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Risk Assessment of eVTOL Operations in Urban Environments: A FRAM Approach

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In recent years, the development of aerial vehicles has gained significant attention as a promising solution to the growing demands of urban transportation, while aiming to reduce the environmental impact of conventional motor vehicles. However, concerns have emerged regarding infrastructure requirements, air traffic management, and operational safety. This paper explores safety-related aspects of Electric Vertical Take-Off and Landing (eVTOL) operations in a prospective context, with a focus on risk identification and management. The study aims to map eVTOL operations in urban environments and conduct a qualitative risk analysis, along with a quantitative estimate, centered on a hypothetical scenario that introduces variabilities with potential safety implications. To model the approach and landing phases, the Functional Resonance Analysis Method (FRAM) is employed, followed by a quantitative risk assessment. Based on the Concepts of Operations (CONOPS) for eVTOLs, the research includes the decomposition of high-level functions into low-level functions to capture the complexity of operation, and the application of FRAM to model the scenario. The resulting analysis offers insights into safety-critical aspects of eVTOL missions, demonstrating FRAM's effectiveness as a tool for evaluating dynamic interactions within complex and highly integrated systems.

Keywords: FRAM, Functional Resonance Analysis Method, eVTOL, Electric Vertical Take-Off and Landing.

1. Introduction

In the last years, investments have been made in research and studies for developing aerial vehicles, known as for Electric Vertical Take-Off and Landing (eVTOL) vehicles (Franciscone and Fernandes 2023). The new urban mobility concept emerges as a solution for many problems arisen from the disordered growth in urban traffic, such as air quality, noise, impacts on environment, high level of fatalities, and others (Fowler et al. 2024).

However, like every technological innovation, a significant effort must be made to assure the safety of solutions (Fowler et al. 2024). This may include several qualitative and quantitative risk analysis, such as Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), and others, focusing on risk assessment and risk management. Moreover, emerging technologies, may drive the development of new methods.

In face of this challenge, this paper aims to map the eVTOL operation in urban environments and conduct a qualitative risk analysis, along with a quantitative estimate, focusing on a hypothetical scenario that introduces variabilities with potential safety implications. The study consists in: (a) definition of Concept of Operations (CONOPS) for eVTOLs; (b) decomposition of high-level functions into low-level functions to capture the complexity of operation; (c) application of Functional Resonance Analysis Method (FRAM) to model the eVTOL vehicle operation; (d) evaluate quantitatively a hypothetical failure scenario using the methodology proposed by Macchi (2010).

To model this scenario, FRAM methodology, proposed by Hollnagel in 2004 and consolidated in 2012, will be adopted. Additionally, the alternative methodology proposed by Macchi (2010) will be applied to perform a quantitative risk evaluation.

2. Literature review

The eVTOL vehicle is an electrically powered aircraft designed for vertical take-off and landing in small urban spaces. Its electric motors reduce noise, pollution, operating costs, and energy consumption compared with conventional airplanes and helicopters (Zhang et al. 2024). However, the implementation of eVTOLs for urban air mobility within a sociotechnical context introduces significant challenges related to safety, reliability, regulation, infrastructure, and operational complexity (Fowler et al. (2024).

Given the complex and tightly coupled nature of these challenges, there is a need for analytical approaches capable of capturing functional interactions, variability, and emergent system behaviour. According to Hollnagel (2012), FRAM is not an event analysis method focused on identifying cause-effect relationships. Instead, it aims to evaluate systems based on how their components and interactions actually occur, recognizing that performance is not linear but shaped by numerous variables, some seemingly insignificant, that can lead to unexpected outcomes. FRAM helps understand a system's ability to adapt to functional variability.

FRAM can have a retrospective emphasis, when used for accident analysis, or a prospective approach, when the objective is to model behaviours and interactions to identify and manage risks (Patriarca et al., 2020). In the context of risk assessment, it entails defining the assessment scope, identifying sources of variability, modelling functional interactions and resonance, and understanding performance variability to support monitoring and mitigation strategies (Hollnagel 2012).

FRAM method is widely used, especially in aviation for incident analysis (Patriarca 2020), but the methodology may also be applied in different areas of research, such as passenger road transportation (Cheberiachko et al. 2023), medical care (Kaya and Hocaoglu 2020), fires (Wang et al. 2023), floods (Togawa et al. 2023). In their literature review, Reiser et al. (2023) identified 11 aviation incident analyses using FRAM —73% conducted prospectively and 27% retrospectively. For example, Da Silva et al. (2023) performed a retrospective investigation of TAM Airbus A320 accident in 2007, while Tengiz and Unal (2023) examined prospective variations in ground operations within aviation. Additionally, Reiser et al. (2024) combined FRAM with flight monitoring data to explore and discuss key variabilities during aircraft landing procedures, enabling the identification of critical processes for targeted training.

