From Modelling to Performance Prediction

Asynchronous Connection of SPAD Federation of Models to RPAS Simulator

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***Abstract*— This paper presents a modeling approach for analysing consequences of automation degradation in the context of large socio-technical systems. This modeling approach involves two different notations: FRAM [6] and HAMSTERS [2] and [8]. In previous work [7] we have proposed a synergistic approach integrating these two views for describing the evolution of system performances under automation degradation. The focus of the paper is on how such modeling approach (and thus the models) can be connected to system behavior either it being represented by a specific model (ICOs [9]) or a simulator. After describing the principles of such integration we exemplify it on an RPAS case study. More precisely we present how this federation of models can be connected to a standalone ATM simulator and how specific extensions can support models integration.**

Keywords-component; Automation degradation, resilience, performance, ATC, RPAS

I. INTRODUCTION

The SESAR initiative intends to deal with the increase of traffic demand and the new business challenges that the ATM system will have to afford in the coming future. The increase of automation is one of the basic elements of all the solutions identified by SESAR to deal with such problems. Automation will support, and in some long term cases even completely replace human tasks, in order to meet the new capacity and efficiency needs. Human operators will be able in this way to manage a higher number of tasks and will shift toward more strategic roles and supervision activities. SESAR projects are validating tools and new operating procedures supporting controllers in conflict detection and resolution, as well as higher levels of automation for data gathering and management.

However, automation brings a range of new challenges including those related to possible degradations. In particular, high levels of automation imply low system flexibility. A system which has been carefully planned, and thus standardized and automated, is hardly able to deal with non-standard and unplanned events such as those caused by technical failures. In addition, the components of a highly automated system are usually tightly interconnected. The consolidation programme of the ATM architecture will lead to fewer and fewer control centres through Europe. Contribution to this increased interconnection will also come from the new gate-to-gate solutions, from the implementation of the SWIM architecture with less information asymmetries, and also from the tighter links among all the stakeholders needed to offer a coherent and homogeneous service and interoperability. Increased coupling may make harder to identify and isolate failures when they occur, and to detect minor malfunctions before they propagate to the whole system. Then, coupling and lack of flexibility can bring to a higher sensitivity of the ATM system to degradation problems.

Current models that support safety evaluation focus on systems before operation or on post-accident analysis. These models consider possible deviations, malfunctions, errors, or "after the fact" information. Even if these models have been very successful in the past and contributed to the very good safety achievements of the ATM system, they risk to be less adequate in a highly dynamic, and coupled system, that adapt dynamically to ensure user-preferred trajectories and to balance the demand. To manage properly the consequences of automation degradation we would need to be in condition to understand, monitor and control how its propagation. We also need to be able to confine and absorb degradation problems (both with and without human contribution), and to understand and estimate the implications of degradations for the overall ATM system performances.

In this paper we describe the use of a federation of models (advancing other the limit of the current models) supporting safety evaluation. The federation has been applied on a large case study to evaluate its ability to:

- understand, model and estimate the propagation of automation degradation in ATM;
- evaluate and estimate the consequences of automation degradation on ATM performances;

- support an effective intervention for the containment of automation degradation.

Section II introduces the models that have been selected to build the federation discussing how each of them focuses on a specific characteristic of the system under evaluation (e.g. functional aspects, human behavior and its interaction with the system) and represent a part of the whole ATM system with variable levels of granularity (from coarse to very fine grain) depending on the interest of the analysis. Section III describes how the federation can be applied during the main phases of the lifecycle of a system and how the different models collaborate in order to support assessment of degradations impact. Section IV reports an application of the federation to a large system with high level of automation where different types of failures and the related propagation of degradation which were simulated. Section V discusses the type of information that the federation can provide to support the evaluation of the system under analysis, evidencing the limitation experienced. Section VI concludes the paper and introduces future work.

II. SHORT DESCRIPTION OF THE MODELS AND OF THE INTERACTION BETWEEN MODELS

Using multiple models to represent different facets of the system under consideration has been the trend for many years in the area of software (with the 9 notations of UML [11]) and more recently of systems (with 2 additional notations of SySML [12] with respect to UML). The approach defined in SPAD project follows a similar path but extend that kind of work to encompass the multiple and more diverse facets of Large Socio-Technical Systems (LSSTS). More precisely we propose the use of 3 kinds of notations: one called HAMSTERS dedicated to the representation elements related to the operators' aspects and one called ICOs dedicated to the system aspects. The last one is called FRAM and is dedicated at representing the organizational aspects and at integrating in a single framework the other aspects (human and system).

