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Civilian Drones as an Exogenous Player on the Search and Rescue Teams Process. Case study analysis of the Rio Grande do Sul State flood using FRAM.

Henri François von Buren
PhD Student,Aeronautics Institute of Technology - ITA, São José dos Campos, Brazil
E-mail: *henri.buren.101754@ga.ita.br*

Moacyr Machado Cardoso Junior
PhD, Professor, Aeronautics Institute of Technology - ITA, São José dos Campos, Brazil
E-mail: *moacyr@ita.br*

Following the 2024 floods in Rio Grande do Sul, Brazil, civilian drone interference significantly hampered a critical search and rescue (SAR) operation despite a flight restriction zone established by the Department of Water Control Air Space (DECEA) and the Regional Body of the Southern region (CINDACTA II), ultimately requiring a complete flight ban. This study employs the Functional Resonance Analysis Method (FRAM) to model the regional SAR activation process and analyze the far-reaching consequences of this external disruption beyond the activities of advanced emergency teams on the ground. The analysis reveals impacts on planning, logistics, ground teams, and the entire chain of command. This research contributes to the development of disaster risk management and accident analysis, focusing on the need for firm control of civilian drone activity in emergencies. The research provides relevant lessons for high-performance organizations like the Brazilian Air Force (FAB), Navy, Army, Civil Defense, and Fire Department, integral to national disaster responses.

Keywords: search and rescue operations, FRAM, functional resonance analysis method, resilience engineering, disasters, complex sociotechnical system

1. Introduction

Approximately 3.6 billion people live in highly vulnerable contexts to climate change, according to the sixth assessment report by the Intergovernmental Panel on Climate Change (Lee and Romero, 2023). Climate change will increase the intensity and frequency of torrential rains and concomitant flooding in much of the world (Togawa et al., 2023). Upon examination of the characteristics of disasters in the state of Santa Catarina, sudden and gradual floods are suggested to be one of the main causes of emergency situations and states of public calamity in Brazil (Kobiyama, 2006).

In this context, it is relevant to bring the flooding of a large area of the state of Rio Grande do Sul (RGS), Brazil, in 2024, as a current link to a problem that dates back decades. The water that fills the basins of rivers such as Taquari, Caí, Jacuí, and Sinos flowed into the Guaíba River, which bathes the capital of the RGS, Porto Alegre and adjacent cities. The flood quickly devastated municipalities such as Guaíba, Eldorado do Sul, and Canoas, causing flooding in parts of Porto Alegre and forcing the evacuation of residents (Centeno, 2024).

2. Disasters

According to the Office of Disaster Risk Reduction of the United Nations, disasters are ”a severe disruption of the functioning of a community or a society on any scale due to hazardous events that interact with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic, and environmental losses and impacts” UNDRR (2017). The concept of a disaster is often associated with sudden evolution and high-intensity natural disasters (e.g., floods, hurricanes, and windstorms) that cause damage and losses to people, properties, and the environment. However, according to the Brazilian National Civil Defense Policy, disasters are defined as the result of an adverse event, of natural origin or induced by human action, in ecosystems and vulnerable populations that causes significant human, material or environmental damage and economic and social losses (Silva, 2023). Therefore, a particular event, such as intense rain, is called an adverse event and the effects of this unfavorable event can or cannot become a disaster, depending on their consequences. (Castro, 2005).

Flooding, commonly known as a flood, is the increase in the level of rivers beyond their normal flow that causes their waters to overflow into nearby areas. Most floods are caused by short-lived storms with high rainfall that move repeatedly over a given region (CAD, 2014). This article focuses on the threat posed by large-scale flooding.

