Pilot's roles in the Urban Air Mobility: individual capabilities for safety and security enterprise concerns

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Abstract. Safety and security are cross-cutting concerns of the Urban Air Mobility (UAM) ecosystem and critical for its future operations. Addressing those concerns requires an integrated approach, including stakeholders, people, processes, systems, and capabilities. While previous research has explored safety and security at the System-of-Systems (SoS) level, this paper embraces the Human Systems Integration (HSI) approach to investigate the pilot as an individual performer. In UAM's early phases, the pilot is expected to be on board, controlling the vehicle and interacting with multiple systems and operators. This study employs the Unified Architecture Framework (UAF) to discern the pilot's roles and capabilities consistent with the UAM as an enterprise. Results include views combining strategic resource exchanges and responsibilities associated with each pilot role. Lastly, we analyze the relationships among roles and capabilities and discuss the pilot's critical capabilities for addressing situation awareness, security, and safety culture concerns. Leveraging the HSI approach allows for understanding the pilot's perspective, facilitating informed decision-making, and fostering a culture of safety and security throughout the UAM ecosystem.

Introduction

The UAM concept of operations (ConOps) envisions an ecosystem involving several key components and stakeholders, all driven by a shared vision of transforming urban transportation. The UAM concept includes electric Vertical and Takeoff Landing (eVTOL) vehicles designed for short-distance urban travel, dedicated infrastructure such as vertiports, advanced technology for air traffic management and communication, regulatory frameworks, and integration platforms seamlessly coordinating different elements (FAA, 2023; Eve, 2022). Safety and security are fundamental considerations in UAM operations due to the challenges of integrating aerial transportation into densely populated urban environments (FAA, 2023; Bauranov & Rakas, 2021). UAM vehicles' proximity to the ground and other airspace users, coupled with the inherently dynamic nature of urban landscapes, necessitates robust safety measures to prevent accidents and ensure the well-being of passengers and ground occupants. Concurrently, the security of UAM operations extends to physical and cyber threats, as the increasing reliance on digital systems introduces potential vulnerabilities.

Addressing systemic concerns such as safety can benefit from a combination of top-down investigation and bottom-up analysis. This dual approach allows for a comprehensive understanding of the system by integrating high-level strategic insights with detailed, ground-level observations (Reason, 1997; Dekker, 2014; Leverson, 2012). Systems engineering, human factors, and organizational safety often emphasize the importance of both perspectives to achieve a holistic view of safety and operational effectiveness. The integration of human operational aspects in the UAM ecosystem is crucial for ensuring safety and security, particularly during the initial piloted phases. Understanding the pilot's roles and the challenges of single-pilot operations (SPO) is fundamental to developing task analysis and safety standards within the UAM ecosystem.

Prior research (Hoffmann et al., 2023a, Hoffmann et al., 2023b, Hoffmann et al., 2024) has adopted a holistic view to explore safety and security in UAM's future operations. The approach considered the UAM system-of-systems (SoS) and evaluated safety and security as cross-cutting concerns of the UAM architecture. Using enterprise architecture modeling and the Unified Architecture Framework (UAF), the investigation of safety and security was divided into three viewpoints: Situation Awareness (Hoffmann et al., 2023a), System Security (Hoffmann et al., 2023b), and Safety Culture (Hoffmann et al., 2024). Results included enterprise strategies, capabilities, functions, personnel structure, and operational considerations. Findings were provided from the system-of-system perspective, or in other words, from the enterprise level.

This paper shifts the perspective and focus on the UAM pilot as an individual operational performer. The objective is to investigate how the pilot, as a component of the UAM ecosystem, behaves according to safety and security enterprise concerns. Using UAF to model UAM views, this study presents the pilot's perspectives, emphasizing its roles and capabilities. The rest of the paper is organized as follows: We present the safety and security challenges considering the UAM operational context, and the human system's integration aspects concerning the pilot. Next, we briefly outline the study method and position it concerning past research. Then, we define the pilot's role for each enterprise concern and present dedicated views with individual capabilities, responsibilities, and resource exchanges. Lastly, we analyze the relationships among roles and capabilities, discuss the insights provided by the model, and present our final remarks.

Background

The human operational aspects within the UAM ecosystem play a vital role in the safety and security concerns. Human Systems Integration (HSI) gains even greater significance, particularly in the initial phases of UAM operation when the vehicle is piloted and human control manages traffic (FAA, 2023). Given the complex and dynamic nature of the environment in which pilots and controllers operate, effective decision-making processes are critical for ensuring safety in UAM performance. Safe UAM operations for passenger transportation involve two main sets of operational factors to consider: (1) those related to operations within shared airspace (Air Operator) and (2) those concerning personnel, including pilots, air traffic controllers, and maintenance staff (FAA, 1978). These factors present additional challenges due to UAM operations occurring at relatively low altitudes and within densely populated urban areas.