A. HAMSTERS to model human aspects

HAMSTERS[1] is a tool-supported graphical task modeling notation aiming at representing human activities in a hierarchical and temporally ordered way. Goals can be decomposed into sub-goals, which can in turn be decomposed into activities, and the output of this decomposition is a graphical tree of nodes. Nodes can be tasks or temporal operators. Tasks can be of several types and contain information including a name and information details. Temporal operators are used to represent temporal relationships between sub-goals and between activities. Tasks can also be tagged by temporal properties to indicate whether or not they are iterative, optional or both [2]. One main element of this notation is the subroutine. A subroutine is a group of activities that a user performs several times possibly in different contexts and which might exhibit different types of information flows [2]. A subroutine can be represented as a task model and a task model can use a subroutine to refer to a set of activities. This element of notation enables the distribution of large amount of tasks across different task models and factorization of the number of tasks. HAMSTERS also provides support for representing how particular objects (data, information...) are related to particular tasks [8]. These relationships (input, output or both) between objects and tasks that can be expressed with HAMSTERS notation representing the relationships between tasks and information in a non-ambiguous way. This notation supports the analysis of the complexity of the operators' tasks and thus can support the identification of which tasks are good candidate for allocation to the system (automation) [3]. However, dealing with a partly autonomous interactive system (as could be defined an RPAS) requires to represent not only the operators' tasks but also the system behavior and the interactions between this two components.

[1]http://www.irit.fr/recherches/ICS/softwares/hamsters/index.html

B. ICO&PetShop to model system aspects

ICO is a formal description technique dedicated to the modeling of interactive applications. This formalism makes it possible to describe the entire interactive application including both behavioral aspects (states and state changes) and interaction aspects (events triggered by the user interface and the graphical rendering) [4]. The behaviour is described by object Petri nets and PetShop is the CASE tool associated the ICO formalism. It allows editing, executing and analyzing models (to check properties). Due to its Petri nets underlying semantics, ICO models are amenable to performance evaluation allowing designers to predict quantitative temporal evolution of model before [14] and during their execution [13].

C. FRAM to model functional aspects

It is a safety management method aiming at supporting both accident investigation and risk assessment processes. It is based on four principles related to complex socio-technical systems structure and dynamics. It describes a failure as a resonance of the normal variability of functions which are characterized by six basic aspects (Input, Output, Preconditions, Resources, Time, and Control). An analysis using FRAM comprises the following five steps: 1) define the purpose of modeling and describe the situation being analyzed, 2) identify the essential functions that contribute to the situation and characterize each function by the six basic aspects, 3) characterize the actual/potential variability of functions, 4) define functional resonance based on potential/actual dependencies (couplings) among functions, 5) propose ways to monitor and dampen performance variability (indicators, barriers, design/modification, etc.).

Additionally, some functions can themselves be refined into other sub-functions according to the required level of detail. This refinement is illustrated in Figure 4 where the "Monitor traffic and separation" function (left-hand side of the figure) is refined into: "Monitor radar image", "Assess traffic evolution" (right-hand side of the figure). This refinement provides

support for the representation of a larger number of functions while keeping the model representation understandable.

D. *Integration of models*

In previous work we have proposed the integration of these three models for providing a "complete" view of the LSSTS. This integration [7] has been done at the abstract level of models having FRAM as the main model in which system and interactive functions were described using ICOs and operators functions using HAMSTERS. We have proposed a development process for the construction of the models [7]. The following section goes beyond this integration at the level of models and present how models can be fed with information flow to be used for assessing the variability of functions of a LSSTS.

III. Two Complementary Uses of SPAD Federation of Models for Safety Monioring and Assessment

A. *Overview*

One of the main concerns with the use of models like FRAM for safety assessment is related to the feeding of models with quantitative information about the LSSTS under consideration. Indeed, all the variability sources (endogenous, exogenous and coupling) and variability dimensions (time, precision, objects, …) are related to the actual information in the system and its current state. Figure 1 presents two different ways of connection FRAM and HAMSTERS models to an interactive system.

