SoS Fault Modelling at the Architectural Level in an Emergency Response Case Study

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Abstract—Systems of systems (SoSs) are particularly vulnerable to faults and other threats to their dependability, but frequently inhabit domains that demand high levels of dependability. For this reason fault tolerance analysis is important in SoS engineering. The COMPASS project has previously proposed a Fault Tolerance Architecture Framework (FMAF), consisting of a collection of viewpoints that support systematic reasoning about faults in an SoS at the architectural level. The FMAF has been demonstrated previously with an analysis of an example fault in an emergency response SoS. In this paper we present further examples of the FMAF's practical use, by analysing different types of faults drawn from the same emergency response case study. These example faults exercise different aspects of the FMAF, demonstrate its use in more complex fault modelling scenarios, and raise new questions for further development.

I. INTRODUCTION

Systems of systems (SoSs) face particular challenges that can increase the risk of faults, whilst typically inhabiting domains which require a high degree of dependability. There are many examples of the types of faults that SoSs may face. For example, communication problems can compromise the distributed constituent systems (CSs) with no warning. CSs are likely to be different ages and make different assumptions; mismatched assumptions (e.g., architectural mismatch [11]) are a real risk. CSs may be independently managed, may be unaware of the SoS or reluctant to participate in it, and may evolve without considering the needs of the SoS or providing advance notice, so there is a high risk of unanticipated failures in SoS functionality. Error propagation may be complex, governance difficult to track, and recovery strategies may not be clear. This is particularly a problem in cases where the failure of one CS may result in an SoS-level fault which must be detected by another CS, or which could be detected by one of several separate CSs, and in cases where CSs which may be required to implement extra (possibly costly) recovery activities. If CSs have separate ownership and motivations, there is often a need to consider the options in advance and agree which CSs are responsible for detecting errors or for implementing and executing recovery strategies.

For these reasons, we argue that an architectural approach to fault modelling is particularly useful for the SoS reliability engineer. The COMPASS project has developed a Fault Modelling Architectural Framework (FMAF) that provides a systematic approach to capturing fault tolerance aspects of SoSs. The COMPASS FMAF has been described in previous publications [2], [3], [4] and its practical use demonstrated with the modelling of a single fault drawn from an emergency response SoS. In this paper we present an extension of previous work, modelling further faults extracted from the same case study. The additional faults exercise new aspects of the FMAF, such as the inclusion of faults which may be detected by multiple constituent systems.

The rest of this paper is laid out as follows: Section II briefly summarises some related work and Section III introduces the FMAF. Section IV introduces our case study and previous work. Sections VI and VII study two separate faults using the FMAF approach. Finally Section VII presents our conclusions. Work presented here forms part of the COMPASS project, building further on work presented in [3].

II. RELATED WORK

Fault tolerant architectures have been widely studied in the literature (e.g., see [5]). Architectural approaches are useful for modelling fault tolerance within an SoS. Some previous researchers have adopted an architectural approach, demonstrating feasibility. For example, [6] and [7] use UML to model erroneous behaviour in embedded systems, whilst [8] use SysML for analysis of dependable complex physical systems. SysML is also used in [9] for verifying safety requirements in embedded, safety-critical control systems.

III. FAULT MODELLING ARCHITECTURAL FRAMEWORK

The COMPASS Fault Modelling Architectural Framework (FMAF) encompasses a series of viewpoints to aid the SoS reliability engineer. In particular it supports:

• Definition of faults, errors and failures in an SoS
• Identification of and reasoning about causal chains
• Definition and identification of the boundaries of CSs
• Definition of erroneous states and recovery scenarios.

Table I (taken from [11]) presents the viewpoints of the FMAF, and briefly summarises their purpose.

When discussing fault tolerance in SoSs, we adapt a well-known dependability taxonomy which was initially provided by [10]. Under this taxonomy, a failure is a deviation from expected service, visible outside a given system. At the SoS level, the failure is a deviation from SoS-level service. An error is part of the SoS state that can lead to a failure. A fault is the cause of an error. We note that, within an SoS, a failure at the level of a single CS becomes a fault at the level of the SoS. A set of rules for ensuring consistency between the viewpoints is described in [3].

1http://www.compass-research.eu/
TABLE I. INFORMAL DESCRIPTION OF THE FMAF VIEWPOINTS (TAKEN FROM [4])

| Structural | Behavioural |
|------------|-------------|
| Fault/Error/Failure Definition | Defines faults, errors and failures of the SoS. Faults, errors or failures may be generalised into abstract categories. |
| Threats Chain View | Identifies progression of faults through errors to failures and relationships between the dependability threats and the constituents. |
| Fault Tolerance Structure | Shows the composition of the SoS with the required redundancy to tolerate a given fault. |
| Fault Tolerance Connections | Shows connections and interfaces between constituents of the SoS with the required redundancy to tolerate a given fault. Includes all the constituents identified in the respective Fault Tolerance Structure View. |
| Errorneous/Recovery Processes | Identifies the processes of the SoS, including erroneous behaviour and any required recovery processes. |
| Errorneous/Recovery Scenarios | Models behaviour in the presence of errors (with and without recovery) as scenarios. Shows erroneous behaviour propagation and recovery procedure triggers. |
| Fault Activation | Defines the behaviour within an SoS process and identifies when faults may be activated, what happens after activation and where in the process the error may be detected. |
| Recovery | Defines the behaviour of the recovery procedures that are triggered once an error has been detected. |

