Jetson's View: Designing Trustworthy Air Taxi Systems

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Keywords: Autonomous Vehicles, Trustworthy Interface, Air Taxi.

Abstract: As the world's population grows and urbanization accelerates, the need for sustainable urban mobility solutions becomes more and more important. Smart cities, considered the answer to urban challenges, are ready to integrate innovative modes of transport, such as electric vertical take-off and landing vehicles (eVTOLs), into their fabric. This paper discusses challenges and opportunities presented by eVTOLs, with a particular focus on safety, security, and user experience. Based on a resilient architecture proposed by STRAUSS, which integrates safety and fault tolerance measures, we characterize a framework for safe and reliable eVTOL operations in smart cities. In addition, we investigate the design of user interfaces for autonomous eVTOL systems by employing personas and use case scenarios. A interface's prototype illustrates the adaptability and functionality of the interface in real-life scenarios, meeting the diverse needs of users and promoting trust in future urban transport systems. Through this interdisciplinary approach, this research aspires to advance the adoption of eVTOLs and enhance urban mobility at the dawn of the smart city's future.

1 INTRODUCTION

According to the United Nations, 55% of the world's population currently lives in urban areas, which is projected to increase to 68% by 2050 (Ferrão et al., 2022a; Nations, 2018). In this context, urban planning is crucial for ensuring quality of life while promoting sustainable economic development and infrastructure capable of meeting present and future demands. Smart cities offer innovative solutions to address the challenges of urban mobility. Electric vertical takeoff and landing vehicles (eVTOLs), often referred to as air taxis, stand out among them. These aircraft aim to provide safe, sustainable, and accessible air transportation for passengers and cargo, as well as emergency services within and between metropolitan areas and hard-to-reach peripheral regions.

Unlike conventional transportation systems, such as cars or trains, which are limited by ground traffic space, air taxis do not occupy spaces within congested traffic areas (Ferrão et al., 2020b). Air mobility solutions offer greater spatial and temporal flexibility, reduced congestion, and less user stress. Designed for vertical takeoff and landing, these aircraft eliminate the need for long runways required by traditional airplanes. Additionally, air taxis are powered by electric motors and batteries, making them more energy-efficient and emitting fewer pollutants than traditional aircraft. However, their practical implementation and deployment face various challenges, especially concerning safety, security, and passenger trust, which are also recurrent issues in other aircraft types.

Passenger mistrust in adopting air transportation systems is often fueled by concerns regarding about safety and reliability, which are frequently exacerbated by past incidents involving conventional airplanes and mistrust in automated systems. Research shows that trust is significantly influenced by design and aspects of appearance, transparency, ease of use, communication style and user control all play a crucial role in shaping user trust (Hoff and Bashir, 2015). Moreover, introducing emerging technologies such as connected air taxis adds a new layer of concern. This connectivity exposes aircraft to potential cybersecurity vulnerabilities, such as network attacks on the vehicle and its sensor systems, which can heighten resistance and discomfort in adopting these technologies.

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Ferrão, I., Filho, J. C. S., Oliveira, K., Espes, D., Dezan, C., Hamadouche, M., Belloum, R., Cunha, B. and Branco, K.
Jetson's View: Designing Trustworthy Air Taxi Systems.
DOI: 10.5220/0013279300003929

In *Proceedings of the 27th International Conference on Enterprise Information Systems (ICEIS 2025) - Volume 2*, pages 517-524
ISBN: 978-989-758-749-8; ISSN: 2184-4992

In this regard, conventional airplane interfaces fail to present flight information in a manner that instills user confidence. Additionally, existing architectures address only safety requirements, disregarding security issues, while both are equally important for user acceptability (EASA, 2021). Neglecting either of these requirements can undermine the trustiness and effectiveness of the systems, jeopardizing the company's reputation.