Critical situations are situations whose risk characteristics require, in addition to immediate intervention by trained professionals with the appropriate equipment, a non-routine organizational position for the integrated management of response actions (Oliveira, 2009). Some examples of these situations are natural disasters that require evacuation of communities and floods. Responders can typically handle an emergency with established procedures and resources. In contrast, a critical situation requires a non-routine organizational stance and integrated management of response actions.This is because critical situations are generally high-risk, dynamic, complex, and confusing, as explained in Table 1. (Oliveira, 2009)

Table 1 :Risk in critical situations

Type	Characteristic
High risk	The possibility of undesirable results materializing is always great. High risk may represent injuries, deaths, homelessness, displacement, or damage to property or the environment.
Dynamics	Scenarios change very quickly, sometimes surprisingly, due to the complex interaction of climate, temperature, wind, light, and people's behavior.
Complex	Involve highly complex actions (technical rescues, spill control of dangerous products, evacuation of populations, triage and relief of multiple victims, police crisis management) and require the intervention of numerous organizations with differentiated responsibilities and jurisdictions.
Confusing	Limited information fragments the scenario, making difficult to understand the full scope. Communication breakdowns impede coordination among those involved, and command overloads further complicate the response. Often, stakeholders do not establish shared priorities and objectives, and available resources are not shared effectively.

2.1. *Drones applications in disaster relief*

Drones, generally known as unmanned aerial vehicles or UAVs, have become a valuable tool in disaster response, especially in the case of flooding, among other emergencies. They can perform aerial reconnaissance to assess damage, identify hazards, and provide real-time situational awareness to emergency responders. Their ability to hover over difficult-to-access areas enables them to locate potential victims efficiently, covering larger territories in shorter time frames than ground-based efforts (Abdellatif et al., 2024). This capability for rapid deployment and operational flexibility positions the UAV as a transformative asset in modern disaster management strategies. Emergency responders deploy drones with high-resolution imagery cameras and thermal imaging sensors for Search and Rescue - SAR operations to perform fast, efficient, and effective searches in vast areas of land.

Furthermore, in a case study of a rescue service over Croatian mountains, researchers observed that: ”Emergency operations are specific in that they are not planned activities, since the need for them occurs suddenly, and thus all procedures to enable safe flight of UAVs for emergency operations must be carried out as quickly as possible while maintaining the appropriate level of airspace safety” Biocic and Vuica (2019).

3. UAV in flood disaster scenarios

During flood events, in terms of situational awareness, the UAV can help emergency services get an ”eye-on” perspective of the operation and provide videos and images to the Incident Commander on the ground (EENA and DJI, 2016).

They assess the effects of flooding on infrastructure, people, assets and identify the gaps in existing emergency plans, including shelter locations and evacuation route. This information is essential in building priorities in emergency responses and strengthening coordination between SAR teams (Baisali, 2023). Equipped with integrated sensors, the UAV can collect mission-critical data that allow more efficient and timely SAR operations and greatly improve the possibility of finding survivors, thus reducing loss of life (Munawar and et al., 2021).

After a flood, UAVs provide important damage assessments through aerial images and useful data to inform the best deployment of rescuers and recovery resources; such data support the evaluation of the impact of flood on various aspects of affected areas and are crucial in the formulation of recovery strategies and the support of long-term disaster management efforts (Moussa and et al., 2024).

4. SAR operations in Brazilian context

4.1. *Civil defense*

The National Civil Defense Policy (Silva, 2023) defines civil defense and includes preventive, relief, assistance, and reconstructive actions to avoid or minimize disasters, preserve public morale, and restore social normality.

Among the primary functions of the municipal protection and civil defense body is to know and identify the risks of disasters in the municipality. This prior knowledge allows municipalities to prepare, using plans to face, prevent, and mitigate the risks of disasters and act in response and recovery from their effects, building cities with resilience, i.e., the capacity to resist, absorb, or recover efficiently from the impact of a disaster.

The complete description of the organizational framework for Civil Defense in Brazil can be found in the technical documents provided by the National Civil Defense Secretariat (Oliveira, 2009).