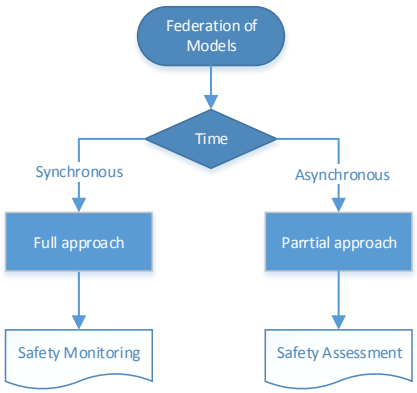

Figure 1: Possible types of application of Federation of models

B. *Full approach (synchronous; from SAFECOMP)*

The first path (left-hand side of the Figure) represents the synchronous connection to the system by connecting the models to an ICO models able to describe but also execute the models. Such an approach has been described in [16]. We qualify this approach as "full" as all the relevant elements of the LSSTS are represented in models. This approach requires the entire development of the interactive system using the ICO formal description techniques. While this might be relevant for highly critical systems such as aircraft cockpits or satellite ground segments (as shown in [15]) this might be extremely expensive in other domains where many systems are integrated such as in ATM. The advantage of this approach is that is allows safety monitoring of a LSSTS as values and information of the can be directly connected to the models and thus variability can be directly and synchronously monitored.

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C. *Partial approach (Asynchronous as in this paper)*

The second path (right-hand side of the Figure) represents the asynchronous connection of the system by connecting a simulator (or potentially the real system) to HAMSTERS and FRAM models. This makes it possible to reuse extant systems and the "only" efforts consist in exploiting information from the simulator (or the real system) to be fed asynchronously in the model. In such case, safety can only be assessed leaving the assessment to be performed manually by an expert. This approach is called "partial" as it only exploits parts of the components of SPAD federation of models.

The partial approach is not able to receive continuously information from the system under execution. In order to be able to perform safety analysis the potential flow of information has to be made discrete in order to be manageable by safety experts. **Table 1** presents the discretization process at the level of variability dimensions. For instance, for dimension 1 (called Factor 1) only 3 levels are considered (on time, too late and omission).

Table 1: Several factors can affect variability

Factor 1	***Factor 2***	***Factor 3***
On time ↑	Precise ↑	Low ↑
Too late ↓	Acceptable ↔	Medium ↓
Omission ↓	Imprecise ↓	High ↓

Similarly, it is needed to discretize the scenarios which will correspond to different FRAM instantiations. Each slice of time corresponds to a specific and determined event that the analyst wants to consider. The sequence of these events can be represented through a timeline (as represented in Figure 2).

