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In-Flight Contingency Management for Unmanned Aerial Vehicles

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Contingency analysis and reaction is a critical task to be carried out by any airplane to guarantee its safe operation in a non-segregated airspace. Pilot's reactions to any kind of incidences that may occur in-flight, like engine malfunctions, loss of electrical power, hydraulic failure, unexpected weather, etc, will determine the fate of the flight. Nowadays, contingency reactions are mainly driven by the airplane manufacturer, with pre-analyzed contingency scenarios covered in the airplane documentation, and by ICAO's rules as defined in the way flight plans should be prepared and landing alternatives implemented. Flight dispatching is the set of tasks related to flight preparation, such as load and balance, meteorology study and briefing, operational flight planning, contingency analysis and planning, etc. However, managing contingencies on a UAS is a much more complex problem basically due to the automated nature of the vehicle and the lack of situational awareness that pilot's in command should face. It is well known from the short history of UAS accidents that many of them are directly imputable to pilot errors when trying to manage an unexpected contingency.

In this paper we will introduce an structured approach to automate contingency reactions in UAS. Our objective is to classify the contingency sources and up to a certain level abstract their impact on the system operation. Contingencies can be related to four wide aspects of the UAS operation: the flight itself, the mission, the payload, and the awareness systems. depending on the level of severity the contingency reaction may involve changing or canceling mission objectives to canceling the flight itself. In this way, the response to the contingency can be selected from a predefined limited catalog of automated reactions that may reconfigure the UAS operation in all aspects. This structured approximation is only possible because the contingency management is built upon a highly capable architecture called USAL (UAS Service Abstraction Layer) that offers capabilities to properly monitor contingencies and the flexibility to command pre-planned contingency reactions that may affect the flight operation and/or the mission carried out by the system.

Contingency management becomes directly dependent upon the UAS dispatching process. USAL provides a dispatching methodology that identified the mission objectives, the UAV airframe and its various characteristics, the software services required for managing the flight and the mission, the sensor and computational payload, etc. All these elements are combined together in an iterative dispatching flow. The result of the process is the actual UAS configuration in terms of fuel, electrical system, payload configuration, flight plan, etc; but also detailed flight plan, alternative routes and landing sites, detailed USAL service architecture and the required contingency planning.

Nomenclature

UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
RNAV	Area Navigation
FPM	Flight Plan Manager
VAS	Virtual Autopilot System
MMa	Mission Manager

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XML	Extensible Markup Language
KML	Keyhole Markup Language
FGFS	FlightGear Flight Simulator

I. Introduction

Nowadays, in civil aviation, a set of procedures and standardized practices are followed in order to operate safely, efficiently and regularly all kind of aircraft. Criteria of safe operating practice is found in ICAO Annex 6, Part I[1] for commercial air transport operators while Part II and Part III of the same Annex deal with general aviation and helicopter operations respectively. In these standards and recommended practices one can find, for instance, what kind of documentation an operator shall provide to flight crews, which are the responsibilities and duties of the pilot-in-command before, during and after a flight etc.

In order to guarantee such operation safety requirements, a flight dispatching process is carried out in coordination by the pilot in command and the flight dispatching officer. During this flight preparation it must be verified that the airplane is airworthy; the instruments and equipment for the particular type of operation to be undertaken, are installed and are sufficient for the flight; a maintenance release as prescribed and has been issued in respect of the airplane; the mass of the airplane and center of gravity location are such that the flight can be conducted safely, taking into account the flight conditions expected; any load carried is properly distributed and safely secured; a check has been completed indicating that the operating limitations can be complied with for the flight to be undertaken; the standards relating to operational flight planning have been complied with; etc. In addition to these classical dispatching tasks, specific UAS dispatching tasks must also be performed. UAS dispatching requires taking into account:

- The UAS mission: its objectives, payload requirements, operation, flight-plan, etc.
- The UAS airframe: its various characteristics, performance, systems required for managing the flight and the mission, available payload bays, fuel and electrical architecture.
- The UAS payload: its required sensors and other payload, etc.

In addition to flight dispatching for nominal conditions, planning for contingencies is also required. Analysis of the potential contingency situations and planning the correct reaction is a critical task to be carried out by any airplane to guarantee its safe operation. Pilot's reactions to any kind of incidences that may occur in-flight, like engine malfunctions, loss of electrical power, hydraulic failure, unexpected weather, etc; are critical and will determine the fate of the flight in case such contingency occurs. Contingency reactions are mainly driven by the airplane manufacturer, with pre-analyzed contingency scenarios covered in the airplane documentation. Pilot and co-pilot study and train to improve their reactions to such situations. Also, rules of the air defined by ICAO's annexes define the way flight plans should be prepared and landing alternatives selected depending the type of airplane, flight and contingency.

However, managing contingencies on a UAS is a much more complex problem basically due to three reasons:

- The automated nature of the vehicle may prevent direct operation by the pilot on it. Some configuration change may be necessary in order to achieve the desired state modification.
- Remote operation adds additional communication latency.
- Highly reduced situational awareness that the pilot in command should face preventing him to make the right decisions.

It is well known from the short history of UAS accidents that many of them are directly imputable to pilot errors when trying to manage an unexpected contingency without an adequate situation awareness.

In this paper we introduce an structured approach to automate contingency reactions in UAS. Our objective is to classify the contingency sources and, up to a certain level, abstract their impact on the system operation. In this way almost all system reactions to contingencies can be automated, or at least, provide correct guiadance to the pilot. Contingencies can be related to four wide aspects of the UAS operation: the flight itself, the mission, the payload, and the awareness systems. According to the level of severity, the contingency reaction may involve total mission cancellation with different levels of emergency returns to base, to restricted cancellation of some parts of the UAS mission. Following this structured scheme, the response to the contingency can be selected from a predefined but limited catalog of automated reactions that may reconfigure the UAS operation in all aspects.

This structured approximation is only possible because the contingency management is built upon a highly capable architecture called USAL (UAS Service Abstraction Layer) that offers capabilities to properly monitor contingencies and the flexibility to command pre-planned contingency reactions that may affect the flight operation and/or the mission carried out by the system. A flexible and reusable hardware/software architecture designed to facilitate the development of UAS-based missions has been previously introduced in.[2] A user-parameterizable *U*AS Service Abstraction Layer (USAL) defines a collection of standard services are their interrelations as a basic starting point for further development by users. Functionalities like enhanced flight-plans, a mission control engine, data storage, communications management, etc. are offered. Additional services can be included according to requirements but all existing services and inter-service communication infrastructure can be exploited and tailored to specific needs. This approach reduces development times and risks, but at the same time gives the user higher levels of flexibility and permits the development of more ambitious applications.