4.2. *Incident command system in operations*

The growing prevalence of unexpected situations presents a significant challenge to organizations, underscoring the need for robust incident management capabilities. An indispensable tool in disaster management is the Incident Command System - ICS, which defines a flexible operational structure capable of adapting to incidents of any magnitude or complexity, allowing its users to adopt an integrated organizational structure to meet the demands and complexities of a critical situation without compromising their competences and jurisdictional limits (FEMA, 2024).

The main functional areas of the ICS are the foundation on which an incident management organization is built (Table 2). These roles apply to incidents of all sizes and types, including planned events and those that occur without warning.

For this article, it was assumed that the ICS, based on the USCG standard and widely distributed throughout Brazil by the National Public Security Secretariat (SENASP), is the system in place for the SAR mission in RGS (USCG, 2024).

5. SAR operation context

5.1. *The immediate response stage*

As soon as the critical situation is perceived, a set of previously established measures must be implemented, starting with the activation of response organizations through their operational re-

Table 2: ICS Management Functions

Function	Description
Incident Command	Defines incident objectives, strategies, and priorities and is responsible for the incident.
Operations	Performs operations to achieve incident objectives. Establishes tactics and directs all operational resources.
Planning	This position supports the incident action planning process, tracking resources, collecting/analyzing information, and maintaining documentation.
Logistics	Organizes the resources and services necessary to achieve incident objectives (resources can include people, equipment, personnel, supplies, and facilities).
Finance/ Administration	Monitors costs related to the incident. Provides accounting, procurement, time recording, and cost analysis.

sources, so that they can travel to the location of the emergency and begin the initial work to assess and control the situation. Since affected areas are usually too large, aerial flood management has always been limited in origin, which means that drones can support disaster management at the local level (Restas, 2015).

5.2. *Brazilian Aeronautical Search and Rescue System*

Operating on 22 million km2, covering mainly the Atlantic Ocean and the Amazon, the Brazilian Aeronautical SAR System is structured to carry out SAR operations according to international and national standards. The DECEA Department of Airspace Control is responsible for planning and overseeing this activity with the purpose of locating aircraft or vessels in distress, rescuing accident victims, intercepting and escorting aircraft in an emergency. There are still coordination links (Rescue Coordination Centers) and execution links, consisting of Brazilian Air Force (FAB) units, the Navy, and other organizations that unite to carry out the SAR operations.

The work of the FAB in support of the rescue operation for those affected by the flood in RGS was intense. The missions have occurred since 04/30/2024 in the region of Santa Maria. During these days of operation, the number of daily air movements in Santa Maria increased by 60 percent since SAR aircraft alone totaled more than 70 movements (FAB, 2024). The Ministry of Defense reported deploying 32 helicopters in various missions, from SAR and aeromedical evacuations to troop transport and essential supplies logistics such as medicine, food, water, and generators. Air, land, and river operations rescued an estimated 25,000+ people (Centeno, 2024).

5.3. *The issue of civilian drones interference*

UAVs are becoming popular among hobbyists for entertainment purposes (Li et al., 2019). However, the recent development of small UAVs with integrated cameras and sensors suddenly allowed ordinary people to view the world from another perspective. Places that were difficult, expensive, and dangerous to reach now become easy and inexpensive for aerial work (photography, inspection, oversight, reconnaissance) (IEEE, 2024).

The reported issues where civilian operators have hampered the work of emergency services by getting in the way of rescue helicopters and fixed-wing aircraft were a major concern for the authorities. It turns out that many civilians flew drones to capture images in affected areas, significantly affecting the safety of the aircraft used in relief efforts. Institutions such as Firefighters and Military Police present in operations in the affected areas reported the risk of these aircraft flying over these locations.

On 05/04/2024, DECEA coordinated with the CINDACTA II Regional Body of the Southern Region of Brazil to impose a Flight Restriction

Zone (FRZ) due to operational needs in rain-affected areas of the RGS, requiring contingency planning and the development of complex scenarios to maintain air navigation safety. (DECEA, 2024). The action aimed to restrict drones that were not registered as Special Bodies for special air operations, as provided by the Aeronautics Command Instruction (DECEA, 2023).