The ability of humans to make informed decisions relies on a solid understanding of the environment and the capability to steer clear of unsafe scenarios. Situation Awareness (SA) is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and a projection of their status in the near future” (Endsley, 1995, p.36). In this context, a user-centric approach is indispensable to design systems conducive to supporting SA, requiring the organization and operation of the UAM ecosystem to align with how users process information and make decisions. In Hoffmann et al., 2023a, we examined the SA behavior in the UAM SoS, showing it as a collective cognitive process distributed at different enterprise levels. Findings include UAF views from strategic, operational, personnel, and service aspects, combining systems, people, and processes committed to achieving SA.

The organizational and human operational aspects of the UAM ecosystem are also relevant for security considerations. The process of avoiding, withstanding, and recovering is not limited to systems and technology (NIST, 2021). Ensuring resilience involves not just systems and technology but also the people and processes within the system (Null et al., 2019). Personnel involved in UAM operations are susceptible to malicious events and play a vital role in maintaining security and resilience. Security events require informed decision-making and, consequently, a good strategy to achieve and maintain situation awareness. Therefore, designing systems and processes that support resilient performance must consider human factors (Holbrook et al., 2020). In the UAM context, a comprehensive work was presented by Hoffmann et al., 2023b proposing UAF views for security strategy, risk taxonomy, and security structure. Findings considered the UAM SoS level, including security controls and mitigations for different scenarios and vulnerabilities within the ecosystem.

Furthermore, the novelty and complexity of UAM services add considerations for providers and operators. Establishing a safety culture encouraging open communication and learning can pave the way for a sustainable operation. Managing safety and fostering learning is a challenge that involves organizational culture. Previous work of Hoffmann et al., 2024, revealed the challenges of implementing a healthy safety culture in the UAM ecosystem. The approach considered different enterprise levels and highlighted the importance of the front-line worker's role in ensuring safe and efficient UAM operations.

Safe UAM operations depend on the complexity of multiple systems integration, operational procedures, and operators' capabilities. The pilot is a critical resource in the earlier phases of UAM and is expected to be on board the vehicle with complete operational control (FAA, 2023). Hence, discussing human aspects and operational tasks from the pilot's perspective is crucial. In this sense, existing literature has explored Single Pilot Operations (SPO) with great concern (Wolter & Gore, 2015; Ebrecht, 2023; Li, Wang, Ding & Wang, 2022; Li et al., 2023). Although there are contributions considering single crew in commercial aircraft (Wolter & Gore, 2015; Zin et al., 2024), SPO is still not a consensus due to safety concerns by the aviation community. UAM operational procedures are still under discussion, and the pilot's task is unknown to this date. Understanding the UAM pilot's roles, responsibilities, and capabilities is key to discussing task analysis and safety standards (Edwards, Verma, and Keeler, 2019).

Method

The results presented in the paper are based on previous research findings which adopted the Enterprise Architecture (EA) methodology (ISO, 2019). Past work has generated enterprise views, or UAM SoS-level views, to systematically address safety and security concerns. Enterprise views were defined using architecture conceptualization and elaboration processes (ISO, 2019). After investigating the problem space for UAM Situation Awareness (Hoffmann et al., 2023a), UAM Security Hoffmann et al., 2023b), and UAM Safety Culture (Hoffmann et al., 2024), the solution spaces were defined using UAM constituent systems and stakeholders. In the current work, the pilot's perspective is extracted from the cross-cutting concerns and defined as an individual performer. EA methodology is also applied, adding the human system's integration perspective for the UAM pilot.

The architecture modeling used the UAF version 1.2 (OMG, 2021). Elements, relationships, and views follow the UAF language and metamodel (OMG, 2022; ISO, 2022). Validation of the model elements and views was performed through consistency check, traceability (with the enterprise level elements), and discussions following the architecture evaluation process in (ISO, 2019). The study aims to define and specify roles, capabilities, responsibilities, and critical resource exchange for the UAM pilot while being consistent with the UAM safety and security enterprise concerns. The architecture concerns covered in this research are Situation Awareness as a collective competence, Security, including physical and logical aspects, and Safety Culture, fostering a learning environment within the UAM organization.

Pilot as a Resource of the Enterprise

The UAM, as an enterprise, has concerns that affect the whole architecture. Safety and security are cross-cutting concerns that must be addressed from different architectural perspectives. UAF has a set of predefined viewpoints (ISO, 2022, p. 14) according to the key stakeholders and their perspectives and concerns. For instance, it is possible to explore organizational resource types in the *Personnel* aspect, including the human capabilities of organizations, teams, and people. From the *Operational* viewpoint, the logical architecture can describe operational behavior, requirements, and structures. The other important element in the UAF grid (ISO, 2022, p. 13) is called *aspects* (also known as model kinds). Different *aspects* are used to describe view specifications for different purposes. The *Motivation* aspect can capture the high-level strategy of the enterprise and is used to frame enterprise goals, opportunities, and challenges that drive different views of architecture.