Contingency management also becomes directly dependent upon the UAS dispatching process. USAL provides a dispatching methodology that identified the mission objectives, the UAS airframe and its various characteristics, the software services required for managing the flight and the mission, the sensor and computational payload, etc. All these elements are combined together in an iterative dispatching flow. The result of the process is the actual UAS configuration in terms of fuel, electrical system, payload configuration, flight plan, etc; but also detailed flight plan, alternative routes and landing sites, detailed USAL service architecture and the required contingency planning.

The paper is organized as follows. Section II generally describes the USAL architecture and the underlying service oriented technologies that will be applied to UAS avionics. Section III describes the structure ans capabilities of the RNAV-based flight plan manager. The built it properties of this service allows to implement automated return-to-base schemes. Section IV overviews the architecture of the contingency management system, including ... Contingency management is the result of a priory analysis of all potential contingencies and the predefined reactions that are required. This analysis is implemented during the *flight dispatching* process as described in Section V. Once identified, contingencies and reactions can be formalized and loaded on the *Contingency Manager*. Finally, Section VI concludes the paper and outlines future research and development directions.

II. System Overview

This section describes the UAS architecture:[3] a distributed embedded system on board the aircraft that will operate as a payload/mission controller. Over the different distributed elements of the system we will deploy software components, called services, that will implement the required functionalities (see Figure 1). These services cooperate to accomplish the UAS mission. They rely on a middleware layer[4] that manages communications between services.

II.A. Distributed Embedded Architecture

The UAS system is built as a set of embedded microprocessors, connected by a standard commercial of the shelf (COTS) Local Area Network, in a purely distributed and scalable architecture. This approach is a simple scheme which offers a number of benefits in our application domain that motivates its selection:

- Development simplicity is the main advantage of this architecture. Inspired by Internet applications and protocols, the computational requirements can be organized as services that are offered to all possible clients connected to the network.
- Extreme flexibility given by the high level of modularity of a LAN architecture. We are free to select the actual type of processor to be used in each LAN module. Different processors can be used according to functional requirements, and they can be scaled according to computational needs of the application. We refer to a LAN module with processing capabilities as node.

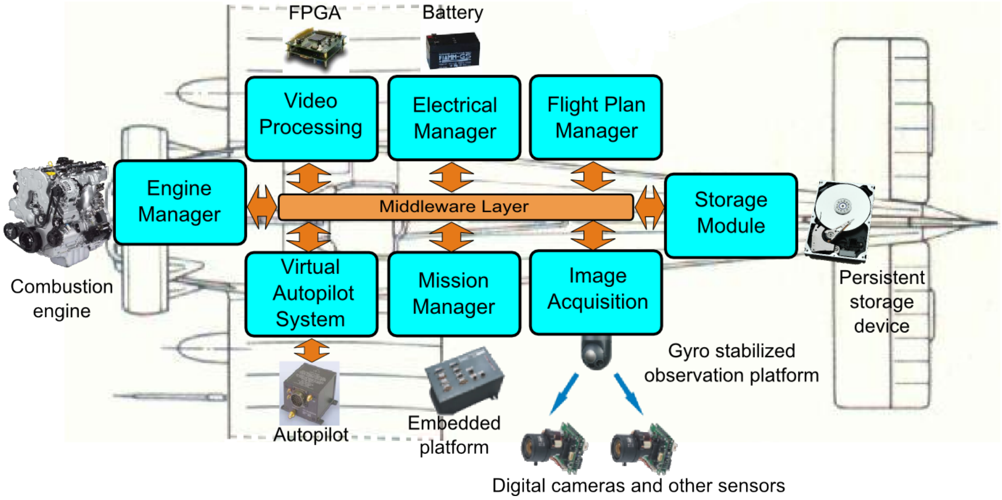

Figure 1. UAS embedded system architecture.

- Node interconnection is an additional benefit in contrast with the complex interconnection schemes needed by end-to-end parallel buses. While buses have to be carefully allocated to fit with the space and weight limitations in a mini/micro UAS, in a LAN based architecture new nodes can be hot plugged with much less effort. The system can even use wake-on-LAN capabilities to switch a node on when required.
- This architecture can be extended to the ground by building a global LAN that connects the ground segment and the air segment of the system. An specific node on each network, the Communications Gateway, routes the information from one network to the other making node location transparent to the developer.

A middleware layer called MAREA, which stands for Middleware Architecture for Remote Embedded Applications, is used to communicate the different services. MAREA provides an execution environment with communication channels and common functionalities. It promotes a publish/subscribe model for sending and receiving data, events and commands among the services of the UAS. Services that are producing valuable data publish that information while other services may subscribe to them. MAREA takes care of delivering the information to all subscribers that declare an interest in that information. In this way, the role of each service is expressed by the action of publishing, subscribing, or doing both simultaneously. The publish-subscribe model eliminates complex network programming and eases the implementation of distributed applications.

II.B. USAL: UAS service abstraction layer

Providing a common infrastructure for communicating UAS services is not enough for keeping the development and maintenance costs for UAS systems low. The existence of an open-architecture avionics package specifically designed for UAS may alleviate the development costs by replacing many development tasks with a simple parameterization. From the study and definition of several UAS missions, one can identify the most common requirements and functionalities present among them.[5–9]

The UAS Service Abstraction Layer (USAL) is the set of available services running on top of the UAS architecture that give support to most types of UAS missions.[2] The USAL can be compared to an operating system. Computers have hardware devices used for input/output operations. Every device has its own particularities and the OS offers an abstraction layer to access such devices in a uniform way. Basically, it publishes an Application Program Interface (API) which provides end-users with efficient and secure access to hardware elements.

The USAL considers sensors and in general all payload as hardware devices of a computer. The USAL is a software abstraction layer that gives facilities to end-users' programs to access the UAS payload. The USAL also provides many other useful features designed to simplify the complex task of developing an UAS application.

The final goal of the USAL is twofold:

1. First, reduce time to market when creating a new UAS system. The USAL together with MAREA will simplify the integration of all basic subsystems (autopilot, communications, sensors, etc) because it will already provide all required glue logic between them.