This article aims to contribute to the state of the art through two pillars. Firstly, we propose STRAUSS, a resilient architecture for air taxi operations in smart cities. STRAUSS is a robust, fault-tolerant architecture capable of operating under adverse and intentional conditions. It integrates security detection and protection modules, decision-making, and flexibility to achieve these characteristics. STRAUSS is designed to automatically adapt to detect failures and attacks, making real-time decisions to ensure mission integrity. We propose incorporating the decision-making mechanism with the mission planning of these vehicles. According to the aircraft's autonomy level, the mission is deployed to match different scenarios an air taxi can encounter. Secondly, we present new and initial ideas for air taxi system user interfaces, based on simple yet realistic scenarios designed to inspire user trust. To this end, these concepts are defined based on the STRAUSS architecture and the mission planning objectives. Furthermore, since many user groups still approach aircraft autonomy with apprehension and skepticism (Lotz et al., 2023), there is a gap in the literature regarding applying Human-Computer Interface (HCI) principles to the context of air taxis within intelligent systems. As air taxi systems become increasingly autonomous, relying on decision-making based on artificial intelligence algorithms, it becomes essential to ensure that decisions are transparently explained to users. This instills confidence and trust in passengers regarding the reliability of the system. Therefore, integrating an interface that prioritizes trust within the air taxi system enhances its reliability and dependability, fostering positive experiences and building long-term trust among passengers.

This work is organized as follows. We discuss related work in Section 2 and introduce STRAUSS in Section 3. Then, we present the methodology for designing a interface prototype in Section 4. Finally, we conclude and outline future perspectives in Section 5.

2 RELATED WORK

Despite various models and system architectures in the existing literature, adequately encompass all encompass all the requirements for creating generic and safe air vehicles. Most architectures primarily focus on defining and developing specialized air vehicles (Ferrão et al., 2022b; Siewert et al., 2019). However, they can serve as reference for replicating security techniques in air taxi architectures, especially considering the substantial ratio of Unmanned Aerial Vehicles (UAVs) to air taxis. Among these architectures, there are dedicated UAVs, such as HAMSTER (Pigatto, 2017), STUART (Ferrão et al., 2020a) and ContainerDrone (Siewert et al., 2019), each employing different approaches.

The Health, Mobility, and Safety Based Data Communications Architecture (HAMSTER) is a data communication architecture designed to improve overall system mobility and security (Pigatto, 2017). Despite significant efforts with HAMSTER, the authors do not consider the resiliency aspects of providing autonomous vehicles.

In (Ferrão et al., 2020a), the authors present STUART, a resilient architecture to dynamically manage UAV networks under attack. This architecture one of the few that consider safety and security as unified concepts. It employs decision-making techniques through a state machine and achieves resilience through restoration techniques and historical data stored in a reference base. It is noteworthy that while ensuring safety requirements has been a primary concern in the design and development of UAV systems, the communication of these vehicles with external entities introduces vulnerabilities. Some architectures intended to meet security requirements may have inherent flaws, and conversely, safety requirements may also contain security weaknesses. Therefore, it is essential to address both security and safety in a UAV architecture. In that sense, STUART is the only architecture that focuses on these vulnerabilities. However, it is still in the simulation testing phase, relies heavily on human intervention throughout all test phases, and has not yet been tested in a real avionics environment.

Likewise, (Chen et al., 2019) presented the ContainerDrone Framework that proposes resilient control of Denial of Service (DoS) attacks for real-time UAV systems using containers. The framework has proven reliable in protecting against DoS attacks launched within the container, limiting the attacker's access to critical system resources. Experiments showed that the proposed framework is effective against various types of DoS attacks. Nevertheless, the authors did not consider physical and software component failures caused by bugs, logical errors, or any other attack besides DoS.

Although the related works discussed so far have contributed to characterizing architectures for aerial vehicles, it is imperative to note that a limited portion of these efforts addresses the specific complexities associated with air taxis. The inherent peculiarities of air taxis, such as their imminent integration into densely populated urban environments, demand meticulous handling. Such environments require strong integration with existing infrastructure and air traffic management systems, making safety and resilience a critical and complex requirements. Additionally, aspects such as redundancy and fault tolerance play a central role in ensuring the safety of both occupants on board and people on the ground.