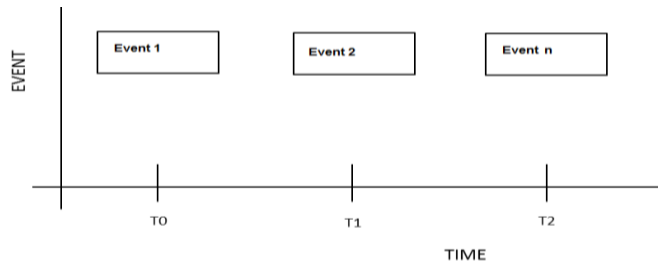

Figure 2: Example of discretization of continuous evolution through timeline

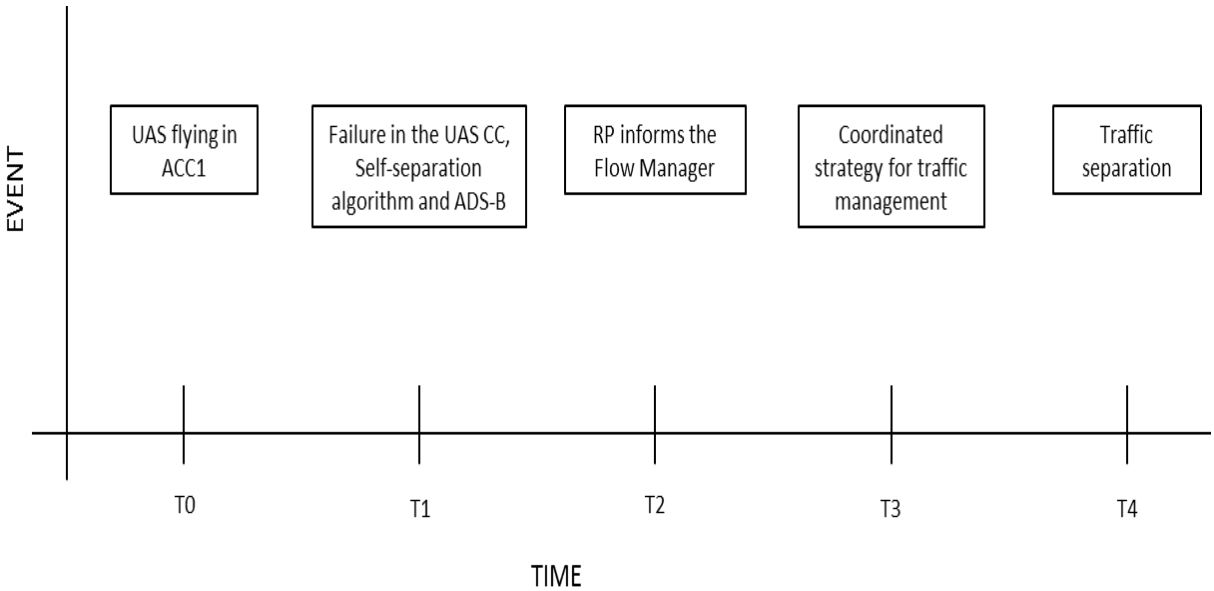

Figure 3: UAS failure - ADS-B failure

IV. UAS Case Study - Example of the partial approach

This section presents the partial approach presented above on a RPAS case study. First section presents an informal description of the case study while the other sections present modeling aspects, discretization and connection to an ATM simulator.

A. Informal description of the Case Study

As illustrated by the following figure, UAS flights from Segregated Airspace 1 to Segregated Airspace 2, avoiding commercial traffic in ACC1. This ACC is the focus of our analysis. ADS-B is the main technology in use to locate aircraft position. Radar is a back-up solution. ATCOs use CPDLC messages to give clearances. CPDLC Messages include standard ATC clearances "ACL" (e.g. "Climb to level 350") or "AMC" (e.g. microphone check) and are intended to augment ATC voice communications and provide additional air traffic control capacity in high density ATC environments.

Aircraft trajectories are shared and managed in 4-D. TMAs in the scenario have a marginal role. Aircraft disappear once entered in the TMA. The UAS Aerodromes are not investigated too. Flight instruments inside the aircraft will not be described/detailed. FMS will be only cited as the interface for CPDLC messages.

This case study presents the following degraded scenario in which the communication channel and self-separation algorithm failures happen in combination with the ADS-B failure. The RPAS data (label, flight level and so on) is invisible to the ATCO's screens and to the RP. The ATCOs can locate the RPAS position on the horizontal level, and use its position to set a restricted volume to separate the RPAS from the commercial traffic. The safety volume is defined taking into account the last RPAS FL known and the shared UAS trajectory. The volume is wide enough to allow RPAS

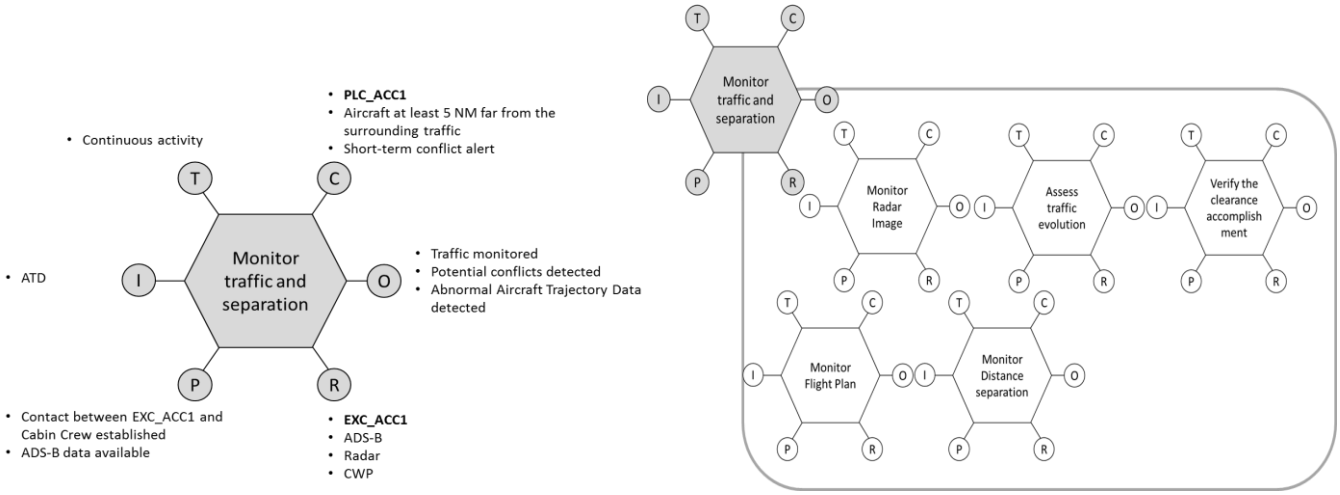

Figure 4 : FRAM function "Monitor traffic and separation"