2. Second, simplifying the development of all systems required to accomplish the actual mission assigned to the UAS. In many cases this complexity is reduced to specifying the desired flight plan and sensor operation and parameterizing the specific services available in the USAL.

Using the USAL allows the UAS integrator to abstract from complex and time consuming underlying implementation details. The USAL and MAREA offer a light weight service-based architecture with a built-in inter-service communication infrastructure. A large number of available services can be selected to create specific configurations, while new services can be easily created by inheriting exiting ones; e.g. to integrate a new camera with some specialized behavior.

Even though the USAL is composed of a large set of available services, not all of them have to be present in every UAS or in every mission. Only those services required for a given configuration/mission should be present and/or activated in the UAS.

Available USAL services have been classified into four categories (see Figure 2):

1. Flight category: all services in charge of basic UAS flight operations: autopilot, basic monitoring, contingency management, etc.

2. Mission category: all services in charge of developing the actual UAS mission.

3. Payload category: specialized services interfacing with the input/output capabilities provided by the actual payload carried by the UAS.

4. Awareness category: all services in charge of safe operation with respect to terrain avoidance and integration with shared airspace.

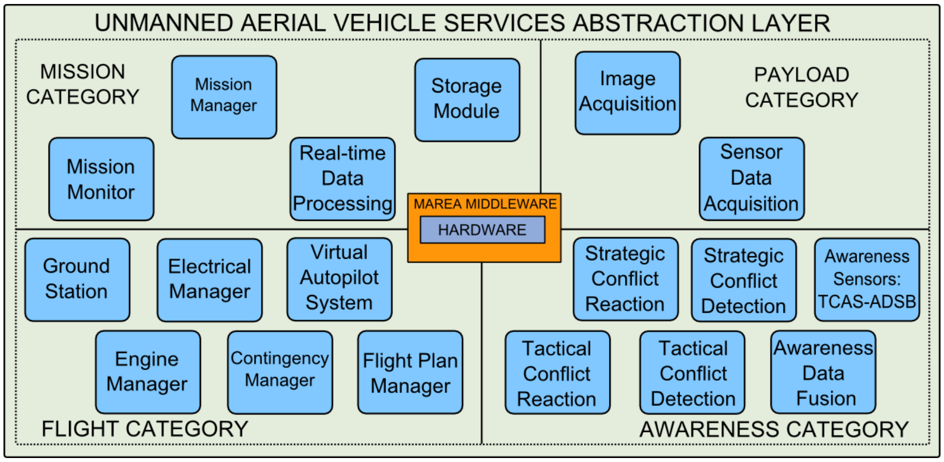

Figure 2. UAS Service Abstraction Layer.

II.C. Flight Category

Many autopilot manufacturers are available in the commercial market for tactical UAS with a wide variety of selected sensors, sizes, control algorithms and operational capabilities. However, selecting the right autopilot to be integrated in a given UAS is a complex task because none of them is mutually compatible. Moving from one autopilot to another may imply redesigning from scratch all the remaining avionics in the UAS. Current commercial UAS autopilots also have two clearly identified drawbacks that limit their effective integration with the mission and payload control inside the UAS:

- The complexity of exploiting on-board the autopilot telemetry by other applications is complex and autopilot dependent. Autopilots telemetry is typically designed just to keep the UAS state and position under control and not to be used by third party applications.
- The flight plan definition available in most autopilots is just a collection of waypoints statically defined or hand-manipulated by the UASs operator. However, no possible interaction exists between the flight-plan and the actual mission and payload operated by the UAS.

Flight category are a set of USAL applications designed to properly link the selected UAS autopilot with the rest of the UAS avionics,[10,11] namely the Virtual Autopilot Service, the Flight Manager Service, the Contingency Service, the Flight Monitor Service, etc. (see Fig. 5).

The Virtual Autopilot Service (VAS) is system that on one side interacts with the selected autopilot and is adapted to its peculiarities. VAS abstracts the implementation details from actual autopilot users. From the mission/payload subsystems point of view, VAS is a service provider that offers a number of standardized information flows independent of the actual autopilot being used.

The Flight Plan Manager (FPM) is a service designed to implement much richer flight-plan capabilities on top of the available autopilot capabilities. The FPM offers an almost unlimited number of waypoints, waypoint grouping, structured flight-plan phases with built-in emergency alternatives, mission oriented legs with a high semantic level like repetitions, parameterized scans, etc. These legs can be modified by other services in the USAL by changing the configuration parameters without having to redesign the actual flight-plan; thus allowing the easy cooperation between the autopilot and the UAS mission. Next section will depict a service overview.

The Contingency Management are a set of services designed to monitor critical parameters of the operation (like battery live, fuel, flight time, system status, etc.). In case contingencies are detected, actions will be taken in order to preserve the security and integrity of the UAS: from flight termination, mission abort or system re-cycle. This service is explained deeply in section IV.

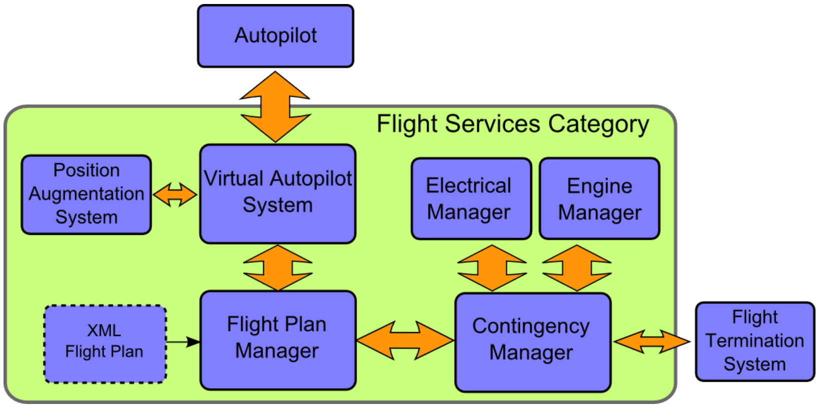

Figure 3. Overview of the available flight service category.