Air taxi architectures must also be sensitive to long-term maintenance and reliability. The complex nature of the technologies employed in these vehicles requires robust strategies to ensure that the systems remain operational and safe over time. In particular, the ability to make concise and real-time decisions during missions is a crucial characteristic to consider and is still a gap little explored in the literature. Furthermore, the effectiveness of an architecture depends not only on its technical functionality but also on intuitive user interfaces to ensure an optimized and reliable user experience.

Regarding HCI, several studies have been dedicated to the design and evaluation of autonomous cars, exploring aspects related to user experience, interface design, and passenger well-being. For example, research on user experience has examined passenger satisfaction, perceived safety, and comfort during autonomous vehicle journeys (Ranscombe et al., 2019). Furthermore, studies have considered user design for drivers, pedestrians, and other public roads users, aiming to ensure safety and efficiency in urban traffic (Verma et al., 2019; Meurer et al., 2020).

Among the approaches to interaction design, metaphors have been explored to make interactions with autonomous vehicles more intuitive and understandable for users (Strömberg et al., 2017). Additionally, there is a growing interest in evaluating passenger well-being during journeys in autonomous vehicles, considering aspects such as physical comfort, relaxation, and stress minimization (Sauer et al., 2021). However, as already mentioned, there is a gap in the literature regarding applying these HCI principles in the context of air taxis within intelligent systems. As air taxi systems become autonomous, it is essential to ensure that decisions are transparently explained to users. This not only fosters passenger trust in the system but also enhances their understanding of how it operates and responds to various situations. Therefore, it is important to investigate the design of interfaces that effectively convey the decisions and actions of air taxi systems to users, presenting information about planned routes, weather conditions, safety protocols, and emergency procedures in a clear and accessible manner (de Souza Filho et al., 2024; Muralidhar et al., 2023).

3 ReSilienT aiR TAXIS architectUre FOR SMART CITIES (STRAUSS)

STRAUSS is a resilient, robust, and fault-tolerant architecture for aerial taxis operating in adverse conditions, whether intentional or unintentional. STRAUSS dynamically adapts its mission, sharing information with other aircraft, consisting of three main modules: detection, decision-making, resilience and Jetson's interface.

3.1 Detection's Module

The ability of an avionic architecture to automatically identify impending failures in aircraft at early stages is crucial, as it prevents costly and potentially catastrophic system failures, ensuring greater safety and reliability of components. This, in turn, reduces damage and operational costs. In this regard, the detection module of STRAUSS plays a fundamental role in the reliability process, being responsible for identifying issues at safety (physical security) (Ferrão et al., 2023) and security (computational security) levels (Ferrão et al., 2024a).

Since STRAUSS focus on detecting issues from both safety and security perspectives, it stands apart from other architectures described in the literature. This stems from the fact that traditional airplanes primarily focused on physical safety, prioritizing structural integrity and proper functioning of mechanical systems. However, security has become an equally important concern with the emergence of autonomous aerial vehicles and the increasing integration of digital technologies such as communication systems and computer control.

Currently, concerning security, STRAUSS encompasses the detection of the most recurrent attacks on aircraft, namely GPS Spoofing and GPS Jamming. GPS Spoofing is a technique in which false GPS signals are sent to the aircraft, causing it to calculate an incorrect position. GPS Jamming involves the emission of radio signals that interfere with the aircraft's

GPS receiver, preventing it from determining its position. Regarding safety, STRAUSS detects seven critical failures that make up the structural and operational integrity of aircraft, such as engine failures, elevator failures, left aileron failures, right aileron failures, failures in both ailerons, left rudder failures and right rudder failures.