FRAM method proposes a qualitative analysis, since the focus of the method, according to Hollnagel (2012), is the study of system variability and dynamics, rather than the calculation of probabilities per se. However, quantitative methods play a crucial role in risk analysis. For this reason, Macchi (2010) proposes an alternative methodology, using the Resilience Engineering approach, based on the analysis of dynamic interactions and adaptations, to quantify the variability of system performance.

Performance variability refers to the natural fluctuation in tasks execution within a system, influenced by factors such as environmental conditions, operating procedures, individual skills, and others. In Macchi's method, the output of a function is considered to have a direct impact on the performance of the subsequent function. The impact depends on variations that occur across the system and the operating conditions. This involves the ability to absorb or compensate for variability in performance, as well as the likelihood of coupling these variations, which can reinforce each other, exceeding the normal limits of a specific function, that results in what Hollnagel (2012) defines as functional resonance.

Macchi (2010) proposes a quantitative estimate of output variability, in terms of precision and timing, represented in Table 1. These numbers represent a quantification of the quality of the output provided by a given function.

3. Development

3.1. Case study

The eVTOL vehicle's CONOPS for this study was adapted from Fowler et al. (2024). Figure 1 illustrates the phases of a standard operation and operational profile shown in Table 2.

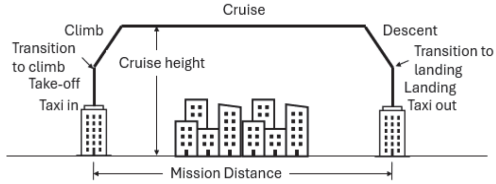

Figure 1: Standard concept of operation (adapted from Goyal et al. 2021)

Table 1: Output quality characterization (adapted from Macchi 2010)

		Timing		
		Too early	On time	Too late
Precision	Precise	**A:** Output is precise, but too early **+2**	**B:** Output is precise and with the right timing. **+3**	**C:** Output is precise, but too late **+1**
	Appropriate	**D:** Output is appropriate, but too early **+1**	**E:** Output is appropriate and with the right timing. **+2**	**F:** Output is appropriate, but too late **-1**
	Imprecise	**G:** Output is imprecise and too early **-1**	**H:** Output is imprecise, but in the right timing. **-2**	**I:** Output is imprecise and too late **-3**

Table 2: eVTOL Operational profile (adapted from Fowler et al. 2024)

Flight phase	Description
Taxi in	Preparation for takeoff, passenger boarding
Take-off	Climb with vertical thrust (hover)
Transition to climb	Transition point to horizontal thrust
Climb	Climb
Cruise	Flight at cruising altitude with horizontal thrust
Descent	Descent with horizontal thrust
Transition to landing	Transition point to vertical thrust
Landing	Vertical descent with vertical thrust
Taxi out	Aircraft stop, passenger disembarkation

Based on SAE ARP-4761A (2023), the high-level functions related to the eVTOL vehicle operation were defined and decomposed into low-level functions, with the aim of mapping the complex operation process, emphasizing operational safety. The high-level functions of the eVTOL vehicle are described below and the decomposition of the functions is presented in Figure 2.

- Aviate: Provide control of the aircraft in all axes, in flight and on the ground.
- Performance: Provide power thrust and range.
- Navigate: Provide navigation capability from origin to destination.
- Communicate: Provide external and internal communication.
- Cabin Environment: Provide a controlled environment and adequate accommodations.