III. Flight Plan Manager Overview

Previous section has introduced the UAS architecture. In this section one of the key flight services, the Flight Plan Manager (FPM), is introduced. The FPM is the service responsible for the execution of flight plans. It receives a flight plan stored in an XML document, processes it and generates control commands (normally waypoint sequences) that are sent to the VAS for its execution. Flight plans are described using a formalism specifically designed to support UAS civil missions.[10] This formalism offers semantically much richer constructs than those present in most current UAS autopilots, which usually rely on simple lists of waypoints.[12] The FPM gives support to contingency handling by enabling the UAS mission designer to specify alternative plans alongside the main flight plan in the XML document submitted to the FPM. When an emergency occurs that should be handled by the FPM it resorts to one of the alternative plans.

The FPM can be either on command, meaning it determines what trajectory the UAS is expected to follow, or in a standby state, where it waits until it regains control (see Figure 4). The FPM will be in

StandBy if the UAS is under manual control or if it has been preempted by another service which now controls the UAS trajectory. Normally the FPM will operate in the Auto state, which is one of the two OnCommand substates. When in this state, the FPM generates waypoint commands that feed the VAS. If it is paused, it will switch to the Pause state and the UAS will be commanded to perform a holding pattern. When an update command is received, the FPM will recompute all affected waypoints. If an emergency occurs it will fall back on one of the alternative plans. FPM operation for alternative emergency plans does not differ from the nominal case where the main flight plan is executed.

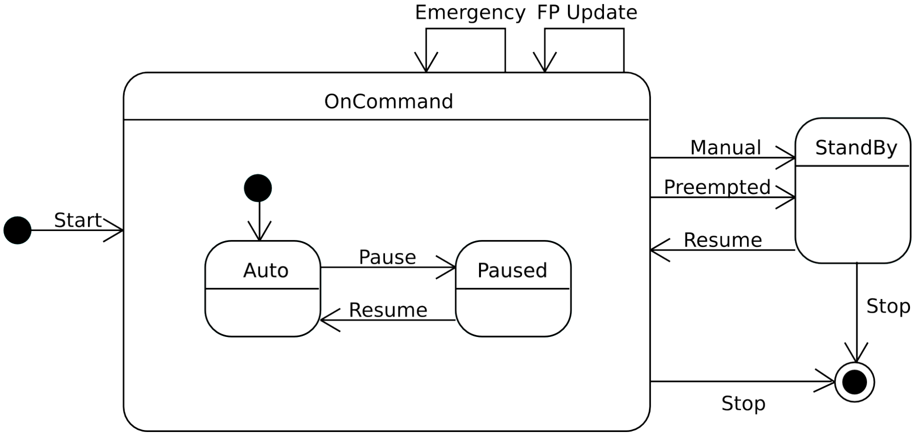

Figure 4. Flight Plan Manager States.

Both the main flight plan and its emergency alternatives are hierarchically structured as shown in Figure 5. The node at the top of the figure represents the whole plan. At the next level the flight plan is decomposed into different stages. These stages correspond to different flight phases, such as TakeOff, Departure, EnRoute, etc. which are sequentially executed. Each one of the stages is formed by a collection of legs. Legs are used to describe the different parts of a stage. In general, legs specify the trajectory to reach a given destination waypoint. Alternative plans can be specified at the root level, for a given stage or for a given leg. If an emergency occurs when executing a given leg, and this leg has an alternative plan associated to it, the alternative plan will be executed. If the leg has no such alternative plan, the FPM will check its parent stage. If no alternative plan is found there either, then it will take the alternative plan associated to the flight plan root node.

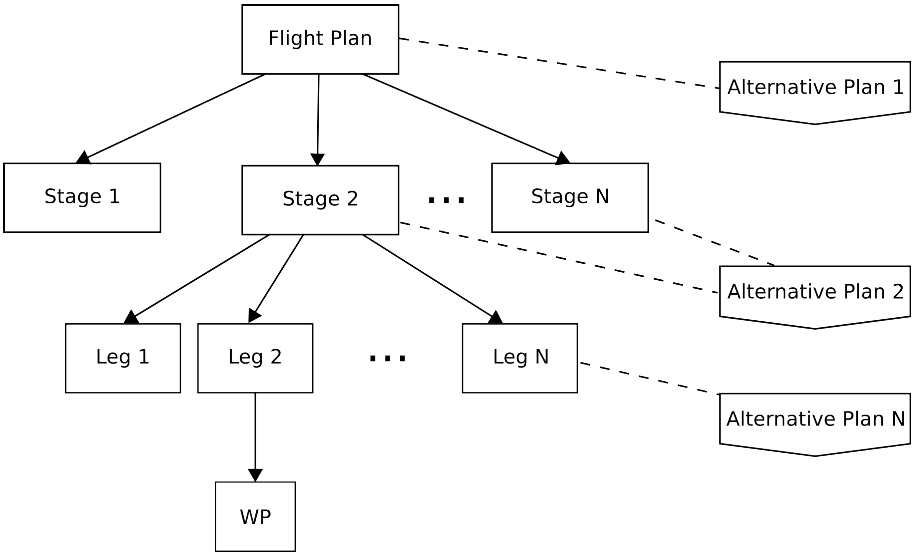

Figure 5. A flight plan is composed of stages, legs and waypoints.

The flight plan specification mechanism supports different types of legs. Some of them are based on existing ones in Area Navigation[13] (RNAV), which is a method used in civil aviation to provide more flexibility and precision for the execution of flight procedures. Since we are going to extend this initial set, we refer to these RNAV-based set of legs as basic legs. These are the available ones:

- Initial Fix: Determines an initial point. It is used in conjunction with another leg type (e.g. TF) to define a desired track.
- Track to a Fix: Corresponds to a straight trajectory from waypoint to waypoint. The initial position is the destination waypoint of the previous leg.
- Direct to a Fix: Is a path described by an aircraft's track from an initial area direct to the next waypoint, i.e. fly directly to the destination waypoint whatever the current position is.
- Radius to a Fix: Is defined as a constant radius circular path around a defined turn center that terminates at a waypoint. It is characterized by its turn center and turn direction.
- Holding Pattern: Specifies a holding pattern path. It can be terminated at a fix or it can depend on a given condition.

The set of basic legs is extended with higher level control structures plus what we call parametric legs. These additional leg types target the specific needs of UAS civil applications.

- Iterative Leg: Provide a mechanism for specifying iterative behavior. Legs forming the iterative leg's body are flown while a certain condition is satisfied or until a given number of repetitions is reached.
- Intersection Leg: Used in situations where there is more than one possible path to follow and a decision needs to be made.
- Parametric Leg: Enables automatic generation of path patterns from a reduced number of input parameters. They can be based on variables that change during mission time, thus providing a high level of adaption.