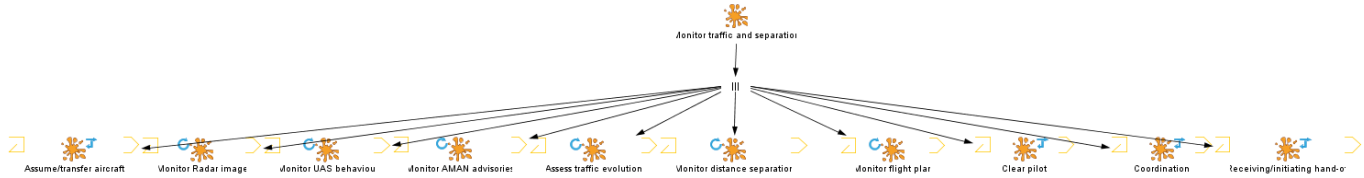

Figure 5 : Executive controller: high level tasks

unexpected trajectory deviations without violating safety distances with other aircraft. The ATCOs working in the sector interested by the RPAS failure inform about the RPAS problem the ATCOs of the surrounding sectors, which may be affected by traffic deviations or that are about to take the RPAS in charge.

B. Modelling of the Case Study using the partial approach

Figure 3 describes a sequence of events associated to a specific time. This timeline allows us to create for each of them a detailed description using both models FRAM and HAMSTERS. Through FRAM is it possible to identify a set of functions related to the scenario and provide a detailed description of each related factors (Time, Precondition and so on). Figure 4 illustrates a function called "Monitor traffic and separation" in which the EXC controller monitors the current traffic situation (aircraft speed and positions, trajectories, separation) and anticipating future situations in his/her airspace of competence.

The EXC controller verifies that the aircraft are following the clearances, they are accomplishing the planned trajectories and they are correctly separated (at the least by 5 miles) from each other. On the basis of the monitoring activity, he/she is able to assess traffic evolution and understand whether there are situations requiring their intervention.