While the *Strategic* viewpoint defines capabilities for the enterprise, including its taxonomy, composition, dependencies, and evolution, the resource viewpoint focuses on capability configuration, which is responsible for implementing the operational requirements. The combination of operational tasks, resource types, and human capabilities must be coherent and consistent with safety and security goals. Different resource types (systems, organizations, artifacts, natural) can realize different functions by exhibiting different capabilities. Thus, understanding how each resource engages in the enterprise is critical for determining the desired effect of the enterprise's capabilities and goals. Past research has proposed enterprise views for SA, Security, and Safety Culture. Figure 1 outlines the pilot's perspective as an enterprise resource and how it was framed concerning previous work.

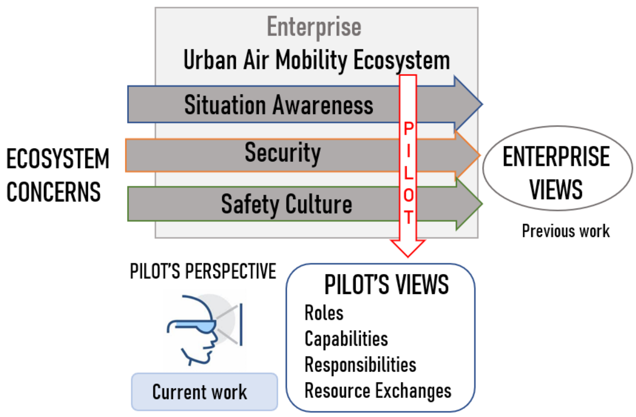

Figure 1. Pilot's perspective as an enterprise resource

The *pilot* can be defined as a <<ResourcePerformer>> of the UAM enterprise and exhibits a *resource* kind of capability. It means that the *Pilot* is a resource that performs functions for the enterprise and implements operational activities defined in the operational architecture. Likewise, <<ResourceRole>> elements are defined as part of a greater resource performer. One resource may perform different resource roles, and different resource performers may perform one resource role. At a more specific level, the *pilot* can also be defined as <<Post>>, which is a type of <<OrganizationalPerformer>> (specific classifier of resource performer). The element *post* is part of the personnel viewpoint and exhibits *personnel* kind of capabilities. This distinction between kinds of capabilities is important because it relates to the individual ability to fulfill the resource capability. In the following sections, we will explore the roles and individual capabilities required of the pilot.

Pilot's roles

The strategy for addressing three enterprise concerns was defining three roles for the pilot. Figure 2 shows the overview of the pilot's roles and main relationships and definitions in the resource, service, and operational architectures. The <<Post>> *Pilot in Command* presents three <<ResourceRole>> elements: (i) *Decision Maker*, (ii) *Safety Agent*, and (iii) *Security Agent* (in the center of the diagram). As depicted, the pilot is commanded by the *Pilot Manager*, another post of the same organization *UAM Operator* (at the top left). The *UAM Operator* implements the <<Service>> *UAM Transportation*, a high-level definition from the service architecture. The operational architecture is summarized in the <<OperationalActivity>> *Fly Vehicle*, implemented by the pilot. Still on the left side, there are three main functions performed by the corresponding pilot's roles: *Make safe decisions*, *Report events*, and *Protect flight*. At the bottom of the diagram are the primary system's interactions performed by the pilot: Operate the *UAM Vehicle*, and input and follow up events on the *Reporting System*.