The availability of a structured flight plan with its different leg types and alternatives, combined with the FPM capabilities to automatically update it, provide the system with a high level of adaption to the different circumstances that can arise during the execution of a mission. These circumstances include contingency situations, whose handling is centralized by the Contingency Manager, but require collaboration from other services for its resolution.

IV. Contingency Manager

This section defines the characteristics of the *Contingency Manager* (CM) intended for use within the USAL architecture. It provides a general view of the architecture and design of the CM. The CM centralizes all the alarms and contingencies of the system. In order to design a robust system to manage UAS civil missions, contingency situations have to be taken in account. Any little failure in the system may preclude the success of the mission or even become dangerous if not properly managed. All this warning, alarms and failures have to be treated to offer an structured response. The CM acquires and processes all the possible hazard situations to recover the correct status of the system.

Basically, the CM is divided in two phases. The first one implemented before flight, identifies all reasons that may lead to a deviation of the expected UAS behavior. For each potential deviation a pre-defined reaction should be defined, going from partial cancellation of the mission to a complete cancellation of the flight. Once the UAS is in flight, its operation should be continuously monitored to check whether its behavior is maintained within a nominal status. If some deviation is detected a pre-defined reaction will be triggered causing other USAL flight and mission services to modify its operation.

The CM is responsible for collecting status information related to multiple sources as: autopilot, engine, electrical, fuel, communications, etc; and identifying contingency situations. It is understood as contingency those situations which the UAS integrity is or will be in danger or its assigned mission cannot be properly developted. If a contingency occurs, all involved services will be alerted and proper reaction will be taken according to the sort of contingency.

In our architecture each service has its own responsibility. Several services take part in order to develop each UAS functionality. For example, we have services to manage the autopilot, the engine, electrical power, etc. Any contingency in one of each service can cause a system chain reaction. To solve this problem the CM will process each alarm and will alert the services involved. It will alert the suitable services to solve the trouble in the correct order.

The main CM interlocutors will be the *Flight Plan Manager*(FPM) and the *Mission Manager* (MMa). The FPM has the capacity of changing the mission flight plan or executing emergency procedures. On the other hand the MMa knows the mission objectives and the payload involved. So in case the CM decides that some reaction is necessary it will be enough to communicate the desired reaction to both the FPM and the MMa. In general, this decision will switch off devices or will coordinate an intelligent emergency response as an emergency flight plan to come back to some airfield.

The CM monitors and alerts contingency situations related to different areas:

- Flight Contingencies: in case of weather changes we may force certain areas to be excluded from the operative flight plan. Other possible causes are that the expected performance of the UAS does not satisfy certain minimums or power sources do not provide the required levels of electrical energy, or fuel consumption does not behave as expected.
- Payload Contingencies: in case a given payload element fails, some predefined actions need to be taken. If the payload element is critical for the flight, the flight plan needs to be terminated as soon as possible; if the contingency is critical for the mission, the mission is canceled or its objectives are reduced. If the contingency only affects the operation partially, the degraded conditions are annotated for further failures.
- Mission Contingencies: in case the expected mission results are not achieved due to any unexpected situation, mission objectives may be reduced or totally canceled.
- Awareness Contingencies: in case the airspace is not segregated another aircrafts can force flight plan changes or mission deviations.

IV.A. In-Flight Contingency Process

Once the UAS is in flight, the UAS operation should be continuously monitored to check whether its behavior is maintained within a nominal status. The next architecture is proposed to achieve this goal.

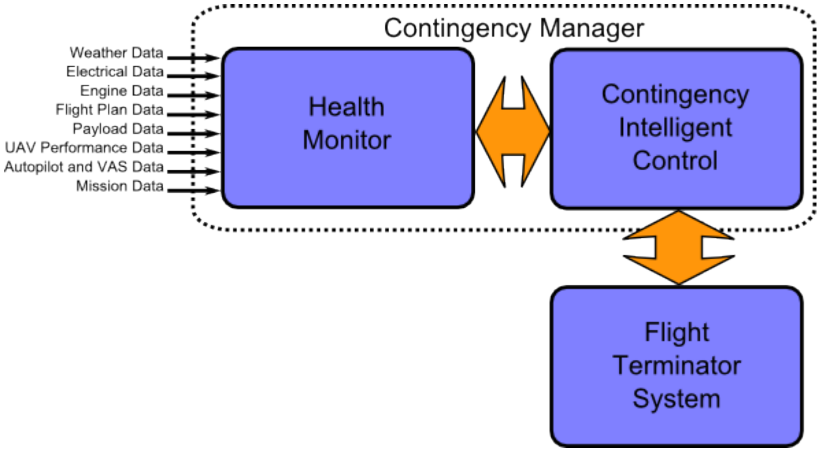

Figure 6. Contingency Manager Architecture.

The CM is composed by two pieces of software: the *Health Monitor* (HM) and the *Contingency Intelligent Control* (CIC). The first one is in charge of gathering all the information required to evaluate the UAS status. In this part the service pre-processes the entire UAV information gathering. The second one implements the CM decition making core. The CIC evaluates all UAS pre-processed information and generates an intelligent response in front of any contingency.

The HM process and gathers all the information needed to take a contingency decision. It is subscribed to the most relevant UAS information. This information is stored in the CM global area periodically the CM information repository is checked in order to find any future contingency. In order to search UAS contingencies, the service will occasionally need mission or flight plan information. For example the mission time has to be compared with energy time or fuel time. This information will be achieved on demand to reduce network traffic. To sum up; the HM gathers all the information needed by the service to look for any contingency. This information can arrive periodically or on demand. When the HM finds a contingency, it is sent to the CIC in order to be classified.

The CIC gives the system intelligence. Basically, it is in charge of response or proposing different responses in front of any contingency preserving the UAS integrity. The CIC classifies the contingency in three categories: minor, hazardous and catastrophic. Each category has different responses as it is shown in the figure 7.