The algorithms and techniques used to detect safety and security in STRAUSS are based on artificial intelligence methodologies that guarantee the early identification of failures and attacks with an accuracy greater than 90%, providing a quick and efficient response. Specifically, STRAUSS employs machine learning models, such as Random Forests and Boosting variations, for anomaly detection, combined with simulated and real data to increase the reliability of detections. These methods have been carefully integrated into STRAUSS to ensure air taxis' safe and reliable operation in unpredictable urban environments. For more details on the technical implementation, see the following: (Ferrão et al., 2024b)

3.2 Decision-Making's Module

Air taxis must be able to continually adapt to missions and effectively detect unexpected internal problems or external threats. In this sense, STRAUSS proposes an architecture for autonomous vehicles capable of making appropriate decisions in real-time, ensuring the successful fulfillment of their mission. STRAUSS considers mission objectives and adjusts its actions according to random events related to mission context, system-wide integrity, mission safety and security, and risk management. It is important to emphasize that the STRAUSS decision-making process relies significantly on the detection module to determine the appropriate time for decisive intervention.

The current STRAUSS study addresses the decision-making mechanism through MDP. MDPs provide a mathematical approach to modeling decision-making in scenarios where outcomes are influenced by both randomness and partly by the actions of a decision-maker. This framework is suited to the dynamic and uncertain environment in which air taxis operate. In this scenario, the state space encompasses all possible aircraft statuses, including sensor readings and detected faults, while the action space consists of all possible maneuvers and responses that the system can perform. This STRAUSS module uses reinforcement learning algorithms to optimize policy for MDPs. Algorithms such as Q-learning and Deep Q-Networks (DQN) are employed to learn the optimal actions in each state to maximize the expected cumulative reward.

3.3 Resilience's Module

According to (Hollnagel et al., 2006), resilience is the ability to return to its original state after deformation. The STRAUSS resilience module communicates directly with the decision-making module and is invoked whenever any safety or security action needs to be applied. The resilience module is responsible for recovering and restoring the air taxi if it is subjected to an attack or a failure. STRAUSS incorporates this module to stabilize the functional level of the air taxi system even in successful operations. The module ensures that the system continues to function even if it is subjected to a successful attack, incorporating techniques that allow the restoration of the aircraft or an emergency landing to guarantee the physical and computational integrity of the vehicle.

The STRAUSS resilience module features fault containment isolation, recovery protocols, redundancy management, post-incident monitoring, analysis and learning, emergency landing and shutdown, and communication with other elements. For fault isolation and containment, upon detecting a fault or security breach, the resilience module isolates the affected components to prevent the issue from spreading to other parts of the system. This containment strategy helps maintain overall system stability and functionality. Additionally, the module includes a set of predefined recovery protocols tailored to different types of failures and attacks. For instance, the system activates a secondary power source in the event of an engine failure or switches to backup communication channels during an attack. To increase reliability, the resilience module leverages redundant systems and components. STRAUSS ensures continuous operation by maintaining backup systems that can take over in the event of a primary system failure. After dealing with a failure or attack, the resilience module conducts an analysis to understand the root cause and enhance future responses. This involves recording incident data, evaluating system performance, and updating recovery protocols.

Finally, the resilience module prioritizes passenger and vehicle safety in scenarios where recovery is impossible. It can perform emergency landing procedures by selecting the safest location based on real-time data. Additionally, it can perform a controlled shutdown of critical systems to prevent further damage.

4 INSIGHTS OF JETSON'S USER INTERFACE

In this section, we present a scenario designed to gain insights into the interface of future autonomous air taxi systems, intended for use by citizens for short trips. As noted by the European Union Aviation Safety Agency, potential users of Urban Air Mobility (UAM) are likely to prioritize safety, reliability, predictability, and ease of use. While affordability and convenience are also mentioned, they fall outside the scope of the system interface (EASA, 2021). According to (Hoff and Bashir, 2015), factors such as appearance, transparency, communication style, and user control are crucial in autonomous vehicles. Although the STRAUSS architecture emphasizes safety, reliability, and security, it is essential that the interfaces effectively convey these attributes to the end user.

To explore and propose an end-user-interface, we defined two personas (Nielsen, 2019) and, based on their needs, designed two scenarios of use, which are detailed in Section 4.1. These initial concepts will be further explored in future work through usability tests.

