Failsafe Mechanism to Hazard Analysis and Risk mitigation in Unmanned Aerial Vehicle based on NCES

Mohamed Naija, Rihab Khemiri, Ernesto Expósito

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Univ Pau & Pays Adour, E2S UPPA, LIUPPA, Anglet, France
{naija.mohamed, rihab.khemiri, ernesto.exposito}@univ-pau.fr

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Abstract: In the last few years, Unmanned Aerial Vehicles (UAVs) are receiving more focus in order to execute a wide variety of applications such as the military, agriculture and medical fields. It is known the high vulnerability of the UAV not only to unexpected faults of their software but also to the environment. For this reason, safety should be considered as the main requirement at design time, since any unexpected behavior of the vehicle or any hazard would lead to potential risks. To maintain their safe operation during their missions, a failsafe mechanism based on Net Condition Event System (NCES) is proposed. The failsafe mechanism is a control logic that guides risk reduction actions to be performed when hazards occur. To generate such a controller using formal models, the proposed process is decomposed into three phases: (1) the first phase consists on hazard identification and analysis according to reactive methods of literature, (2) the second phase allows risk estimation using the standard ISO 13849, and (3) the third phase consists of performing reconfiguration scenario in order to risk mitigation while analyzing safety requirements. The motivation behind the use of formal methods is that they have proven to be useful for making the development process reliable at early design stages. We demonstrate the applicability and feasibility of our proposal on an illustrative medical drone as a case study.

1 INTRODUCTION

Air Transportation System has become the most important sectors in the global transportation system. Unmanned Aerial Vehicles (UAVs), *aka* drones, have been encountered a significant focus to be used in transportation purposes in smart cities in order to reduce costs and increase delivery efficiency. The popularity of Unmanned Aerial Vehicles is confirmed by the Federal Aviation Administration, which expects that the number of drone's users will increase from 1.1 million in 2016 to 3.55 million in 2021 (Atkinson, 2018). The UAVs are considered high-assurance since errors during execution could result in great damage, injury, and loss of life (Zhang et al., 2009). We emphasize that more than 4,889 incidents have been reported between 2014 and 2017. Therefore, a stronger form of verification is likely to be needed to ensure the correctness of the system and provide sufficient evidence for safety certification.

Safety can be defined as a "*state in which the system is not in danger or at risk, free of injuries or losses*" (Sanz et al., 2015). Because nothing is totally safe and there is no situation where no risk can occur, safety is also defined as the absence of unacceptable risks (Allouch et al., 2019). Since UAVs are highly interconnected and prone to external disruptions, the vehicle must be able to detect and evaluate hazards along with their consequences in order to apply the necessary measures for reducing the risk to an acceptable level and ensuring resilience. Consequently, a failsafe mechanism that controls all the components of the system and ensuring safe operations despite the presence of faults is needed.

At present, the failsafe mechanism design for drones is seldom investigated (Dong et al., 2019). In this paper, we propose a new failsafe mechanism allowing safety assessment for UAVs at an early design stage. Our proposal consists of hazard identification and analysis. Based on this analysis, we estimated the required Performance Level (PLr) needed to manage the failure in a safe way. For this purpose, we use the risk graph of Standard ISO 13849. Finally, the controller makes a decision on the recovery mode to perform. So, we apply reconfiguration-based risk reduction. The reconfiguration scenarios consist of switching from an initial mode to a recovery mode and modify the software configuration to ensure resilience, using formal models.

Model-checking offers an attractive approach to automatically analyzing models for adherence to safety properties (such as efficiency, reliability, robustness, stability, and vivacity). In particular, we use the Net Condition Event System (NCES) (Rausch and Hanisch, 1995) formalism, which is modular with extra condition/event signals and can be verified using the model checking (Li et al., 2013) and the model checker SESA (Vyatkin, 2007). Moreover, the hierarchical composition of the NCES component allows reducing the size and complexity of the nets (Vyatkin, 2007) (Li et al., 2013).

Compared with current failsafe mechanisms, our approach has three main advantages which are correct by design, compact and modular. This has been well presented in the application of a medical drone crash scenario.