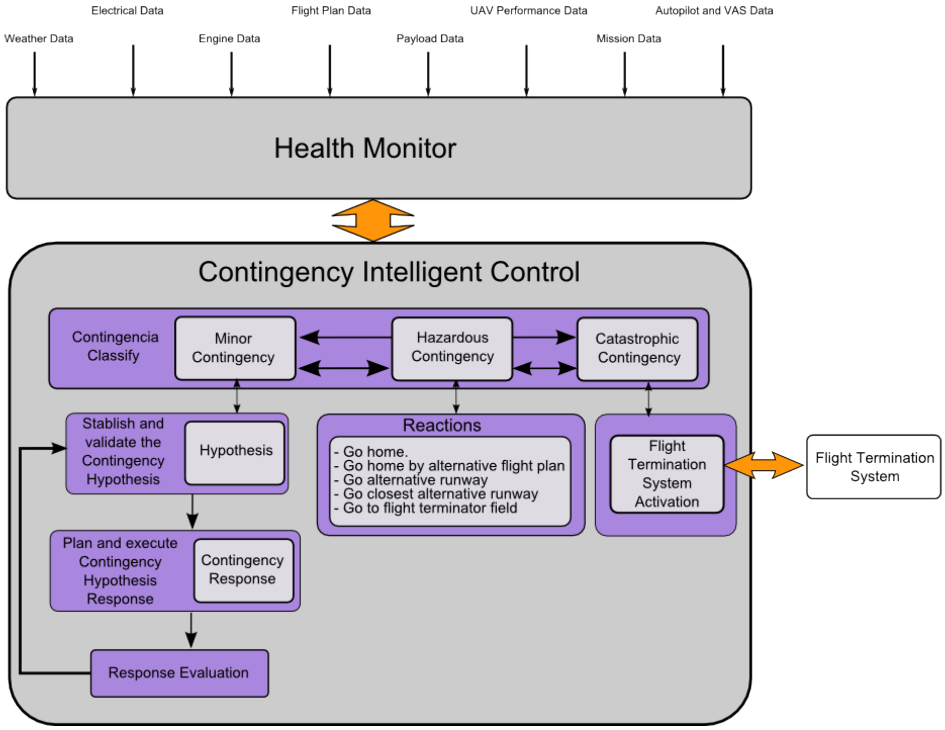

Figure 7. Contingency Intelligent Control Overview Architecture.

Figure 7 depicts the contingency reactions for each category:

- The most important and restrictive category is the *catastrophic contingency* one. The system enters in this state when the UAS cannot be recovered. So, we have to immediately terminate the mission bu at the same time ensure the safety. The CM will activate the Flight Termination System (FTS). The FTS will commonly be composed by a parachute system. The parachute ensures the system safety and reduces ground crash risk.

- Next to the catastrophic contingency category is the *hazardous contingency* category. With this component we manage any contingency which interrupts or will interrupt the normal mission development. It is very important to prevent this type of risks because they might develop into a catastrophic contingency. On the other side; a proper and quick contingency detection can save the UAS platform.

- Finally the *minor contingency* category is shown on the left of Figure 7. Minor contingency treats any little anomaly or failure which can be recovered. This module establishes a contingency hypothesis and it plans and executes a response. After that, the module monitors the system response until the contingency disappears.

IV.A.1. Catastrophic Contingencies

Inside this category we have classified all the contingencies which interrupt the UAS flight or a safety landing. In practice it means loss of the platform. For example: a structural defect in the fuselage, in the autopilot or a flight management failure. In order to respond to these contingencies, it is considered an emergency component aggregated to our architecture called *Flight Termination System* (FTS). This system will be triggered by the catastrophic category. The FTS commonly will be composed by parachute system. The main objective is to guarantee that the potential impact to the ground of the UAS will not fatally damage any person or infrastructure. As it is mentioned before, this module will be out of the MAREA middleware to ensure its suitable operation even after a local network failure.

IV.A.2. Hazardous Contingencies

This category manages all contingencies which reduce the aircraft airworthiness. This lack of airworthiness may put in danger the mission success or sometimes developt into catastrophic contingency. Also this category is composed by those contingencies which make impossible the mission objectives, as for example any failure in the payload needed for the mission. This component has different reactions in front of these contingencies:

- *Go Home*: In this response the UAS will be sent directly to its final destination and the mission will be aborted. The UAS damage is important enough and makes impossible the normal mission development. The path to go back home is managed by the Flight Plan Manager.
- *Go Home by Alternative Flight Plan*: In the dispatching phase, it is defined the flight plan to come back home. If the emergency situation in critical enough, it may be needed an alternative path to go back home. For example, the weather conditions have changed and the UAS airworthiness is in danger. Our flight plan description is composed by alternative paths; these paths are managed by the Flight Plan Manager.
- *Go Better Alternative Runway*: A UAS flight plan presents different landing possibilities. Due to its little size a lot of airfields may be suitable enough to ensure safety landings. This response is focused in finding the best alternative runway. The parameter in order to classify a runway as good can be the air traffic, number of runways, state of the airfield, etc.
- *Go Closest Alternative Runway*: When the contingency is very restrictive, it is needed landing as soon as possible in order to preserve the UAS platform. This response is addresses to this type of contingencies. The Flight Plan Manager will guide the UAS to this new runway.
- *Go to Flight Termination Field*: We can find specific situation where the UAS cannot arrive to the closest runway. In these situations the UAS must find somewhere to terminate the flight. This place must guarantee that the potential impact to the ground of the UAV will not fatally damage any person or infrastructure.

Figure 8 shows a simulated flight plan containing dispatching information related to in flight contingencies. For each flight plan segment best alternative landing sites are identified. Also, parts of the flight plan can be canceled, *i.e.* scans can be skipped, if direct return to destination is necessary. Also, termination fields are indicated. Usually, the closest termination fields will be chosen in case of a catastrophic contingency develops. The figure also details the fact that the approaching routes to each alternative field are pre-defined at dispatching time, and therefore the Flight Plan Manager only needs to find a suitable track to a fix that identifies the closest initial approach point to the selected airfield.

One of the responsible service of the hazardous contingency responses is the FPM. However, there are different ways to develop each response. For example, the UAS can go back home as soon as possible. Another way is switching off part or full of the payload. If the contingency is related to the fuel consumption; the UAS can flight optimizing it. This decision is proposed by the CM. However, it is executed by the Mission Manager (MMa). This service orchestrates the operation of the flight and payload services in order to achieve the mission goals. So, it can manage the way of execute these CM responses.