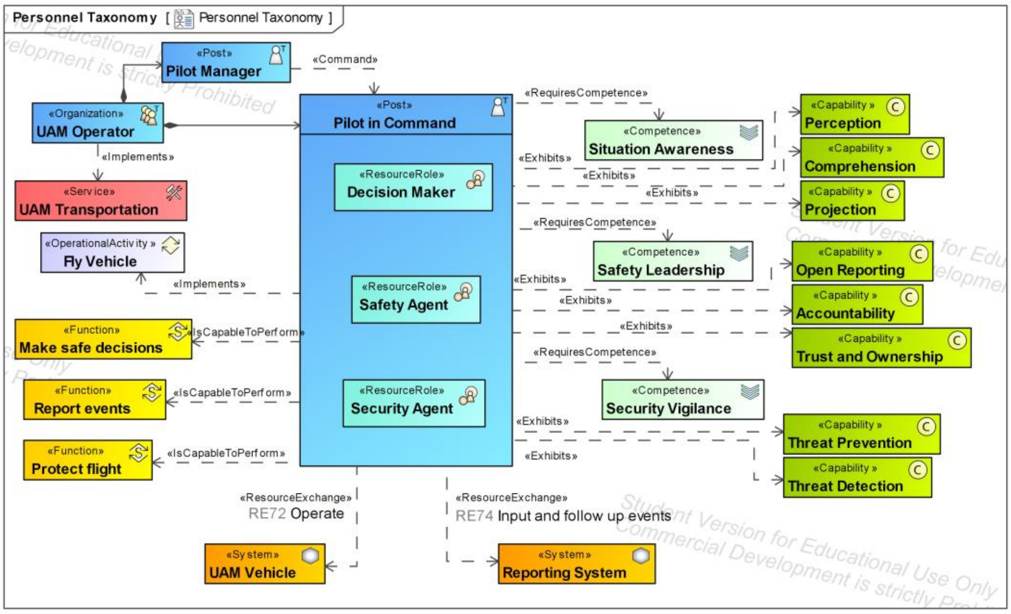

Figure 2. Overview of Pilot's roles

On the right side of the diagram, there are three sets of required competence and capabilities exhibited by the pilot (each set corresponds to one specific role). In UAF, competence is defined as a specific set of abilities defined by knowledge, skills, and aptitude; capability represents the enterprise's ability to achieve a desired effect. In the *Pilot Resource Taxonomy* view (diagram above), the pilot exhibits capabilities defined by the resource architecture's specification (resource kind of capability). In other words, the pilot is being represented as a generic resource for the enterprise. Therefore, the pilot, in the role of a *Decision Maker*, is a resource that requires competence in *Situation Awareness* and should exhibit the capability of *Perception*, *Comprehension*, and *Projection*. When the role is *Safety Agent*, the competence required is *Safety Leadership*, and capabilities such as *Open Reporting*, *Accountability*, and *Trust and Ownership* are exhibited. Likewise, when the pilot is a *Security Agent*, the competence required is *Security Vigilance* with *Threat Prevention* and *Threat Detection* capabilities. The scheme in Figure 2 is a simplification of the taxonomy regarding roles, competencies, and capabilities. Remarkably, the roles and capabilities are not independent or disconnected from each other. For instance, being a safety agent requires perceiving the environment (*Perception* capability), or, developing security vigilance (competence) involves personal accountability and open communication. Competencies and capabilities in this view were defined at the enterprise level (from previous study). The objective of Figure 2 is to summarize the pilot's roles, main competencies, and capabilities that are considered when addressing the three enterprises' concerns. Detailed capabilities, at the individual level, are defined in the next section.

Pilot's capabilities, responsibilities, and exchanges

In this section, we will focus on each pilot's role. The diagrams below present the necessary individual capabilities, responsibilities, and exchanges for when the pilot performs its roles.

Pilot as a *Decision Maker*. When *Situation Awareness* is the problem to be addressed by the UAM ecosystem, the pilot must undertake the role of *Decision Maker*. Notably, SA is a competence required in other pilot's roles. The pilot makes decisions in multiple roles, in different scenarios, and for different purposes. This paper focuses on the SA problem during vehicle operation (pre-, post, and during flight). Thus, a definition notation was added (linked to the <<ResourceRole>> element) to make clear the operational frame of the decision maker role. The ability to perceive, understand, and effectively respond to any event while controlling the vehicle makes the pilot a critical resource for the operation. The list of responsibilities related to the role of the *Decision Maker* (while operating the vehicle) is presented in Figure 3 (bottom left). *Vehicle Health Status Monitoring*, *External Communication*, and *Stress Level Management* are some examples of the pilot's duties for maintaining a safe level of situation awareness. The necessary resource exchanges between the pilot, system (UAM vehicle), and other posts are on the top right of the diagram. Because shared information is key for situation awareness, reporting and communicating with other agents of the ecosystem is highly expected and required, as illustrated. Another crucial aspect to be monitored and assessed is the technical and personal condition of the pilot, also represented by resource exchanges and responsibilities.