4.1 Defining Personas for Air Taxi Systems

A persona is a fictitious representation of an application user (Nielsen, 2019), created by defining the characteristics, needs, and objectives of real users. Developing personas aims to humanize and better understand the target audience, allowing us to design solutions that meet users' specific needs and preferences. With the idea of autonomous air taxi systems, we defined the two following personas:

- **Jane Jetson** – Jane is always interested in new technologies and is open to trying new experiences. She works in digital marketing and plans to use air taxis for her holiday trips. Although Jane has no piloting experience, she is familiar with conventional airplanes. In the event of an emergency, Jane wants to understand what is happening to feel safe, but she lacks the knowledge to grasp all the technical details.
- **George Jetson** – George is an economist who works for a multinational company, and traveling is a part of his job. He is a flight enthusiast with amateur flying experience who enjoys visiting the pilot's cabin to follow the journey on the in-flight panels. He plans to use air taxis for various purposes, including commuting to work and going on holidays. In the event of an emergency, George wants to understand what happened, along with the measures being taken to address the situation.

4.2 Scenarios of Use – Activity Diagrams and Prototype Interface

Based on the two personas, two scenarios of use were defined as activity diagrams (OMG, 2017) to support the definition of possible user interfaces. We detail each scenario as follows.

Scenario 1 – Jane decides to travel to Nice for the weekend after a tiring week. It starts when the user (Jane) takes an air taxi in Lille (Fig. 1). Once seated inside the aircraft, the system displays the dashboard, and the flight begins. After a while, Jane selects the stop-over option to pick up a friend in Lyon, France. Thus, the system decides if the stop-over is safe asks the Control Tower for authorization, which may or may not be granted. The system displays the result, adapts the interface accordingly, and continues the journey. The system continuously refreshes the dashboard with the position from where it is being from which is flying until it reaches its destination (Nice).

The first scenario exemplifies a successful flight with no incidents. As illustrated in Fig. 1, the interface features a straightforward communication style that aligns well with Jane's profile. Additionally, users can personalize their routes by adding strategic stops, providing a sense of control. Transparency is emphasized through all information displayed alongside the map, including system health (battery, engine, elevator, rudder, and aileron), detected issues, and feeds from front, rear, and side cameras. The interface cues are designed to provide information that enhances users predictability and reassures them about the safety of the flight.

We designed interfaces as high-fidelity mock-ups, which serve as a detailed visual representation of the interface by simulating the expected design and features of the end product (Wiegers and Beatty, 2013), using support design tools such as Figma[1]. Fig. 2 presents the high-fidelity mock-up for scenario 1.

Scenario 2 – George planned a trip to Porto Alegre to visit relatives and decided to take an air taxi (Fig. 3). Once seated, the system displays the dashboard (as shown in Fig. 2(a)). The journey begins, but at some point, an attacker executes a GPS Spoofing on the aircraft. At this moment, the dashboard displays

[1]The elements used to create the mock-ups were retrieved as follows: icons from Figma Community (https://www.figma.com/community), geolocation from Google Maps (https://www.google.com/maps), and unlicensed pictures for cameras from Google Images (https://www.google.com.br/imghp).