IV.A.3. Minor Contingencies

This category address those contingencies which do not reduce the UAS safety. They do not affect the UAS airworthiness; however in a future they may to become hazardous contingencies. Only in this category the contingency manager tries to solve or compensate the problem, so in this case the important objective is to know the cause of the contingency. For example, if the engine temperature is out of range, we must know the cause of this change to solve the problem or at least react to avoid the problem to further develop.

As it is shown in Figure 7, the contingency manager has a protocol to look up the cause of the contingency and respond in front of the minor contingencies. In order to correctly respond the CIC is divided in three different elements:

- *Hypothesis*: During this phase the CIC searches the cause of the alarm. The CIC studies all the information gathered by the Health Monitor. The result of this study is the hypothesis of the warning. Sometimes the CIC may find several hypotheses. In these cases the operator will have to choose the correct cause of the warning (if ground link is available). The CIC, through a probabilistic method, will propose the origin of the failure. To sum up; in this phase we establish and validate the contingency hypothesis.
- *Contingency Response*: When the contingency is located, the CIC has to plan and execute the contingency hypothesis responses. This phase has pre-defined responses which have been pre-loaded during the dispatch process. The CIC may present different responses in priority order to the operator for its selection (if ground link is available).
- *Evaluation Response*: When the operator has taken the decision, the CIC starts a new process to evaluate the response. This phase has to check that the contingency has terminated. In other case and after a timeout, all the process has to be repeated again.

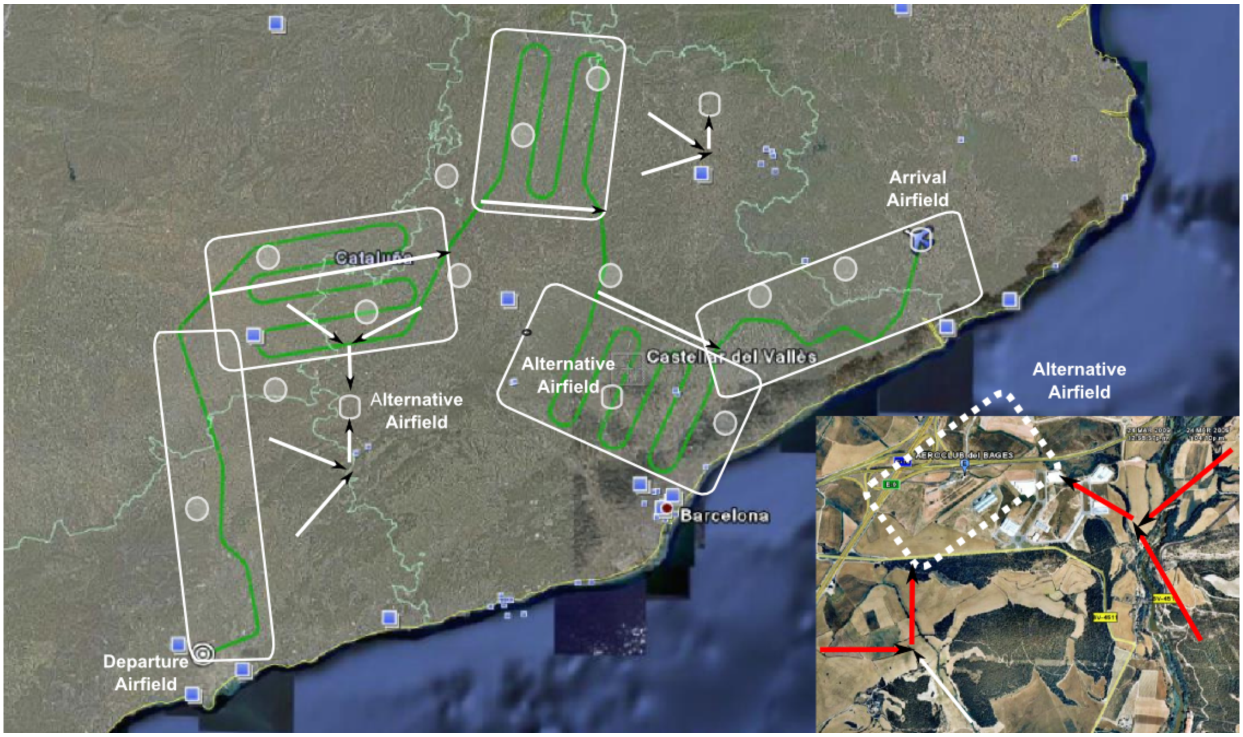

Figure 8. Example of flight dispatching with alternative airfields and emergency landing areas indicated.

IV.B. Contingency Dispatch Process

Before the flight, a mission dispatching process is developed in order to configure all the system and mission parameters. It works on four conceptual levels: mission, airframe, USAL services and finally the payload; evolving from general mission requirements to a precise UAV configuration. As it is mentioned before the Contingency Manager is divided in two phases: the In-Flight Contingency process and the Dispatch process.[14] The fist one has been explained in section IV.A. The second one is a piece of the UAS dispatch process. This part of the dispatch process is called Dispatch Contingency Analysis.

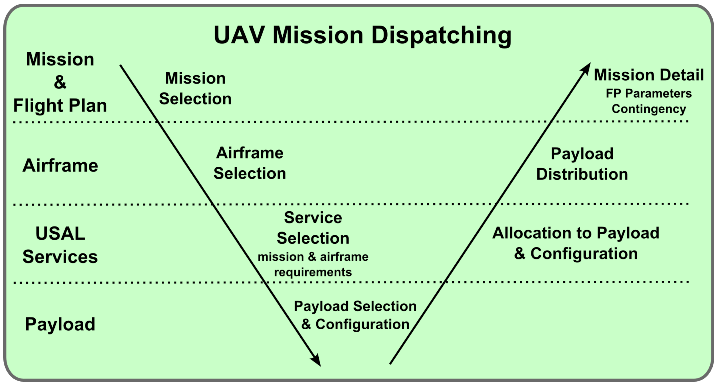

Figure 9. Organization of the UAS mission dispatching process.