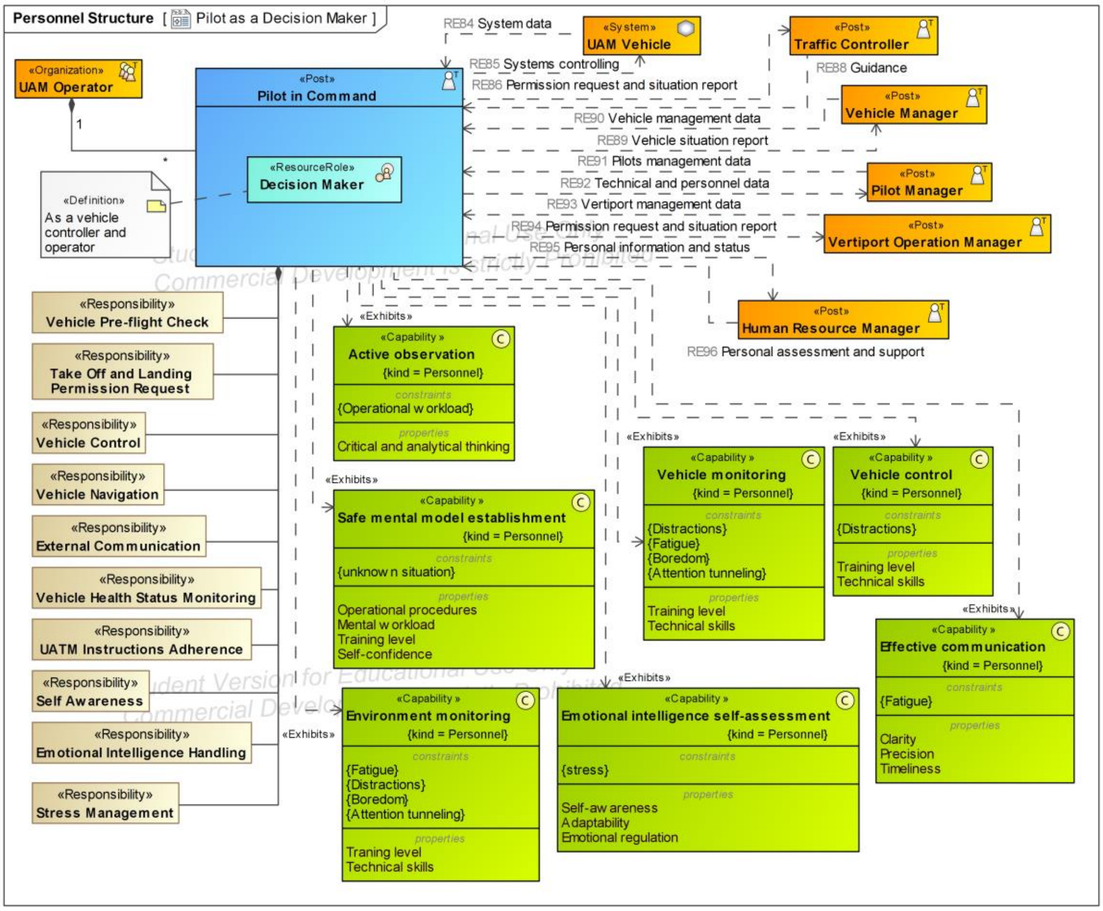

Figure 3. Pilot as a Decision Maker (during vehicle operation)

In terms of capabilities, preparing, developing, and maintaining situation awareness requires a complex set of individual abilities that rely on training, practice, and also human aspects (e.g., personal conditions, attitudes, knowledge, skills, traits, etc.). As shown in Figure 3 (bottom center/right), these human aspects that impact individual capabilities are represented using properties and constraints. As illustrated, properties support the capability strength, and, in the opposite direction, constraints impact them negatively. For instance, the pilot's ability to monitor the environment (capability *Environment monitoring* on the center bottom) depends on training and technical skills (defined as properties). Nevertheless, fatigue, distractions, boredom, and attention tunneling can impair the pilot's perception (defined as constraints). The same applies to the *Monitor Vehicle* capability (in the center). Moreover, *Active observation* (below pilot in command's box) requires analytical and critical thinking, which is fundamental for projecting scenarios (important ability of situation awareness). Operational workload can jeopardize the ability to observe and make sense of any possible threat. Emotional aspects, mental model, and communication are equally explored with their properties and constraints.

Pilot as a *Security Agent*. The second role of the pilot concerns the security viewpoint. As a security agent, the pilot's role is to protect the flight by performing security processes before the flight (prevention) and adapting the operation if any threat occurs during flight. Monitoring and reporting are equally significant in this role (as in decision maker role). Figure 4 depicts the responsibilities of the pilot with security matters. *Vehicle Pre-flight Check*, *Vehicle Integrity Verification*, *Passenger Screening Check*, and *Flight Plan Approval* are some examples of activities charged to the pilot's security agent role. On the top right is the security process that the pilot performs and security enclaves used to exchange information. In addition, exchanges with posts like *Vertiport Security Access Manager*, *Vehicle Security Access Manager*, *Ground Guard*, and *Traffic Controller* are presented due to their relevance to protecting the operation. More details of those exchanges are in the diagram below.