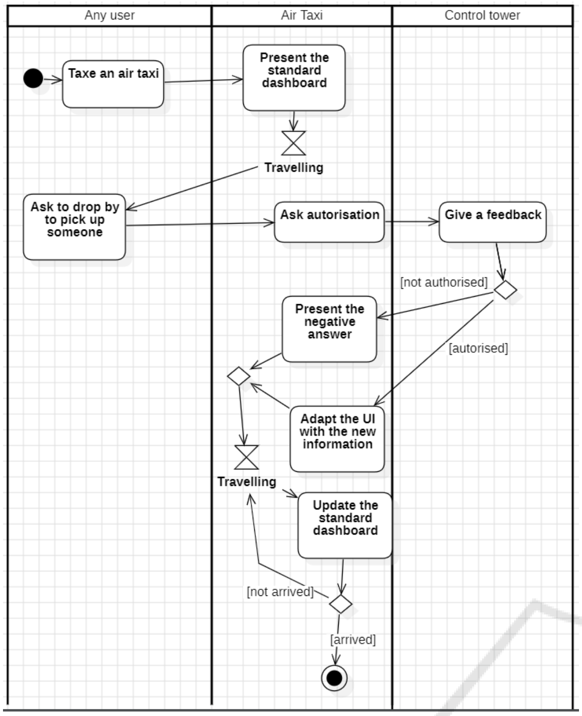
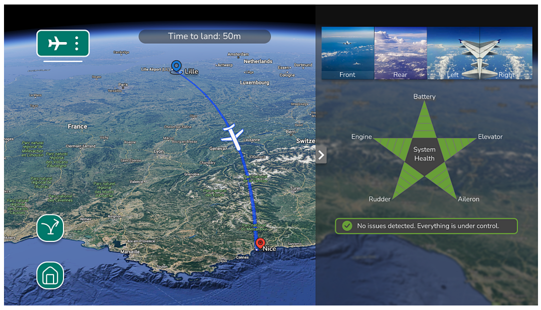
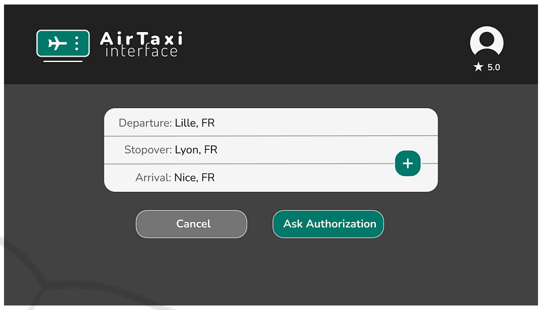


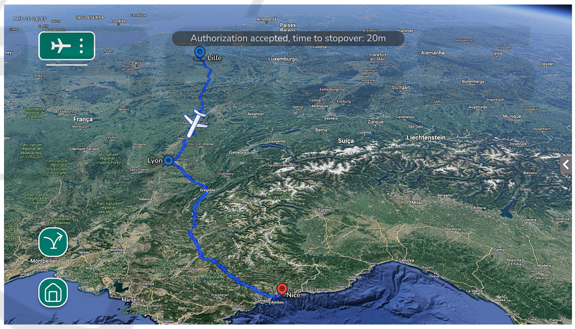
Figure 1: Scenario of use 1 - Jane Jetson's journey.



(a) Dashboard containing stopover button; time to land; cameras; degrees of battery, engine, elevator, rudders, and ailerons; and diagnosis.



(b) Screen to request authorization for a stopover.



(c) Authorization was granted, and the dashboard was updated.

Figure 2: High-fidelity mock-up for the scenario of use 1.

a completely different situation: the aircraft appears to be flying over Europe, while it is actually in South America (Brazil) (Fig. 4(a)). The air taxi system analyzes the situation, identifies the attack, and initiates the decision-making process. As the battery is not full (indicated in Fig. 4(b) as a yellow star), the decision is made to change direction and execute an emergency landing at the nearest location. Authorization is requested from the Control Tower, which is granted. The interface provides a one-level textual explanation "The air taxi is conducting an security landing. Everything is under control. More information will be provided by aircraft attendants after landing.". At this point, George selects the option to find more details. Thus, the decisions are explained through three levels of progressive disclosure (Springer and Whittaker, 2019) presented one at a time as requested by the user. First, the explanation unveils the detected attack (see message (1) in Fig. 4(b)). Second, if the user ask for more details, it reveals the causes of the attack, including the spotted location and time (message (2) in Fig. 4(b)). Finally, when the user request one more detail, the explanation indicate the decision (i.e., emergency landing) (message (3) in Fig. 4(b)) and its reasoning.

In the second scenario, the explanations were tailored specifically for users with piloting experience, like George. For users such as Jane, however, these details may not only be unnecessary but could also hinder their experience. The scenarios illustrate the importance of defining user profiles prior to the flight, as communication style and transparency must be aligned with user needs. George feels comfortable with additional information, as he understands technical terms and the decision-making process, unlike typical users. Our designed interface demonstrates the levels of transparency that can influence users' perceptions of system safety and readability.