This part identifies all reasons that may lead to a deviation of the expected UAV behavior. For each potential deviation a pre-defined reaction should be defined, going from partial cancellation of the mission to a complete cancellation of the flight. Reactions to contingencies may lead to mission modification in three different areas:

- Mission Deactivation: the mission manager service may go either into a limited operation mode for limited mission objectives or even into a total mission deactivation mode in case to complete mission cancellation.
- Payload and Service Deactivation: in case of partial or total mission cancellation some selected services may be deactivated in order to save energy and reduce the on-board communication traffic. Additionally, associated payload elements can be also disconnected if possible (either by software or because the electrical architecture allow to power down the modules).
- Alternative Routes and Landing Sites: the operative flight plan may include various predefined alternatives that can be activated from the USAL Flight Plan Manager in case the Contingency Manager notifies certain predefined conditions. Alternatives may range from taking the shortest route to an alternative airfield (in case of serious contingency), to skipping various mission related flight legs and proceed directly to the predefined return route of the original landing site.

V. Overview of the Dispatching Process

On top of the USAL a mission dispatching process has been proposed that follows the classical V-shaped process depicted in Figure 9. It works on four conceptual levels: mission, airframe, USAL services and finally the payload; evolving from general mission requirements to a precise UAS configuration.

All elements required for the dispatching process need to be previously characterized in terms of a predefined classification scheme. In that way, the mission requirements, the suggested flight-plan to be operated, all characteristics of the UAS airframe, the payload elements, the USAL service modules, etc; are characterized using XML patterns that describe their requirements, characteristics, configurations, dependencies, etc.

When a mission dispatching process is started a specific database is created. Information is added to this database and cross-checked in order to validate that requirements and dependencies are satisfied. If not, the user is informed in order to add further information (by adding more payload modules, changing the configurations, etc) or to eliminate conflicting elements in a backtracking process. The database will evolve until all phases are completed and all information cross-checked. The result will be the actual UAS configuration suggested by the dispatching analysis.

Figure 10 overviews the actual number of steps that must be executed in order to achieve such evolution. These steps are grouped into four phases according to the inter-dependences among them; namely: *mission and airframe selection*, *payload, service and flight-plan coordination*, *detailed configuration* and *contingency analysis*.

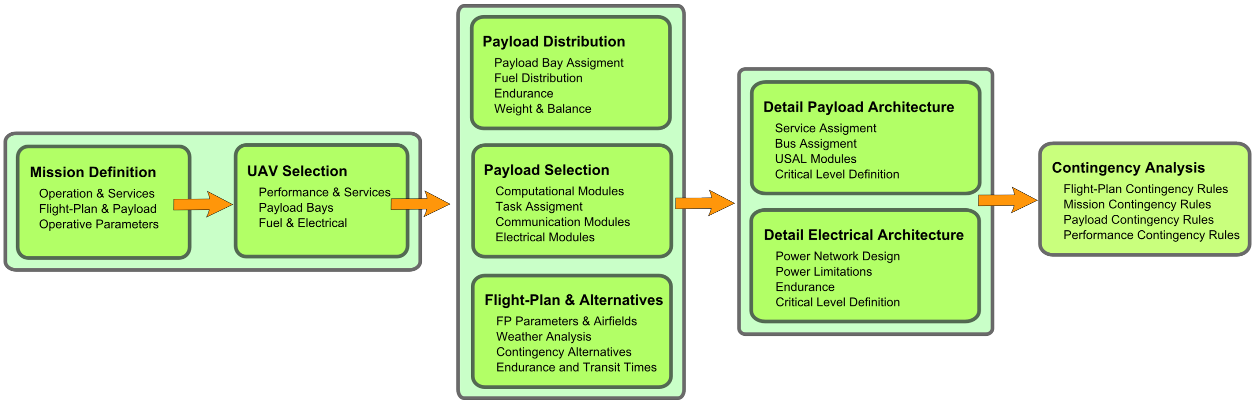

Figure 10. Overview of all phases in the mission dispatching process.

Mission and airframe selection simply requires that a concrete UAS mission to be selected in order to start the dispatching process from it. Then, the UAS airframe must be also selected. It is true that certain elements of the dispatching process may be determined without having the airframe at hand, but we believe that the gains will be small. Eventually, if the airframe does not fit the mission requirements the decision can be backtracked to another airframe.

Payload, service and flight-plan coordination is the main core of the dispatching process. It is formed by four interrelated steps: payload selection, payload distribution, flight-plan and alternatives; and service dependencies analysis. These steps can be re-executed as many times as necessary until the necessary payload, fuel/energy and required USAL services are selected and convergence among their inter-dependencies is reached.

In the *detailed configuration* phase various parts of the UAS system are analyzed to provide a detailed configuration that will guide the actual setup of the UAS. All interconnection buses are specified in a detailed level: including the power electrical network, the intra-UAS communication networks, the sensor-CPU connections, etc. Once all these details are available criticality levels can be defined. These levels will allow to decide which payload modules are essential for a safe flight or simply essential for the mission itself; or in case of power malfunction decide which modules can be powered of in order to increase the safety levels.

Even though previously included in the *Payload, service and flight-plan coordination* phase, dependencies need to be continuously validated because any minor change may violate a restriction or a dependency, forcing a backtrack to re-evaluate the selected configuration.

Finally, the *contingency analysis* phase will put all available information together to define a particular reaction scheme for pre-defined contingencies. These contingencies range from performance contingencies (in case expected UAS flight performance is not being achieved), to fuel/energy monitoring, and to system malfunction (either sensors, computers or the software itself).

The final result of all these dispatching steps is a database of configuration information. From these database configuration files can be automatically generated in order to be used at UAS start-up by the USAL service architecture, or configuration check-lists to be used for UAS setup on ground or even pre-flight checklists to be validated on the ramp.

VI. Conclusions and Future Work

UAVs may eventually replace manned aircrafts allowing much more cost-effective operations for example as complementary to classical satellite applications. However like for the rest of aerial means, the UAS engineers have to take in account contingency situations. To keep operations cost-effective we need to reuse the hardware and software platform for different civil missions. During these missions we may find UAS failures, bad weather, payload failures, etc.

This paper presents the architecture of a service called Contingency Manager (CM) which centralizes all the alarms and contingencies of the system. The CM is an important piece of the USAL flight category. It works with the Flight Plan Manager (FPM) to offer alternative responses in front of contingency situations. With these two pieces of software the UAS can manage hazardous situation, guaranteeing the UAS integrity.

Also the service is capable to recover from minor contingencies and remain the UAS mission.

Future work will be addressed to improve the service intelligent response in front of hazardous and minor contingencies. All the contingencies have to be studied in order to offer several responses and help the operator in her decision. Another research line is to integrate and coordinate contingency responses with all the USAL services. A coordinated response will be more effective than a CM service response.

Acknowledgments

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