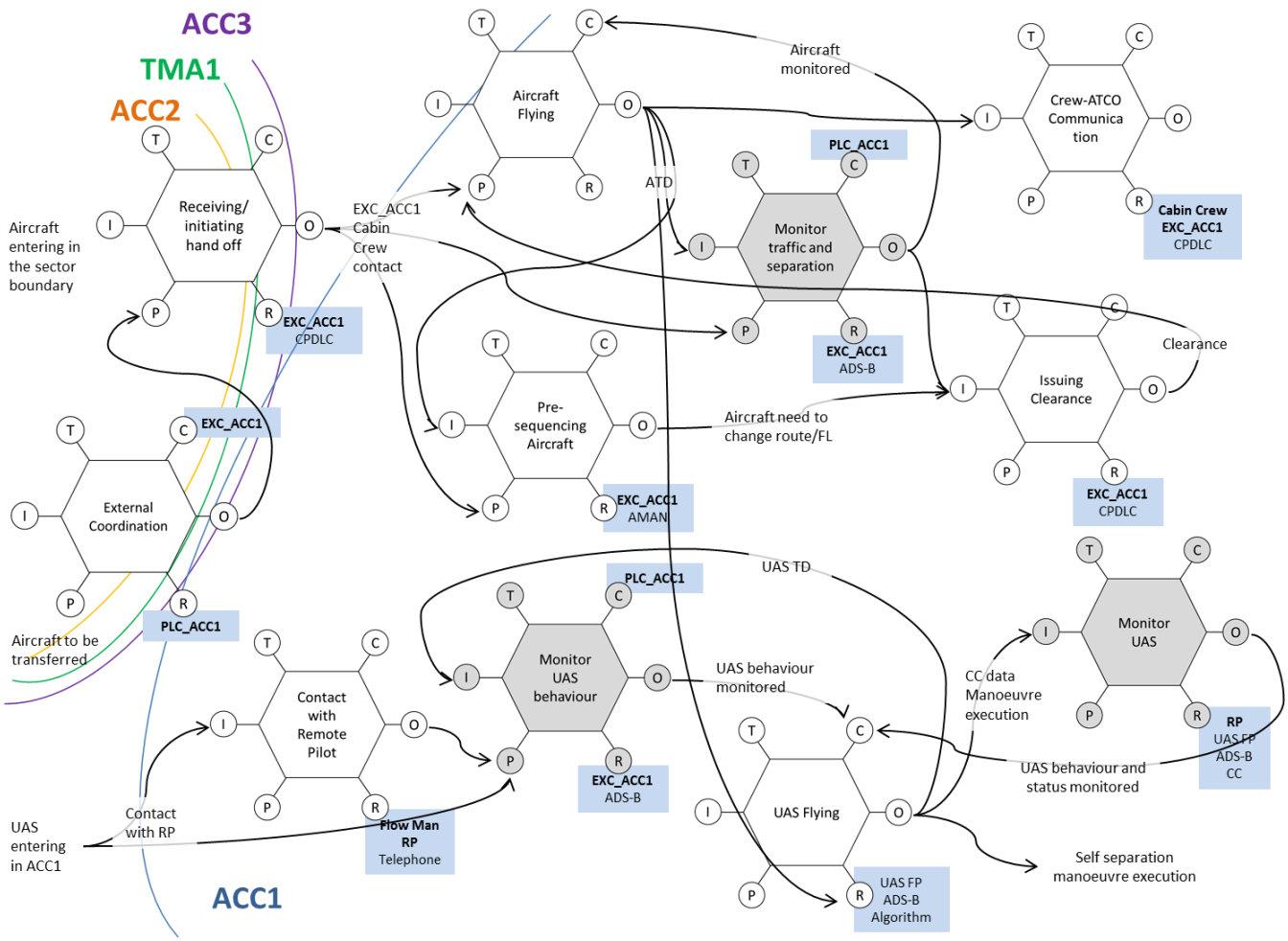

Figure 6: FRAM instantiation at T0 - UAS is flying in ACC1

TABLE 2 : VARIABILITY SOURCES (ENDO/EXOGENOUS FACTORS)

ATD Time	*ATD Precision*	*Traffic*	*Situation Awareness*	*Time resource*	*Traffic Complexity*
On time ↑	Precise ↑	Low ↑	Low ↓	Low ↓	Low ↑
Too late ↓	Acceptable ↔	Medium ↑	Medium ↔	Medium ↔	Medium ↓
Omission ↓	Imprecise ↓	High ↓	High ↑	High ↑	High ↓

This function can be integrated with the analysis performed through HAMSTERS (on the same function). As illustrated in Figure 5 to achieve the main goal "Monitor traffic and separation" the EXC controller has to perform several sub-goals. Each sub-goal corresponds to a FRAM function and redefines it. Moreover, some sub-goals such as "Monitor AMAN advisories" or "Receiving/Initiating handoff are not represented in Figure 4 because they can be described as FRAM functions themselves but in HAMSTERS model are sub-goals that have to be performed to accomplish the main goal.In this case study the system component is not modeled using the dedicated notation but it could appear in HAMSTERS model (i.e. as system function and/or interactive tasks.

Once each model is built, it is possible to create the associated instantiation. As illustrated in Figure 6, according to the timeline (Figure 2), at T0 the UAS is flying in ACC1. The EXC controller of this ACC is "Monitoring traffic and separation" (FRAM function represented in Figure 4) and for accomplishing this main goal, he/she has to perform several sub-goals (which are detailed in HAMSTERS model Figure 5).All the functions can be affected by several variability sources (some of them are reported in the following table). These can be associated to human factors (i.e. SA) and/or to system side (i.e. Traffic and its Complexity) and can affect both the function itself and/or also its output. As presented in section III, in the partial approach, the variability sources have to be discretized. In TABLE 2 (last column), for instance, traffic complexity (which is by definition a continuous value) has been discretized in three values i.e. Low, Medium and High. Similarly traffic can be measured in number of aircrafts (e.g. from 1 to 30) and this has been discretized with the same three values: Low, Medium and High.

It is important to note that such discretization process is critical for the safety analysis that will be performed afterwards. Indeed, too broad clustering of values might end up in missing possible resonance (which typically appears with continuous values contributing together to go beyond a given threshold)

C. *The Federation of Models and SPAD simulator*

The SPAD Simulator aims at representing the air-traffic in a delimited geographical area. The simulated traffic is supposed to be composed of a mix of traditional commercial aircraft and RPAS, in order to study the potential impact of RPAS malfunctions over the whole ATM system providing data for the Federation of Models (as represented in

Figure 7).