It is important to note that the architecture provided by STRAUSS allows for the exploration of specific scenarios related to interface functionalities, prioritizing aspects such as safety, security, and decision-making. In other words, our architecture provides a framework for exploring User Experience (UX)

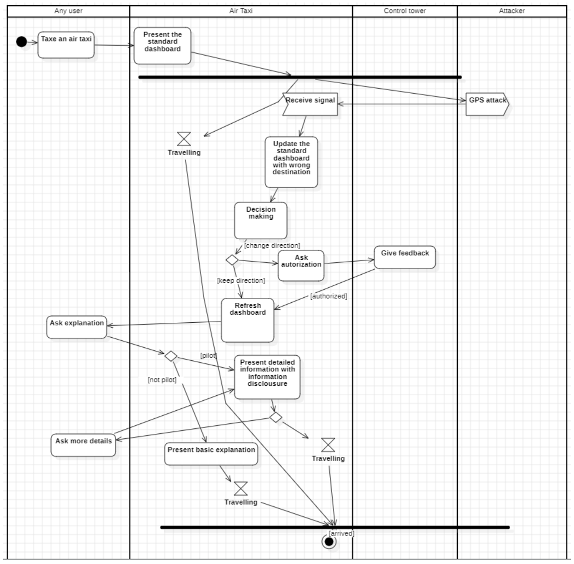


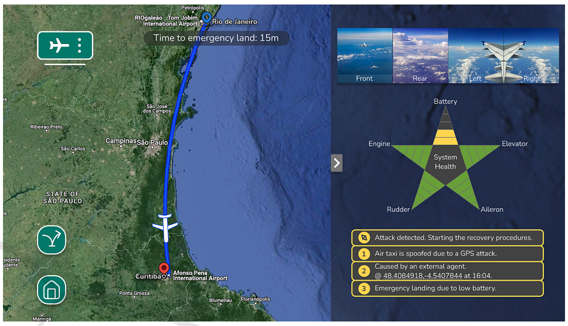
Figure 3: Scenario of use 2 - A journey with GPS attacker.

dimensions highlighted by potential users, such as safety, reliability and predictability, as the end-user is continuously informed trough the graphical interface. Regarding user control, we anticipate that certain actions will be available for customizing routes. However, since safety is a primary concern, the system evaluates whether any unplanned actions are risk-free and conducts a permission protocol accordingly. We also considered the facets of transparency and communication style. As represented by the characteristics of our personas, it is essential for the interface to accommodate different user profiles, as this can significantly impact users' perceptions of safety. Furthermore, we considered aspects of ease of use and appearance (i.e., aesthetics). Although the personas supported our design, users evaluations will be essential for assessing usability and hedonic aspects.

5 FINAL REMARKS

To improve the robustness and accuracy of STRAUSS security, we incorporate machine learning techniques to enhance detection and decision-making in the face of random events, as one of the main causes of vehicle problems is human error. Therefore, our architecture includes autonomous decision-making capabilities, even in the face of random events. Another differential of STRAUSS, compared to other architectures in the literature, is the inclusion of a resilience module, which is essential for maintaining the vehicle's operational stability even during successful operations. In future works, we will implement the resilient module and conduct boarding tests on a real aircraft.

(a) Dashboard updated to a wrong destination due to the attack.



(b) Dashboard updated the direction and explains the decision in three progressive levels as the user requests more details.

Figure 4: High-fidelity mock-up for the scenario of use 2.

Additionally, this paper presents initial concepts for the user interface design of air taxi systems. In our prototype, we designed screens that focus on safety, reliability, predictability, and ease of use, taking into account different transparency levels based on user profiles. Our next step is to conduct a deep literature analysis on the design of the user interfaces for this domain and to conduct user studies to gather the needs and preferences of potential users, as well as insecurities, in managing different flight scenarios (e.g., hailing, pick-up, travel, and drop-off). In this scenario, trust is a key factor that will be assessed during user evaluations. The results will be used to design initial interface prototypes following an iterative process.

ACKNOWLEDGEMENTS

Scania Latin America funded this study — Project Code 27192*54. It also received financial support from CAPES (Coordination for the Improvement of Higher Education Personnel — Brazil) — Funding Code 001.

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