorities – such as UTM supervisors, pilots, and automation. A theme that many of the interviews revealed was the need to share information across the system. Often the information is not easily apparent beforehand or only becomes available as a situation evolves over time (and as actors perform work to make sense of the situation). This creates challenges in which decisions need to be made under uncertainty but in which new relevant information needs to be shared efficiently when it becomes available.

Furthermore, different actors have access to different kinds of information, and each actor has different needs for information, which do not necessarily align. Thus, the development of further standard operation procedures and support tools would allow for opportunities to support communication and information sharing when needed. The CTA insights highlighted the need for a wide variety of distributed work system strategies (i.e., detecting, sensemaking, planning, coordinating, and deciding). Further, the participants noted a series of actions and tools that would be helpful when communicating and supporting the operations (i.e., UVRs, NOTAMs, etc.). Through information sharing and communication, the robustness and resilience of the system can be improved. The ability for the system to respond and adapt to faced challenges can support the distributed work. This can be achieved through sharing information and communication as it achieves the aspect of coordination. Coordination helps support and share resources, which is necessary to achieve a robust and resilient system.

Insight 2: A need for sufficient control authority of the UTM supervisor to support human expertise and custom responses

The second insight is the need for control authority of the UTM supervisor. The complexity and dynamics of the UTM system, including the unpredictability of the exact nature of each contingency, often resulted in custom responses that are difficult to codify in procedures or automation ahead of time. Previous research in other domains has noted benefits of procedures and task aids but also highlight how these require human expertise to execute and add contextual information [16]. Likewise, automation of contingency responses has benefits but effective shared human-automation is important to avoid pitfalls of automating too much [17]. Highly automated and/or proceduralized systems need support for human involvement and the ability to customize responses (i.e., planning, supervision, adjustments, etc.) [18]. The need for custom responses was present throughout the interviews. Participants discussed choosing custom reroutes over standard solutions - such as prioritizing an airspace with a UVR and rerouting the affected vehicles' operation. This finding also connects to related research on calls for teaming intelligence for high-authority automation [19] and human-autonomy teaming in urban air mobility operations [20].

When further evaluating the design implementations, the interviews revealed a design tradeoff between supporting quick, automated responses and supporting human user input to customize solutions. Participants revealed that quick responses would be needed in the system due to the rapidly changing situations when an anomaly arises. In many of the interviews, it was evident that there were many time pressures involved. Thus, preprogrammed automated responses can speed up responses when necessary. Previous research on resilience, however, has revealed automating contingency management poses a risk factor of creating a brittle system and can be overly restrictive. This results in failures when challenges arise outside of the design envelope, particularly when preprogrammed solutions fail to consider all context to a, perhaps unique, combination of contingency factors.

A potential solution would be to have a staggered responses that allow a quick initial response, followed by a more fine-tuned custom intervention. Initial quick responses could include using a UVR, or some participants had suggested using an early alert, for example, a Notice to Airmen (NOTAM). More detailed operator engagement in follow-up interventions would allow the opportunity to mitigate risks and allow the UTM supervisor to custom create solutions in the future.

Insight 3: A need for standard operating procedures that increase mutual predictability and afford implicit coordination

Lastly, the results showed the need for creating predictability within the UTM operations. The interviews revealed challenges with uncertainty, primarily when elements of the system were beyond the control of the UTM supervisor. In order for the operations to be scalable, the need for standard operating procedures for actors in the system can allow a more predictable response for the UTM supervisor. In addition, standard operating procedures allow the opportunity to create common ground between other actors in the system and the UTM supervisor, which supports more implicit forms of coordination. Implicit coordination can be powerful when quick responses are needed, reducing the need to explicitly communicate all intentions and actions that are taken [6].

The three main insights correspond roughly with three requirements for effective coordination, between humans and between humans and automation: mutual observability, predictability, and directability. Observability refers to one's knowledge and status relevant to the team's knowledge or environment. Predictability refers to whether the actions one takes are predictable enough for others to understand and anticipate. Directability refers to the ability for one to influence the behaviors of others and be influenced by [21]. The insights from the study reinforce the need for these three coordination mechanisms in UTM through information sharing, custom responses that support control authority, and procedures that can reduce uncertainty in distributed responses.

The challenges and needs described in this paper can be further explored by modeling the work involved in UTM in more detail. The authors are involved in related work that developed computational models of the work involved in UTM contingency management, which can be simulated over time to explore temporal dynamics of coordination [22]. In addition, insights from this study point to a broader need to better understand coordination strategies under time pressure. Earlier research has pointed out how human coordination and communication strategies are adaptive based on time pressure and workload [6]. Supporting effective coordination during UTM contingency management requires understanding and supporting such adaptive behaviors in procedures, communication aids, and further role and system design. One research avenue to do this is to perform further human subjects studies in high-fidelity simulated UTM environments to identify how human teams adapt their coordination behavior when anomalies arise.

VI. Conclusion

This paper reports on a study on the cognitive work involved in contingency management for future UTM operations. CTA was conducted to identify and examine patterns that support anticipation and coordination across multiple roles within the envisioned UTM ecosystem. Five edge case scenarios were developed that represented stories and challenged the envisioned system. These edge case scenarios were evaluated through seven semi-structured interviews.

The interviews allowed a better understanding of thought processes and potential coordination and communication requirements. Following the interviews, data analysis was conducted to discover potential themes in the domain. A coding scheme was used to evaluate the data from the interviews. This revealed eight themes that would potentially make the work challenging and a model of macrocognitive functions that support coordination. This was then evaluated to determine decision-making strategies through an abstraction hierarchy. This includes resources and assistive characteristics that would be useful in the UTM ecosystem. Furthermore, coordination needs were characterized by developing an information flow diagram. Lastly, to understand the work and support contextual activities, a visualization was developed. This visualization was used to support the potential coordination requirements in the system.

These findings point to (1) the need for supported communication that would assist in standard operating procedures and support tools, (2) the need for sufficient control authority of the UTM supervisor that supports custom responses when a contingency arises and (3) the need to create predictability in the system that supports common ground between many roles in the UTM system. This study was able to support coordination requirements for the future design of the UTM system.

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