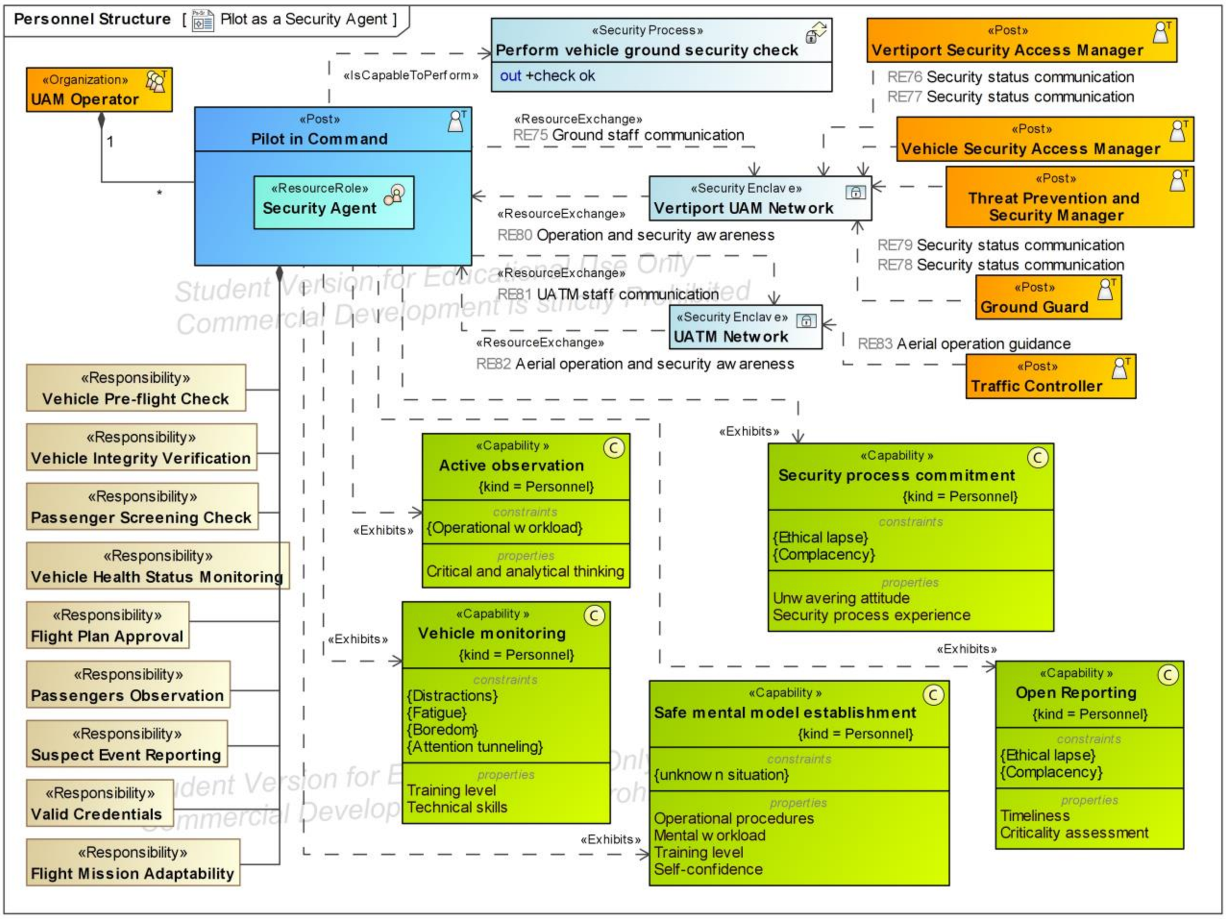

Figure 4. Pilot as a Security Agent

The capabilities of the security agent's role, *Active observation*, *Vehicle monitoring*, and *Safe mental model establishment* are the same as exhibited by the decision maker's role. *Open reporting* (capability on the bottom right) is the ability to report events on time while assessing their criticality.

Ethical lapse and complacency (constraints) can affect this capability in time or misjudgment. The specific capability for this role is the *Security process commitment* (on the center right). As a security agent, the pilot must be committed to protecting the vehicle and flight. This is represented by the *Security process commitment* capability in Figure 4 (on the center right). In the case of this capability, field experience (for enhancing judgment skills) and unwavering attitude are represented as its properties, which are crucial to preventing any security threat. In addition, complacency (constraint) can affect security's commitment capability when the pilot becomes too experienced or familiar with his/her security processes and starts to develop an overly relaxed attitude toward tasks. Lastly, ethics also builds the individual's commitment to security matters. Ethical lapse is defined as a constraint because it can jeopardize the operation's security.