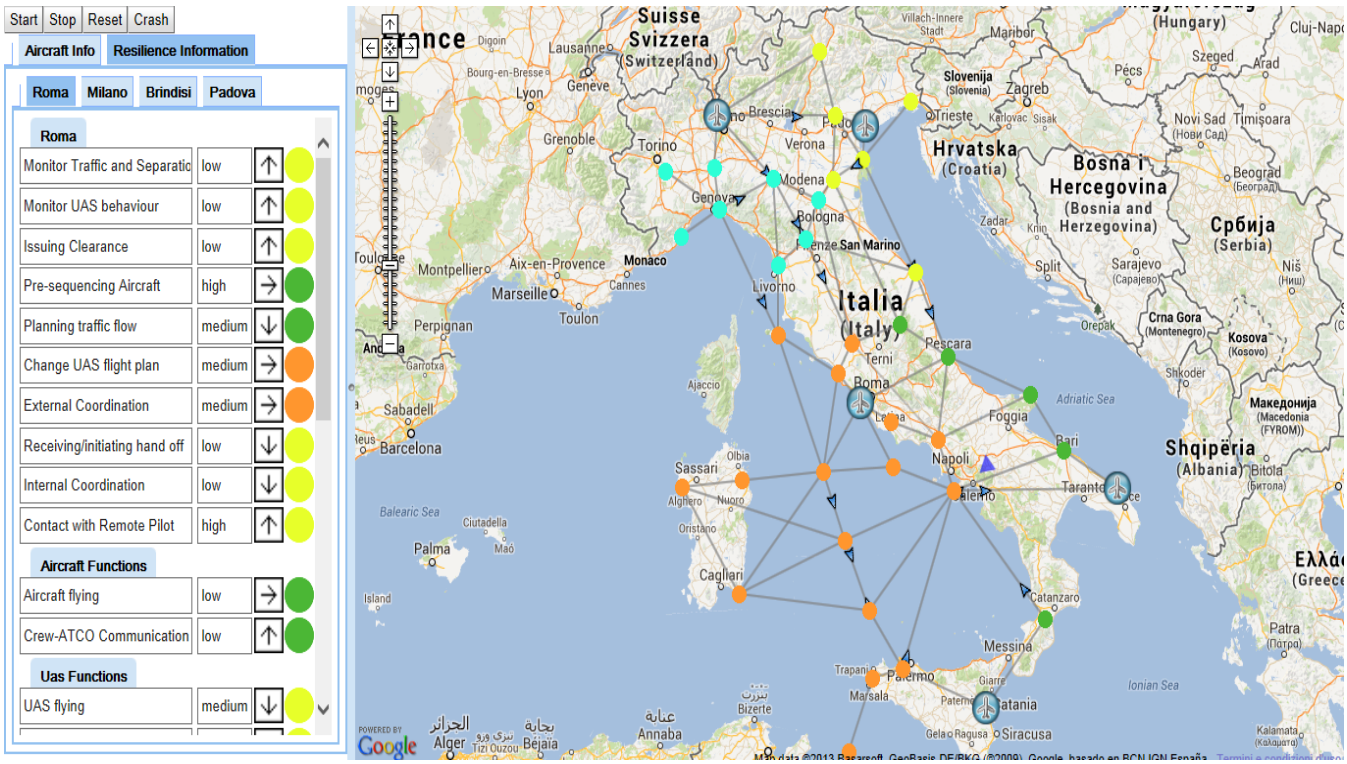

Figure 7: Screenshot from the simulator (in its integration with the Federation of Models)

The Simulator has been designed and implemented following the principles of Agent Based Modelling, an emergent framework suitable for simulating the actions and interactions of autonomous agents (both individual and collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole [1].

The system is composed of two fundamental components:

- The network is a graph representation of a real air-traffic network, composed of waypoints (graph vertexes) and routes among them (graph arcs);
- The agents are aircraft flying on the network. Basically two classes of agents are here identified: traditional manned aircraft and remotely piloted aircraft (RPAS).

The main functionalities of the Simulator are:

- The computation of conflict-free routes for all the agents, commercial and RPAS, involved in the simulation, basing on their starting point and destination (planning phase);
- The execution of the routes computed in the planning phase (execution phase);
- The introduction of UAS malfunctions, leading to the deactivation of graph arcs included in the "safety bubble" and the consequent routes re-planning by all the involved agents (re-planning phase).