The rest of this paper is organized as follows. We propose a background of the NCES formalism in Section II, in section III, related work to drone's safety is discussed. After introducing the UAV model in Section IV, Section V presents our failsafe mechanism based on three phases, Section VI shows that our approach can be effectively applied to a case study. Section VII concludes the paper and sketches some future work.

2 BACKGROUND

This section presents the basics of the Net Condition Event Systems (NCES) formalism, which will be useful for describing our proposal.

Net Condition/Event Systems is an extension class of Petri nets. It consists of modules whose dynamic behavior is modeled by means of Petri nets. This formal concept was introduced in (Rausch and Hanisch, 1995) according to which a hierarchical NCES component is a Place-Transition Net described by the following tuple:

$$NCES = \{P, T, F, M_O, \Psi , CN, EN\} \quad (1)$$

where:

- P : is an ordered set of n places p;
- T : is an ordered set of m transitions t;
- F : is the incidence matrix;
- M_O : is the initial marking;
- Ψ : is the input/output structure;
- CN $\subseteq (P \times T)$ is a set of condition signals;
- EN:$\subseteq(T\times T)$ is a set of event signals.

The semantics of NCES are defined by the firing rules of transitions (Khalgui, 2010). There are several conditions to be respected to enable a transition to fire. First, as it is in ordinary Petri nets, an enabled transition has to have a token concession. That means that all pre-places have to be marked with at least one token. Furthermore, a transition in NCES may have incoming condition arcs from places and event arcs from other transitions. A transition is enabled by condition signals if all source places of the condition signals are marked by at least one token. The other type of influence on the firing can be described by event signals which come to the transition from some other transitions. Transitions are spontaneous if there are no incoming event arcs to the transition, otherwise they are considered as forced. A forced transition is enabled if it has token concession and it is enabled by condition and event signals.

In regards to the formal verification engine, the model checker SESA (Vyatkin, 2007) allows an automatic validation of NCES models of components by checking functional and non-functional requirements. So, SESA allows performing analysis of typical properties such as (i) the liveness of transitions, (ii) boundedness of places of the net, and (iii) the reachability graph of the net. Other safety property can be specified using the computation tree logic (CTL) (Clarke et al., 1986) and verified by the model checker SESA.

3 RELATED WORK

Due to the current lack of international standards, tools, and guidelines that govern the design and safety certification of drones, many approaches have been proposed in the literature for safety assessment and fault tolerance in UAVs from high-level models.

In (Mhenni et al., 2016), authors have benefited from UAV case study to design a framework called *SafeSysE*, which allows the automatic generation of safety artefacts. They combine Model-Based Systems Engineering (MBSE) and Model-Based Safety Analysis (MBSA) to provide safety assessment by integrating Failure Mode (FM), Effects Analysis (EA) and Fault Tree Analysis (FTA) for safety checking. Nevertheless, this process is not fully prototyped and has not been tested in real scenarios.

In the same vein, (Sankararaman, 2017) have presented a framework for identifying and predicting the occurrence of a simple case of hazards (i.e. battery discharging and collision) that can affect drones at runtime. Unlike this approach, our contribution studies various risk factors and hazards that affect the dynamic operation of drones.

In (Neff and Garman, 2016), the authors turn on the identification of errors and hazards in Unmanned Aerial Vehicles related to human factors, which are inevitable mistakes. In addition, the proposed mitigation techniques cannot be applied to software.

Other efforts have been specifically based on using ISO standards for safety analysis. Sang et al.

(Sanz et al., 2015) present an iterative approach including identification, assessment and reduction procedures to find sources of hazards when using UAVs in performing agricultural missions. Unfortunately, the paper does not provide a full description of the validation test, which is an ad-hoc test.

In (Allouch et al., 2019), the authors propose a functional safety methodology for Unmanned Aerial Vehicles operations by using both ISO 13849 and ISO 12100 standards. The paper present two-approach for qualitative and quantitative risk analysis and safety assessment. The proposed methodology starts with hazard identification and risk assessment to safety analysis with probabilistic modeling without proposing solutions for fault tolerance.