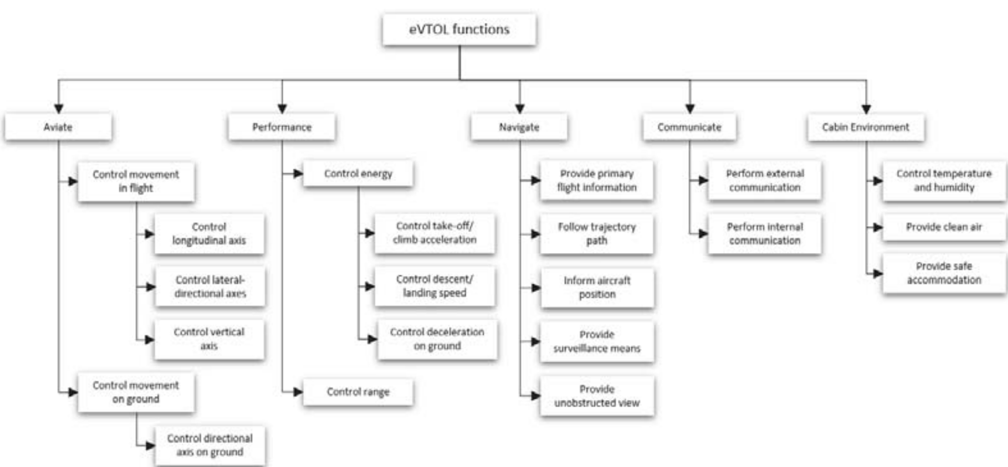

Figure 2: Decomposition of high-level functions of an eVTOL vehicle for standard operation

To delimit the study's scope, a specific scenario during vehicle descent was assessed. To carry out the descent operation and prepare for landing, the following functions are involved in the process:

- Control movement in flight.
- Control thrust, that can be composed of the following sequence of subfunctions:
    - Control forward thrust.
    - Provide thrust transition.
    - Control vertical thrust.
- Follow the trajectory path.
- Control descent/landing speed.
- Perform external communication.
- Perform air traffic control communication.

To support the functions listed above, background (supporting) functions provide the resources required for their execution:

- Provide electrical power
- Provide engine indications
- Provide primary flight information

For the purposes of this study, a hypothetical scenario was adapted from Royal Aeronautical Society publication (2024), in which landing clearance is issued late due to heavy air traffic and inaccurately as a result of communication errors. Such delays and inaccuracies may increase battery consumption and deplete energy reserves, potentially leading to a total loss of electrical power and, consequently, to the loss of propulsion and control of the vehicle.

3.2. Analysis

Regarding the nominal operation conditions (work as imagined), the descent-related functions associated with the hypothetical scenario were modelled and quantitatively analysed in FRAM, using the software FRAM Model Visualizer, version 2.2.0[a].

To quantitatively assess variability in the eVTOL approach and landing process under the hypothetical scenario, the methodology proposed by Macchi (2010) was employed. Variability was introduced in the output "clearance for landing" within the function "Perform air traffic control communication". The influence of this variability on subsequent functions was evaluated qualitatively, as the parameter serves as a temporal, control, or precondition variable for multiple functions. Based on the output quality characterization scale (Table 1) proposed by Macchi (2010), output variability was quantified sequentially throughout the model by computing mean of the variabilities provided as inputs to each function. The purpose of the numerical analysis is to obtain a final quantified measure of variability in the "Perform landing" function. This value is related to the dampening potential of the function, indicating whether the system absorb the variabilities (positive value) or if their interaction resulted in functional resonance (negative value).

It is important to emphasize that this numerical value is not related to probability calculation or failure rates of the elements involved in the process. Instead, it serves as an indicator of how the system responds to variability, determining whether it can absorb these fluctuations or if their interaction leads to systemic resonance. This distinction is vital, it ensures the results are interpreted from the standpoint of systemic resilience, focusing on the system's ability to sustain a safe operation.

3.3. Results

The descent-related functions modelled in FRAM is presented in Figure 3. The model considers the functions required to execute the descent operation and their interrelationships in a standard scenario.

To clarify the modelled descent and landing process, the following key aspects are illustrated: (a) the model initiates with descent operation and culminates in landing, represented by the function highlighted in green; (b) essential functions required for descent are marked in blue within the model; (c) supporting or background functions are indicated in yellow, illustrating their auxiliary role; and (d) external function related to communication with the air traffic entity is highlighted in red. The system variability is introduced through the external function "Communication with the air traffic", representing an external disturbance.

[a] Hollnagel, E., and R. Hill. 2016. *FRAM Model Visualizer (FMV), version 2.2.0*. Software. Functional Resonance Analysis Method. https://functionalresonance.com/the-fram-model-visualiser/