Left-hand side of

Figure 7 presents the values of the variability sources that have been identified in the FRAM modeling and described in TABLE 2. We can see for instance that, according to the current state of the scenario run on the simulator, the safety analyst has set the value for "External coordination" to medium which ends up in a negative impact (represented by a red circle). Similarly, "Pre sequencing" parameter has been setup to high which has a positive impact (represented by a green circle).

V. Application Feedback

We have seen how the Federation can model different perspectives of the system under study and analysis it at different levels of granularity. We have also explained how the models information is combined offering sufficient information for the questions of interest during the analysis. Each model focuses on specific characteristics and can adopt different levels of granularity representing a part of the whole ATM system. Through this approach we are able to provide information about variability of the different system functions as defined in [5] and its impact.

To ensure a synergetic and coherent support to the analysis, the different models shall:

- reference a shared system;
- exchange information that are usable across them and compatible to each other logic;
- exchange meaningful and compatible information in the context of the analysis for which the federation was designed.

The models of the federation are not intended to be used as stand-alone models but rather to support the analyst during his analysis. Then, the analyst is the mediator of the interaction between the models and he is the manager of the federation. The analysis remains human centred, that is, under the control and responsibility of the analyst and requires a significant contribution from analyst and operational experts with a significant degree of experience.

This prevented a complete application of the federation to monitor in real time the behavior of a system whose dynamic and evolution is not compatible with the time required for the human analysis. On the other hand the federation offers a well-structured and enlightening support to the analysis and facilitate and guide the interaction between the analyst and the operational expert. Our experience in applying the federation shown that its usefulness depends from the purpose of the application.

It can be very useful to support accident analysis, that is, to understand what happened. In this role it can offer a new perspective and point of view (based on the concept of resonance) to understand what happened. The effort required for the application of the model federation is acceptable, however the results can depend on the expertise and the operational knowledge of the analyst and the operational experts supporting the analysis.

The federation can also be useful as an instrument to support the analysis of a system, for example as a support to safety assessment and safety analysis, that is, to understand what may happen. However, in such a role the application effort is extensive because of the different instantiations required for each possible future event to be investigated. The effort can become unacceptable when the complexity of the system under analysis grows and if the analysis pretends to investigate all the possible future events. This implies the need to focus the analysis only on the most relevant parts of the system and choose the right combination of levels of granularity for its parts. Also in this role the federation can support interactions between the analyst and the operational experts. The representations and preliminary analysis of the federation can be used to elicit the opinion of the operational experts in a structured and stimulating way.

The federation is of limited use to monitor a system in real time, that is, to understand what is happening. The analysis requires a significant human involvement and in most of the cases cannot be automated. In the case study presented in this paper the federation of models has been used off line to explore in advance a limited number of possible future events and estimate their possible consequences. If we consider the space of the possible future events as a two dimensional like in figure

5, this means to investigate a small portion of it, like the one represented by the 4 black spots and the surrounding gray areas. Then the functioning of the system was monitored in real time, and if there was evidence that one of the explored events was going to happen, the estimate about the possible consequences was used to manage the event. Figure 8 shows in red the trajectory of the system within space of the events, evidencing how it degrades and then returns to the axis of the normal operational conditions. While doing this the system "crosses" some of the grey areas that have been explored by the federation.

However, this procedure can be very expensive in terms of application effort, and the number of possible future events that can be investigated remains small. In addition, the selection of these events can be biased towards the most likely ones or those with the most severe consequences.

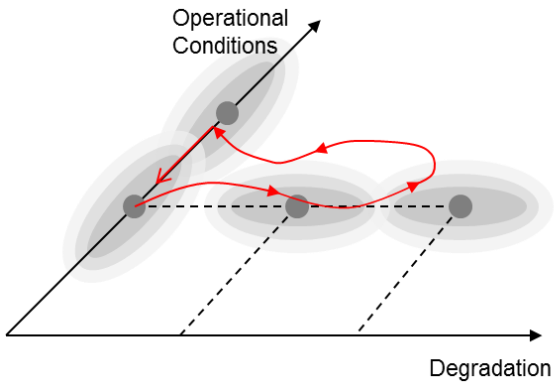

Figure 8: Information on variability and its impact

VI. Conclusions and Future Works

This paper has presented possible use of the federation of models and how they can be integrated with extant systems or simulators.

The overall objective of the ongoing work presented in this paper is to define an overall design framework of automation degradation propagation in complex networks, and an associated method supporting the framework in order to study automation and more precisely automation degradation.

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