This entire situation ends up generating specific problems that negatively impacted the management of operations. In this sense, the response of state and federal bodies reveals an organizational issue in the emergency plan that hinders effective action.

6. Resilience Engineering

Resilience engineering is a field that has evolved significantly over the past few decades, drawing on concepts from various disciplines, and has garnered attention as a model for emergency management in general (Hollnagel, 2019). In the context of disaster risk, resilience is: ”the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate, adapt, transform, and recover from the effects of an adverse event in a timely and efficient manner, including the preservation and restoration of its essential basic structures and functions through risk management” UNDRR (2024).

Resilience is defined according to Resilience Engineering as ”the intrinsic ability of a system to adjust its functioning prior to, during, or after changes and disturbances, so that it can sustain required operations under expected and unexpected conditions” Hollnagel (2011). This approach emphasizes four key capabilities for proactive management: responding, monitoring, learning, and anticipating. Monitoring allows real-time adjustments while responding to address immediate issues. Anticipation involves predicting future changes and preparing accordingly (Hollnagel, 2011). The concept of resilience engineering has a practical technique, the Functional Resonance Analysis Method (FRAM), designed explicitly for resilience engineering (Hollnagel, 2012).

6.1. *FRAM as a a tool for understanding system resilience*

”The purpose of the FRAM is to analyze activities – how something has happened, happens, or could happen – to represent the activity systematically using a well-defined format. The resulting representation constitutes a model of the activity, encapsulating its essential operational features” Hollnagel (2024). FRAM focuses on six key aspects of each function: Input - what it receives, Preconditions - what needs to be in place for it to work, Resources - what it needs to function, Time - time frame for its execution, Control - how it is monitored and adjusted, and Output - what it produces). FRAM creates a visual map that represents the entire system as a network of interconnected functions by analyzing how these aspects connect functions.

7. Using FRAM to model the SAR process for the RGS floods

This study proposes to analyze the existing emergency SAR system, based on the ICS framework, for the real-world example of a state flood in RGS using FRAM to model the SAR functions involved, their couplings and interactions. The fundamental features of FRAM are the necessary and sufficient functions to account for activity and the way in which functions are coupled or mutually dependent (Hollnagel, 2018). The first step was to identify, in the ICS framework, the core functions characterized by their six basic parameters (input, output, preconditions, resources, time, and control) and to indicate how they interact. The functions were separated, referring to the relative importance of a function in the model, into seven foreground functions, described in detail and displayed in hexagon type and five background functions in rectangle shape in Figure 1. ”The foreground functions denote that which is being analyzed or assessed, that is, the focus of the investigation [...] and the background functions constitute the context or working environment” (Hollnagel, 2012). In a second step, the study aimed to characterize the potential variability (context dependent) considering the normal variability and the worst-case scenario, using a checklist. The Excel add-on MyFram facilitated the initial identification of the twelve main functions involved in the SAR mission (Patriarca et al., 2017). It was possible to detail the expected interactions and variability in terms of time and precision for the model of a regular SAR operation. A completeness check confirmed the model consistency; therefore, it was possible to export the file to the FRAM Model Visualizer (FMV) for graphic visualization exhibit in Fig.1 (Zerprize, 2024). The third step was to define the functional resonance based on possible dependencies (couplings) between the core functions. By examining these interactions, FRAM helps identify potential weaknesses and suggests corrective actions. The next step was to perform an instantiation of the previously generated model, which was achieved by inserting a civilian drone function into the operating space. Then the FRAM was used to analyze how the activity of the civilian drone as an exogenous player could disturb (or resonate with) other parts of the ICS system. The main assumption was to consider all different organizations bodies involved in the SAR operation as one single entity under one unified incident command control as proposed by the ICS framework. This analysis was intended to determine whether the system in place during emergencies can adapt effectively to disruptions or if these variations might lead to failure of the structure deployed by Brazilian agencies. The uncertainty of the model lies on the ICS process, that allows officers at any rank from any agency to come together and develop priorities, objectives, and plans to manage an incident. The coordination of diverse teams without compromising their individual authorities is not a simple task and subject to several shortcomings and constraints such as limited training for sufficient numbers of personnel. In the graphical rendering, it was possible to see the functional resonance throughout the model after the introduction of this minor change in the initial conditions. The addition of a new function altered the regular functioning of the SAR mission; as a result, there was a delay in the essential parts of the system, as seen in Figure 1. It was revealed that civilian drone activity interfered with the control part of another function, namely the 'To activate Air Operations Sector" and affecting its precision. In addition, its presence affected the ability to react in time for many characteristics, namely "To deploy Operations" and "To activate Rescue group", resulting in variability (delays) in the effectiveness of the SAR response. The use of a civilian drone inside the SAR area of the RGS mission affected the model from the initial risk identification phase through the activations of the air operations sector and the rescue group. This demonstrated impact on the whole system revealed by FRAM justifies the Brazilian authorities' decision to create a zone of exclusion for civilian drones, as they interfere with SAR activities (DECEA, 2024).