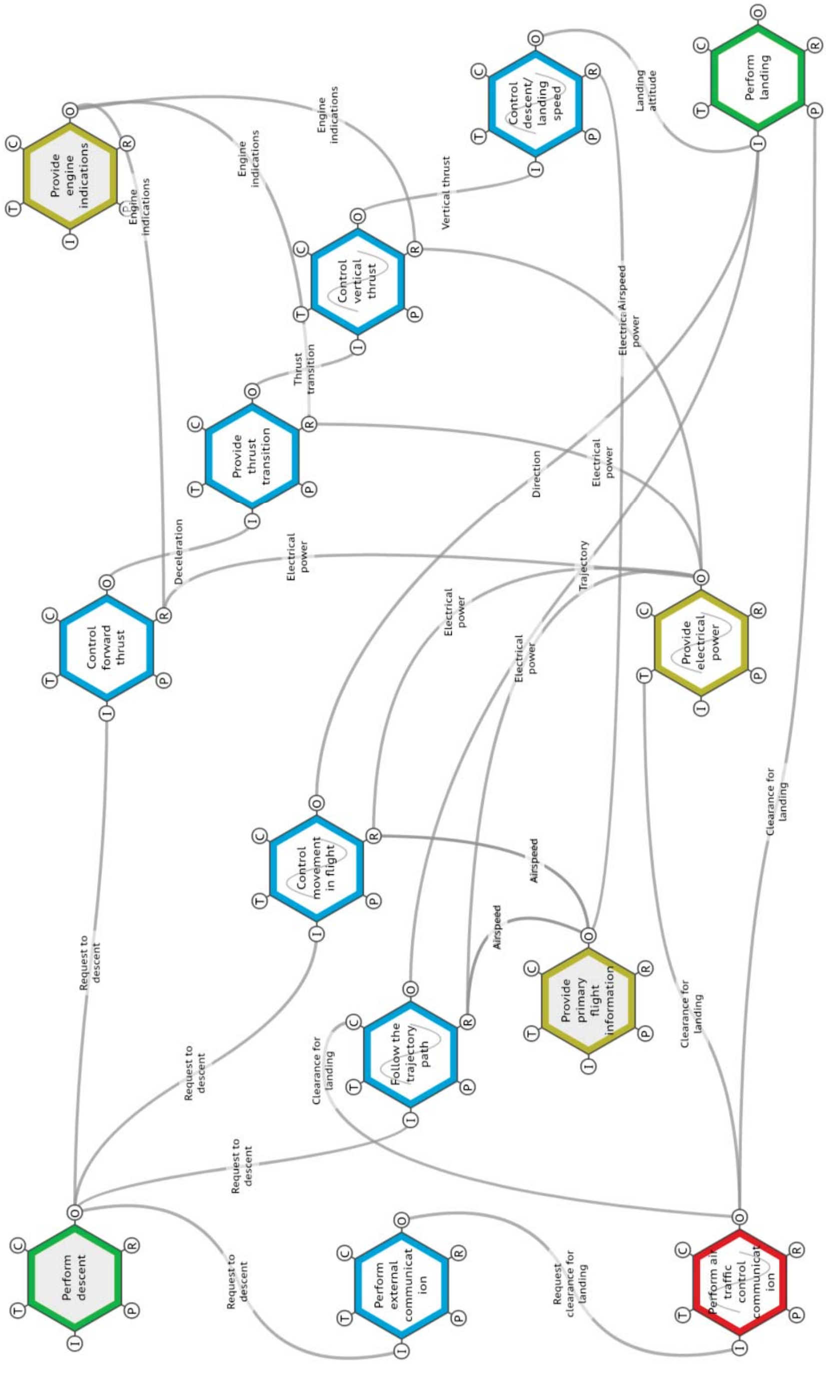

Figure 3: FRAM model for descent operation (Perform descent)

Regarding the hypothetical scenario described in Section 3.1, a variability in the output of the external function ‘Perform air traffic control communication’ was introduced into the FRAM model. The results indicate that the following functions are directly affected:

- Follow the trajectory path: “landing clearance” define a new trajectory path.
- Control descent/landing speed: “landing clearance” is a prerequisite for landing readiness.
- Provide electrical power: “landing clearance” influences the battery's available charge time, consequently affecting functions that require electrical power.

The output of these functions, in turn, is also subject to variability and propagates that variability to other functions within the system through their existing interrelationships. According to Hollnagel (2012), functions may compensate for or absorb such variabilities and can deliver unchanged outputs. However, in certain cases, couplings between the variabilities present in the functions can occur, resulting in unexpected or imprecise outcomes that cause a functional resonance effect.

In the analysis of the proposed scenario through the FRAM model, it is observed that the function “Provide electrical power” is directly affected by the output of the function “Perform air traffic control communication,” since this variability impacts battery endurance. According to FAA’s Special Federal Aviation Regulation (SFAR) for eVTOLs requires 20 minutes of reserved power for visual flight rules (VFR), and 30 minutes for instrument flight rules (IFR).