In (Dong et al., 2019) a failsafe mechanism design for autonomous aerial refueling is devoted. The authors use the State Tree Structures (STS) to risk analysis and mitigation at design time. A supervisor is synthesized to cover common system failures and interaction among receivers, tankers and pilots. The design procedures presented in this work deals only with command conflicts that lead to dangerous maneuvers.

4 UAV MODEL

In what follows, we present the architecture of the UAV system, we explain the flight modes and we state the UAV system limits.

4.1 System Architecture

The drone system is decomposed into three modules that are responsible of running specific tasks and algorithms with respect to hardware and timing constraints. Each module unit can repeat a variety of algorithms in a constant frequency for performing their task, as detailed below:

- **Localization unit**: The UAV is able to localize its operating environment and itself accurately using sensory input (such as a monocular camera, IMU, and GPS). Localization information is then transferred to the Perception unit.
- **Perception unit**: Received data are used by the obstacle detection algorithm to build the Vision-based Navigation Guidance. Based on this navigation model, a guidance algorithm is executed to determine the flight path. Finally, accurate commands are sent to the motion control system of the drone.
- **Control unit**: On this level, reference data for the flight stability and waypoint tracking manoeuvres are computed and converted to applicable variables.

4.2 Flight Modes

The communication between the ground control station and the unmanned aerial systems is necessary to ensure the functioning of the system. They typically communicate through a wireless connection and exchange a set of messages using the Micro Air Vehicle Link (MAVLink) protocol (Koubâa et al., 2019). To ensure the safety of the drones, it is crucial to study flight modes that were supported by the MAVLink protocol:

- **The STABILIZE mode**: This mode allows controlling the drone manually through the RC controller. When the autopilot becomes unable to control the vehicle system in any other mode, it is highly recommended to switch to this mode.
- **ALTITUDE HOLD:** this mode is considered the most comfortable one to control the vehicle. In this mode, the user does not have to take care of maintaining a fixed altitude for the unmanned system, since the autopilot will be in charge of controlling the altitude automatically. The user will be responsible for manually controlling the position of the unmanned system and the direction. In this mode, we do not need a GPS, since the altitude is estimated using the barometer. It has to be noted that this mode is more suitable for beginners than the STABILIZE mode.
- **LOITER**: The LOITER mode is very similar to the STABILIZE mode, but it will have to take care of maintaining orientation, altitude and current location of the unmanned system if the user does not make inputs to the RC controller. To maintain the position, this mode needs a GPS 3D or optical flow. In this mode, high performance is related to some factors (i.e. low vibration, low magnetic interference of the compass and GPS Lock).
- **LAND**: This mode allows the unmanned aerial system to land to the ground.
- **RTL (Return-To-Launch)**: This mode strength the drone to return to the home position and land to the ground. It has to be noted that the LAND and RTL mode are

adapted in the case of geofence and violation of navigation safety.

- **GUIDE**: In this mode, the drone is guided to autonomously navigate to a specific location chosen by the user and defined by the GPS coordinates. The GUIDED mode only works with GPS mode. Indeed, when the GPS performs a 3D fix and is activated, the drone may be sent to navigate autonomously to a specific ground station defined by the GPS coordinates. In this context, a ground station is usually exploited to send navigation waypoints to the unmanned aerial systems to autonomously navigate to it.
- **AUTO**: it's the autonomous mode where the drone will follow a preprogrammed mission, consisting of a set of waypoints. If the AUTO mode is activated, the drone will autonomously navigate to each waypoint.

4.3 System Limits

This subsection summarizes the limits of the drone system so as to evaluate their possible consequence later. They are the list of failures that should be taken into the inherent activities in the design phase of a UAV system. According to (Sang et al., 2015), the drone's limits are divided into four categories depending on their nature. The description of each category is shown in Table 1 through concrete examples.

Table 1: The limits of UAV according to their nature.