Pilot as a *Safety Agent*. The pilot is a safety agent, the third role of the pilot, and an essential piece of the UAM safety culture. In this concern, trust and accountability are the leading aspects of developing relationships and processes for a healthy learning culture. Reporting is the main verb in terms of actions and responsibilities. *Event Reporting*, *Event Assessment Support*, *Resource* and *Workload Inadequacy Reporting* are listed as responsibilities in Figure 5. Likewise, being part of the safety guidelines and developing an ownership sense is crucial for accountability. In this role, the pilot is a *Front-Line staff* (<<Post>> defined from safety culture viewpoint). Therefore, the pilot carries (<<import>> relationship in the center) the resource exchanges defined for a *front-line staff*. It means that operational perspectives, feedback, and co-participation are required for the pilot. More exchanges are detailed on the right side.

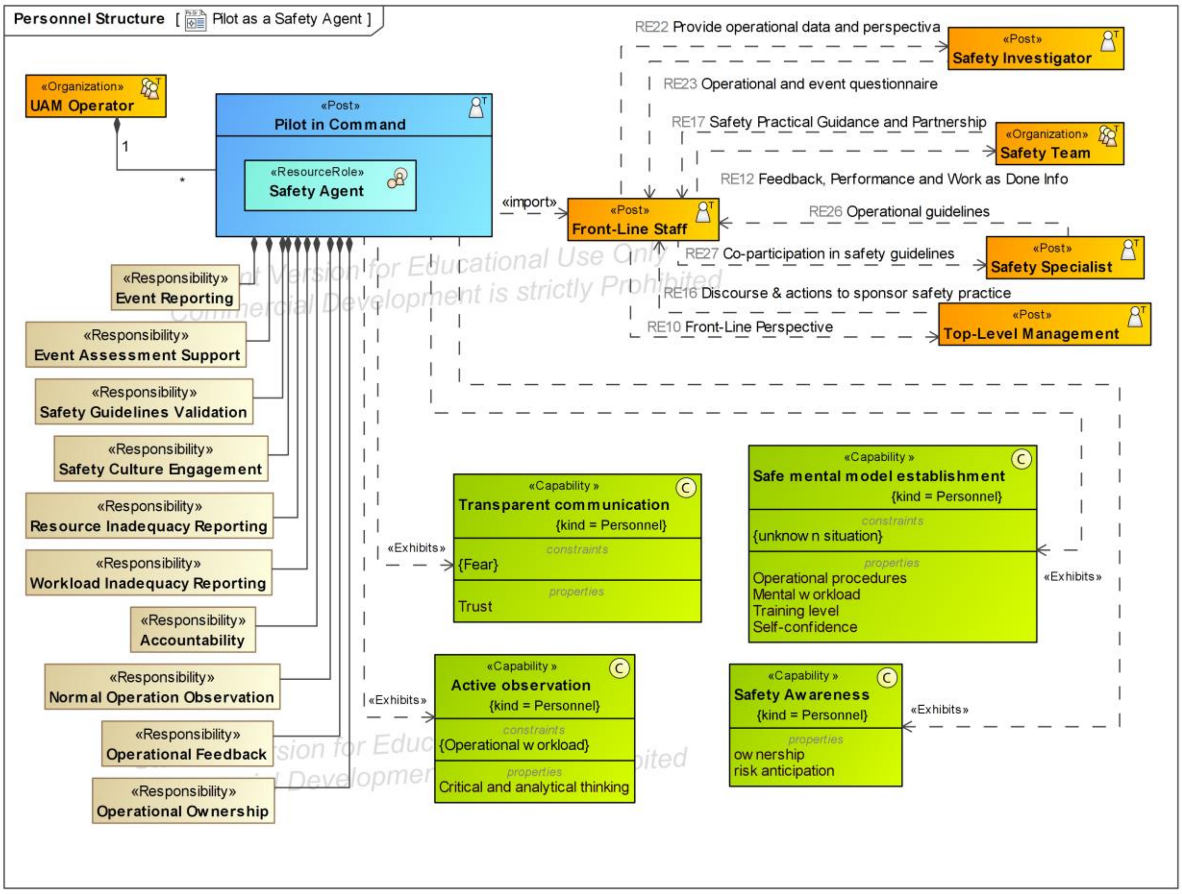

Figure 5. Pilot as a Safety Agent

Active observation and *Safe mental model establishment* are shared capabilities, already described above. *Transparent communication* is the capability that allows the organization to know about events and learn from possible mistakes. Transparent communication is only possible if the employee trusts (property) that it will be used in the best interest of safety learning and does not fear (constraint) being judged and blamed. Furthermore, *Safety Awareness* (in the bottom right) is driven by ownership and accountability (properties). In this viewpoint, the *front-line staff* must understand the differences between honest mistakes, at-risk behaviors, and reckless actions. When the pilot is engaged in the safety culture and is part of the guidelines and decisions, he/she can develop ownership and accountability for his actions.