If the output delay in output remains within acceptable limits, the vehicle’s electrical system can absorb the variation without compromising, the landing. . Otherwise, in the worst-case scenario, prolonged hovering (the most energy-intensive phase of eVTOL flight) may lead to battery depletion, resulting in loss of power-dependent systems, such as engines, control surfaces and avionics, thereby jeopardizing landing, as illustrated by the hypothetical scenario in Royal Aeronautical Society publication (2024).

For quantitative analysis, the methodology proposed by Macchi (2010) was employed to evaluate the outcome of the “Perform landing” function. Variability was incorporated into the output of the “Perform air traffic control communication” function (clearance for landing), accounting for delay and inaccuracy.

Based on Table 1, a value was assigned to the output variability of the “Perform air traffic control communication” function. This variability was then propagated throughout the model according to the defined interrelationships. Furthermore, the variabilities of other functions were coupled, ultimately determining the outcome on the “Perform landing” function.

While Macchi (2010) originally suggests using the median to determine output variabilities, this study proposes the use of the arithmetic mean. This approach aims to increase the model’s sensitivity to all input fluctuations. ensuring that atypical or extreme observations (outliers), often critical in aviation safety, are fully reflected in the resilience indicator.

Quantification was performed sequentially for each function across the model, ultimately determining the outcome of the final “Perform landing” function. The summarized results of the quantitative analysis are presented in Table 3.

Analysis of the results highlights the quantitative impact of the “Perform air traffic control communication” output on subsequent functions. The negative outcome for “Perform landing” (-0.59) falls within the quality range F-G (see Table 1), indicating that the output may be either appropriate but too late or imprecise and too early.

In the hypothetical scenario, the landing clearance is issued too late; therefore, the outcome may be classified as quality F (appropriate but delayed). The results indicate a degraded performance of the “Perform landing” function. In the analysed scenario, this degradation may hinder the attainment of the required landing speed, potentially resulting in a hard landing.

To address the methodological choice of data aggregation, a sensitivity analysis was performed. While the original median-based approach (Machi, 2010) would yield a positive outcome (0.75), indicating variability absorption, in fact it filters out the critical outlier produced in the “Provide electrical power function”. Therefore, the arithmetic mean was deliberately selected to ensure that these “tail risks” are not disregarded. As an exploratory proposal, this approach provides a more conservative and robust indicator for high-risk scenarios.

According to Macchi (2010), high-quality inputs minimize downstream variability; whereas low-quality inputs demand significant local adjustments to sustain system performance. In this study, the output for 'Perform landing' was classified as quality F reflecting a critical accumulation of variability.

This result signifies a severely degraded landing performance, demonstrating that the cumulative functional variability can lead to systemic resonance and safety risks. Such findings highlight the importance of monitoring functional interdependencies to ensure the operational safety of eVTOLs in complex urban environments.

Table 3: Summary of quantitative analysis for the "Perform landing" function

Function	**Output**	**Timing**	**Precision**	**Aspect quality**	**Influence**
Perform air traffic control communication	Clearance for landing	Too late	Imprecise	I	-3
Perform descent	Request to descent	On time	Appropriate	E	2
Provide primary flight information	Altitude; Airspeed	On time	Precise	B	2
Provide engine indications	Engine indications	On time	Precise	B	2
Provide electrical power	Electrical power				-3
Follow the trajectory	Trajectory				-0.5
Control movement in flight	Direction				0.33
Control forward thrust	Deceleration				0.33
Provide thrust transition	Thrust transition				-0.22
Control vertical thrust	Vertical thrust				-0.41
Control descent/landing speed	Landing altitude				0.80
Perform landing					**-0.59**

4. Conclusion

This study applied the FRAM to explore how process variability in a descent operation of an eVTOL might impact the safe landing. The analysis of a hypothetical scenario, where a delay in the ATC communication forces the vehicle to extend the hovering, demonstrates how a single source of variability propagates through the functions, impacting critical power-dependant functions

The quantitative analysis followed the method proposed by Macchi (2010), but it was adapted, by using arithmetical mean instead medina, to ensure sensitivity to extreme fluctuations (outliers). This adaptation resulted in Quality "F" classification, indicating accumulation of variabilities, that exceeds the damping capability, leading to a state of systemic resonance and degraded performance on landing. Although this approach does not provide probabilistic failure rates, it offers an indicator of resilience that helps identify functional interdependencies, systems weaknesses and the need for mitigation measures, such as redundancy, segregation or barriers.

Despite of limited to a specific descent case, this research serves as a preliminary proof-of-concept for integrating systemic safety models into the project development, allowing for a better understanding of the system within its overall context. Future work should expand this framework to include other operational scenarios and expert validation to refine the model.

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