Nature	Description
Physical	Maximum payload, maximum kinetic energy and maximum speed
Temporal	Maximum time of flight, response time, engines life time and battery degradation
Behavioral	Minimum distance to the operator, sensing capacities of the vehicle and procedures of piloting
Environmental	Weather conditions, minimum distance from populated areas, GPS coverage and communication degradation.

5 RECONFIGURABLE FAILSAFE MECHANISM

In this paper, we address the problem of safety in Unmanned Aerial Vehicles based on reconfiguration as a recovery technique. The proposed failsafe mechanism (refer to Figure 1) is divided into three-step allowing the analysis of safety requirements at an early design stage. Since the first step consists of detection and analysis of hazards according to their sources, the second step implies estimating the performance level required to risk reduction using the international standard ISO 13849. Finally, the third step include risk mitigation via a reconfiguration scenario, which allows avoiding a potential breakdown and accident during the drone's mission.

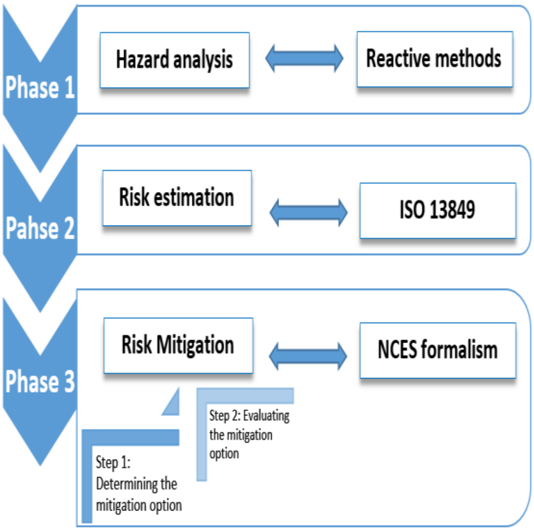

Figure 1. Overview of the proposed process.

We use the NCES formalism to represent three types of modules (*i*) a Listener module that takes into account the hazard analysis step, (*ii*) a Coordinator module able to evaluate the risk and the inherent decision-making process and (*iii*) Modes modules representing the normal behavior together with the potential failure behavior. Each module is achieved by algorithms that sustain the functionalities of the specified entity and interact with the hardware to perform its role. Formally, each NCES component is modeled with three transitions, which allows receiving data from the sensory input, running a specific algorithm corresponding to the received data and activating the corresponding modules.

In what follows, we detail the three phases of the proposed approach.

5.1 Phase 1: Hazard Analysis

The first step of our proposal consists of hazard identification and analysis. For this purpose, we implement an NCES component, called Listener, that oversees the system and detect errors at run-time. When running the Listener module uses a list of potential UAV errors according to their sources as a checklist (see Table 2) during hazard identification. This list is prepared from the US Federal Aviation Authority (FAA), the NASA's Aviation Safety Reporting System (ASRS) and the European Aviation Safety Agency (EASA). Once identified the candidate hazard, the Listener sends an event signal to the control module that is responsible for the drone mission achievement. In this paper, we assume that only one fault can occur at the same time in the system.

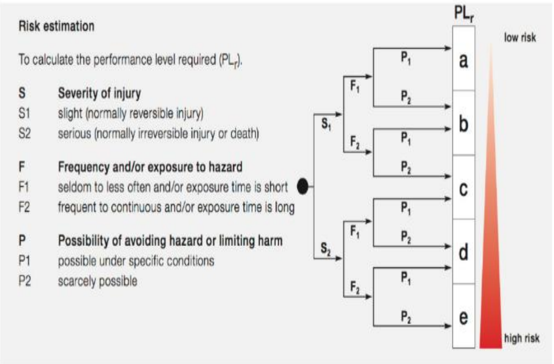
Risk estimation
To calculate the performance level required (PL_r).
S Severity of injury
S1 slight (normally reversible injury)
S2 serious (normally irreversible injury or death)
F Frequency and/or exposure to hazard
F1 seldom to less often and/or exposure time is short
F2 frequent to continuous and/or exposure time is long
P Possibility of avoiding hazard or limiting harm
P1 possible under specific conditions
P2 scarcely possible
PL_r
low risk
S_1
S_2
F_1
F_2
F_1
F_2
P_1
P_2
P_1
P_2
P_1
P_2
P_1
P_2
a
b
c
d
e
high risk

Figure 2. Risk Graph for Evaluation of the PLr according to ISO 13849.