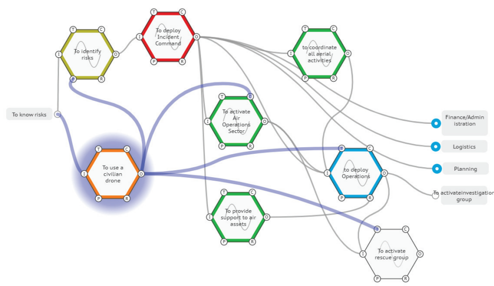

Fig. 1. Instantiation of the model with a new function: civilian drone operation

As seen in the instantiation, since the first function "to know the risks," the process is affected since taking into account the function "to use a civilian drone" was a precondition necessary to perform the function "to identify risks." Without this information, the Incident Commander could not correctly address the function "to activate Air Operations sector", and the cascading effect of the function "to deploy operation" is pronounced and reveals the resonance throughout the system. As seen in the graphic view, the presence of the civilian drone activity directly affects the time needed to deploy the function "to activate the Rescue group." This justifies the intervention of the authorities, which created an NFZ and grounded civilian drones until the end of the SAR operation (DECEA, 2023). The last step in FRAM analysis, that is, identifying the possibilities of damping variability (functional or structural barriers), was not covered in this article.

8. Challenges and Limitations

FRAM is particularly adept at identifying specific functions and their potential implementation variations. However, in this study, the decision to use the ICS framework as a structure during the SAR for the flood event in RGS might have limited the ability to capture the full extent of these variations in practice and some challenges were not addressed by the modeling. The use of drones in SAR operations during flood disasters is subject to several technological constraints that challenge their effectiveness, such as the limited range of UAVs, which can affect the total area covered, particularly in regions with poor signal coverage and adverse weather conditions, such as rain and high winds, which can make UAV operations unsafe or ineffective, affecting the timely acquisition of necessary data. In addition, UAVs can struggle with limited access to certain areas that exhibit low visibility or signal interference, further complicating disaster response efforts. The improvement of coordination and communication flows was reported as a challenge for the overall effectiveness of SAR missions, particularly in scenarios involving interorganizational communication marked by diverse terminology, styles, protocols, and UAVs (Steen et al., 2024).

9. Conclusion

The unwanted and unforeseen presence of civilian drones during a complex SAR operation resulted in a resonance within the entire system. Given the tightly coupled structure of the ICS, changes in situational conditions impact the operational design of the system and can jeopardize its effectiveness. Although this analysis focused specifically on a flood event, the FRAM can be used to model other crisis response operations in complex sociotechnical systems due to its functional approach. This research contributes to the literature on crisis management by showcasing FRAM as a method to analyze SAR in disaster response. Further studies may reveal the deepening influence of UAVs unwanted action on downstream functions following the function ”to activate rescue group.”

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