Discussion

The pilot's roles presented in the previous section are not disconnected nor independent. Behaviors, skills, and responsibilities overlay. The purpose of framing responsibilities, capabilities, and exchanges in a personnel structure diagram is to facilitate the understanding of the pilot's performance in three different enterprise concerns: Situation Awareness, Security, and Safety Culture. Using model traceability and matrix features, we analyzed the relationships between roles and capabilities that will be summarized and debated in this section.

All pilots' roles share *Safe mental model establishment* and *Active observation* regarding individual capabilities. This is explained by the criticality nature of the SA competence. Making safe decisions is relevant for achieving and maintaining safe and secure UAM operation. A mental model is a cognitive framework or representation of how something works. In the pilot's context, it is an internal mechanism that helps him/her understand safe behavior in UAM operation. Mental models are formed through education, experiences, and exposure to information. Situation awareness, security, and safety culture depend on individual and collective mental models and must plan for training, practice, and shared information systems. Likewise, the pilot must exhibit active observation, which includes being critical and analytical of the interacted environment and systems. Active observation and a safe mental model depend on each other. The pilot needs both to predict outcomes and make safe decisions, the desired effect of all three viewpoints.

The individual capabilities for the pilot as a decision maker must be planned according to the organizational context and personnel aspects. Since previous work has delved into SA as an enterprise competence, in this paper we identified the properties and constraints of individual capabilities that are consistent with organizational enabling processes. For instance, training level is decisive for building a proper mental mode and for preparing the operator on monitoring skills, among other operational tasks. The organization and their resources must provide for the pilot training needs in all its roles. The same applies regarding stress and emotional instability. The organization should be prepared to monitor and handle individual conditions on pilot that may affect its ability to make safe decisions. Therefore, continuous assessment and adaptation of organizational processes to meet the evolving needs of pilots are crucial for sustaining high standards in aviation operations.

Communication is another significant capability defined for the UAM as an enterprise. When we move to the personnel domain and define individual capabilities, communication has different facets. Namely, the pilot must exhibit *effective communication* as a vehicle operator. Clarity, precision, and timeliness are properties for communicating while operating the vehicle. On the other hand, *open reporting* is the communication capability that the pilot as a security agent requires. Lastly, *transparent communication* is the type of communication that the pilot must exhibit as a safety agent. The strategic capability of the enterprise must be analyzed from the resource perspective. For each pilot's function, different individual capabilities (specialized types of strategic capabilities) are defined.

The need for a safe mental model, active observation, and effective communication is fundamental across various aviation environments. While the architecture was explicitly modeled for UAM operations, many of its principles are relevant to other aviation contexts, including single-pilot operations (SPO). The mapping presented in this paper is tailored to the unique requirements of UAM operations in the early phases, with one pilot onboard the vehicle. Still, the results have broader applicability to other aviation contexts and highlight the importance of aligning individual capabilities with organizational processes.

Final Remarks

The research presented in this paper framed the UAM pilot as an individual operational performer of the UAM ecosystem. Systemic approach was explored in previous work considering the whole UAM enterprise. In this work, we investigated the pilot's perspective when performing different functions for the enterprise. We proposed three roles and provided specifications for responsibilities, exchanges, and capabilities. Using UAF modeling, we presented views combining individual-level elements following the enterprise-level architecture. Lastly, we analyzed the pilot's capabilities according to its roles and discussed critical resources for addressing safety and security challenges.

The UAF has proven to be a suitable framework to synthesize the holistic aspects of a complex operation, and as presented above, helpful for exploring individual-level perspectives. Modeling eases the burden of dealing with complexity but also carries limitations. Inconsistency and incoherency can happen with conceptual representations, for such iteration and validation are encouraged. The diagrams presented in the results were scrutinized and validated by experts on human factors, system engineering, and conceptual modeling.

Future contributions include analyzing how ontologies can improve the representation of individual and organizational capabilities in the UAM domain, as was proposed in Calhau & Almeida, 2022. In this case, ontologies can allow the zooming in on competencies/individual capabilities to better understand how their elements (knowledge, attitude, skill, and other human aspects) are related, as was done by Calhau & Almeida, 2022. Furthermore, concerning the zooming out on individual capabilities, ontologies can also help to improve the modeling of the phenomenon of emergence in EA, as approached by Calhau et al., 2023. In this instance, they can help answer questions such as: how do the SoS's capabilities emerge from the individual capabilities? How can capabilities of distinct human resources (e.g., Pilot and UAM Operator) be better combined? How can human aspects (e.g., attitude, knowledge, represented as capability's properties and constraints) impact the whole system?

Finally, recommendations include performing task analysis using operational activities and combining them with personnel and resource capabilities. In addition, other roles in the ecosystem, like traffic controller or maintenance staff, can benefit from the approach presented in this paper.

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