Table 2: List of Hazards.

Source	Type
External	Environmental conditions
	Radiation
	Aerodynamics
	Obstacles
	Networking
	Human element
Internal	Software error
	Hardware error
	Flight control
	Mechanical
	Power supply breakdowns
	Electronic
	Thermal

5.2 Phase 2: Risk Estimation

At this level, the risk must be estimated to specify the ability of the UAV to achieve a recovery function under predictable conditions. For this purpose, we define an NCES component, called Coordinator, which refers to the Standard ISO 13849 to determine the required Performance Level (PLr).

In this sense, risk estimation is a function of three factors: (1) severity of possible injury or the damage to health (S), (2) frequency of exposure to hazard (F) and (3) the possibility of avoiding the hazard (P). These three parameters take into account both quantity and quality aspects of each hazard:

- *Severity (S)*: This parameter is a key factor in determining the seriousness of the hazard. The severity rate is equal to S2 if the hazard induces high injury or death. Otherwise, the rate of severity is equal to S1.
- *Frequency (F)*: This parameter reflects the exposition time of the UAV to the hazard. The exposition value is evaluated as an F2 if the UAV is continuously exposed to the hazard. Else, the frequency value is estimated as an F1.
- *Possibility (P)*: It is the ability to avoid/limit the injury/harm when a hazardous situation occurs. The probability of avoiding such damage can be represented by P2 if there is no chance of avoiding the hazard. Alternatively, the probability value is P1.

The relation between the parameters described above estimates the PLr to manage the hazard using a risk graph. As depicted in Figure 2, the Performance Level is classified at five grade ranging from the low level 'a' to the higher-level 'e'.

5.3 Phase 3: Risk Mitigation

The Coordinator entity tries to manage the residual risk and keep the system in a safe state. The undertaken measures by this making-decision entity are at the level of switching from an initial mode to a recovery mode via a reconfiguration scenario. For this, two steps are necessary.

5.3.1 Determining the mitigation option

The coordinator's role is to choose the target configuration that keeps the system in a safe state. However, the coordinator will decide on the operating mode that can allow the autonomous vehicle's mission to be achieved as much as possible or to stop the mission, if necessary. This step is very delicate because an inaccurate decision can lead to catastrophic situations and injury. Based on the PLr estimation, we define a decision graph guarantying a sufficient safety level when hazards occurs, as shown in Figure 3. It is important to note that the NCES coordinator-module encapsulates the implemented algorithm that supports the functionalities of the decision graph when applying reconfiguration.

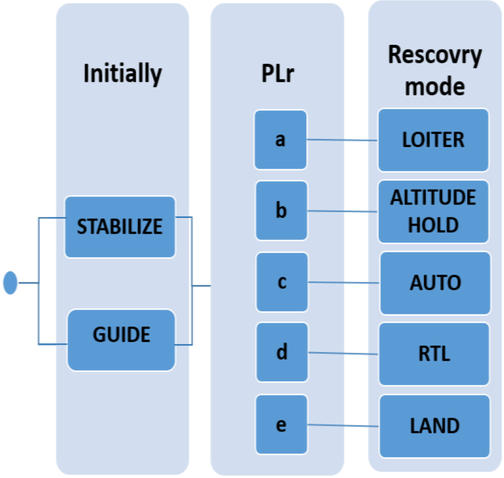

Figure 3. Decision Graph for risk mitigation.

Initially, the UAV can run either in manual mode (i.g. Stabilize mode) or in AUTO mode, depending on user preferences. When a failure is detected, and after an estimate of the risk, the coordinator switches from the initial mode to a recovery mode depending on the the required PL for managing hazard. For example, if the Plr is at level 'e', the decision made by the coordinator is to stop the mission and nail the vehicle to the ground by switching to LAND mode. If the PLr is estimated at level 'a', the LOITER mode will be selected that allows accomplishing the mission.

5.3.2 Evaluating the mitigation option

In this step of the process of risk reduction, we verify that the decision of switching behavior does not lead to an inconsistent state or cause any damage to the system, i.e., safety requirement.

To this end, it is important to specify all possible configurations that represent all modes of a system, the Listener module and the Coordinator module. Then, additional information describing the switching modes and limiting changes must be specified using event signals and condition arcs. The source and target operating modes should not include information about each other or about reconfiguration.

As soon as the NCES systems model is available, the safety requirement can be checked. As already mentioned, the advantage of NCES-based models is that offers an effective and optimal solution to make the verification process easier with a low complexity (Zhang et al., 2013) (Naija and Ahmed, 2016). The safety of an UAV requires the correctness of each configuration and also of the reconfiguration scenarios. Thus, the verified properties are (*i*) Liveness of the net by checking that all modes are achievable, (*ii*) Deadlock cannot occur by verifying boundedness of all places of the network and (*iii*) Stability of the network, that can be proved with the generation of the reachability graph with finite state of the system. The reconfiguration is applied only if these properties are well-checked.

6 CASE STUDY

To better explain our contribution, a medical drone use case is used to validate the advantages and effectiveness of our proposal, since the medical drone service has become an emerging topic in a smart city. The vehicle's services are revolutionizing the way time-critical medical supplies are delivered to patients who require immediate medical attention. Medical drones are considered as a complex and high-assurance system.

We consider the scenario of an UAV that goes from pickup to drop-off in an urban city and fly at an altitude of fewer than 150 meters through the GUIDE mode. The control station is able to assign missions to the UAV in real-time or modify the initial mission by adding waypoints as required to reach victims within minutes. In this work, the UAV has embedded Wi-Fi and Bluetooth interfaces. We also assume that the physical properties such as vehicle's speed and safety distance varies according to the operating mode and final user's requirements. The communication link with the ground station is assured through a 4G connection using the MAVLink protocol.

6.1 Phase 1: Hazard Analysis

The UAV starts the mission into the GUIDE mode, which is characterized by a stable communication with the ground station. During run-time, the Listener module detects a packet loss due to communication degradation (i.e. firing the transition source *t_entrance* of the Listener module in Figure 4). Therefore, to analyze this hazard an algorithm is executed (i.e. firing the transition *t_start).* After identifying the nature external of the hazard and the type as a Network, an event signal is sent to the Coordinator module. We emphasize that the only role of the Listener is the continuous control of the system for hazard detection and identification.

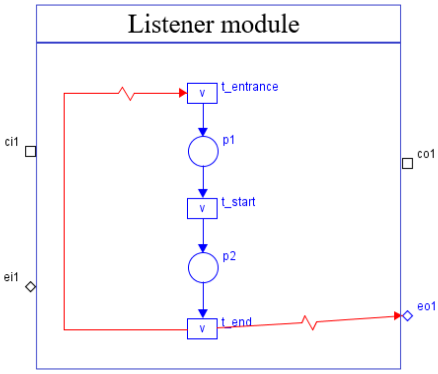

Figure 4. The Listener module.

6.2 Phase 2: Risk Estimation

Once the event signal is received, the Coordinator module evaluates the Hazard in order to estimate the required performance level based on the ISO 13849 risk graph. The communication degradation hazard can lead to the interruption of the mission. So, the severity (S) of the communication hazard is estimated (S1). Generally, this type of breakdown is persistent and leaves the vehicle exposed to risk for a long time (F2). In addition, it is impossible to avoid this hazard because it is due to a loss of signal or a connection problem. So, the possibility of avoiding hazard (P) corresponds to (P2). It is then easy to deduct the level '*c*' of the needed PLr, using risk graph.

6.3 Phase 3: Risk Mitigation

In the first step, the Coordinator module that is responsible for decision-making determines the recovery mode regarding the required performance level. Using the proposed decision graph, the system will switch into the AUTO mode that allows accomplishing the mission without the station's instruction need. After determining the mitigation option, the second step consists of checking some safety requirements before applying the failsafe function. This safety analysis allows for increasing the level of confidence and validating that the switching modes do not affect the proper functioning of the system. Formally, we specify in Figure 5 the Listener module that supervises the system, the Coordinator module which is the decision-making entity and the source mode together with the recovery mode. When hazard occurs, the Coordinator receive an event signal from the Listener module through the input port *ei2*. After executing the evaluating algorithm, the Coordinator, through a condition signal, stop the STABILIZE mode and trigger the recovery mode (i.e. the AUTO mode in this case) via the output port *co2* and *co3* respectively. This formal model is then verified using the SESA tool. As part of safety analysis, we successfully verify the functional properties such as the vivacity of the net, boundedness of places and generate the reachability graph. This analysis result allows proving correctness, consistency, and stability, of the model-based system.

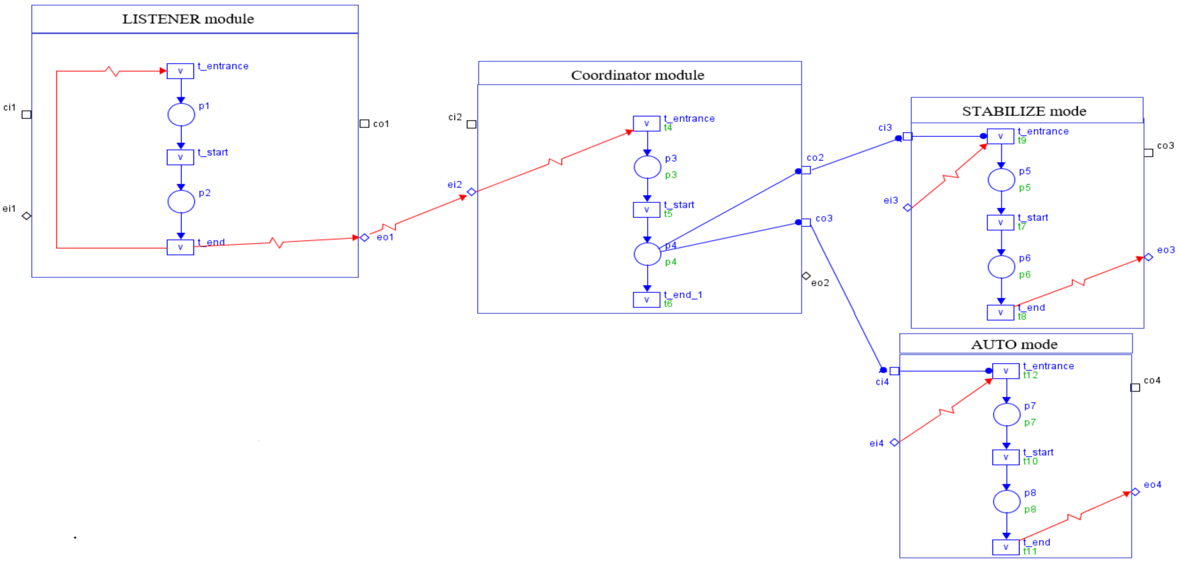

Figure 5. NCES component based-model of the UAV.

7 CONCLUSIONS

In this paper, we propose a failsafe mechanism to hazard analysis and risk mitigation in Unmanned Aerial Vehicles. The proposed mechanism starts on identifying and analyzing hazards according to a defined list. Therefore, the required Performance Level for ensuring safety is estimated according to the standard ISO 13849. Finally, a risk mitigation technique is defined allowing vehicles to avoid damage and remain secure and controllable. This three-step mechanism provides an iterative manner in defining the logic control system, which achieves less ambiguity and more consistency compared with classical works. Medical drone's example was given to illustrate the feasibility and correctness of the proposed mechanism.

In the future, we will implement an artificial intelligence model based on the BDI style architecture to allow supervising and monitoring of the reconfiguration of vehicles during their mission. In addition, we will investigating how to incorporate machine learning in order to improve the risk mitigation phase.

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