IV. CASE STUDY AND PREVIOUS WORK

Our case study is an emergency response SoS, supplied by the Italian company Insiel. Insiel supports an SoS in northern Italy incorporating separate emergency services (such as fire departments and ambulance services). The services are separately managed and funded. The SoS provides a single emergency point of contact for the public, and delivers the appropriate aid within a target time frame. The case study has been described in previous publications [2], [4], [3] that illustrate the use of the FMAF using a single potential fault drawn from the case study (the failure of the radio system used for communications).

In our analysis, we concentrate on the services within the emergency response SoS that supply medical aid. For the purposes of the fault tolerance analysis presented here, the constituent systems of the emergency response SoS include:

- A system of distributed, mobile Emergency Response Units (ERUs), comprising one or more medical staff and a driver.
- A radio system employed for communications
- A mobile phone system employed as a backup for the radio
- A central call centre which consists of expert operators and software (‘CUS’) to provide workflow

In [3] the nominal behaviour of the SoS and initial recovery processes for one fault (failure of the radio system) are presented in SysML. The simplified nominal behaviour of the CSs described above can be briefly summarised as follows:

- Call centre receives and processes emergency calls using the CUS
- Call centre operator finds an appropriate ERU (which may be idle or already on a lower priority assignment) and dispatches it to the new emergency
- The ERU travels to the target, dispenses aid and sends updates on current status over the radio to the call centre
- The call centre workflow software (the ‘CUS’) tracks specified metrics e.g. time to arrive
- The ERU staff decide on the next action: either further aid is not necessary and the ERU returns to idle state; or the casualty is transported to hospital for further treatment

The nominal behaviour of the system described here is our starting point for describing the emergency response SoS.

Three example faults for this SoS were proposed in [2] (also shown in Table I). Fault 1 has been modelled using the FMAF viewpoints previously [2]; in this paper we present FMAF models and analysis of Faults 2 and 3 for the first time. We consider Fault 3 first, in Section V, presenting a selection of FMAF viewpoints to model the SoS behaviour. There are several possibilities for presenting Fault Activation Views; we present one approach in our analysis of Fault 3, and in analysis of Fault 2 we present a second approach, for comparison. The alternative method adopted in Fault 2 is described in Section VI.

V. FAULT 3: ERU IN INCORRECT LOCATION

Fault 3 arises when ‘an operator sends an ERU to wrong location’. [2].

A. Threats Chain Views

The FMAF Threats Chain View (TCV) illustrates where in the SoS:

- the initial fault is located;
- the error can be detected; and
- the failure can be observed (this should be outside the SoS, as failures are observable at the external boundary of the system/SoS)

The TCV requires us to address the question which CS is responsible for activating the initial fault?. On considering all possibilities, we find that the same outcome (the ERU receives incorrect information from the operator) may have several
quite different sources: the caller; the call centre operator; the radio system; or the ERU crew. Dependent on this, the fault is detectable in different ways by different CSs, so we partition the fault for separate analysis as follows:

1) **Fault 3.1**: the caller provides poor quality location information
2) **Fault 3.2**: the call centre operator receives good information from the caller, but makes a mistake and provides incorrect location when transcribing this, or when transmitting it to the ERU over phone or radio
3) **Fault 3.3**: the radio quality is poor and the ERU mis-hears the location
4) **Fault 3.4**: the call centre and radio provide good information, but the ERU crew makes a mistake when transcribing or recording the target destination

We do not have space here for a full analysis of all four faults; we concentrate on the scenarios presented by 3.1 and 3.2 as representative samples.

Examples of TCVs are presented in Figure 1 (for Fault 3.1) and Figure 2 (for Fault 3.2). According to our dependability taxonomy, a fault should be introduced by a CS, and visible to external entities only at the boundary of the SoS (as a failure). In Figure 1 however, the caller both introduces the fault (incorrect location information), and also is responsible for detecting it, which is not correct according to our dependability taxonomy. Fault 3.1 is not in fact a ‘fault’: the SoS is behaving as expected, and the poor outcome is a direct result of poor information received from the environment (we regard the caller as part of the environment, not a CS). The TCV is not a good vehicle for modelling propagation of incorrect input data; the concept of an internal fault arising and propagating does not apply and we regard Figure 1 as an incorrect usage of the view. However, we do desire the emergency SoS to cope well with the inevitable eventuality that some information received from the environment will be of poor quality; this needs to be considered in the design of nominal and recovery behaviour, so although the TCV is not appropriate for Fault 3.1, other FMAF approaches are still useful.

Figure 2 shows that Fault 3.2 is activated in the Call Centre constituent system. In this situation the fault introduced by the call system becomes an error state at the level of the SoS, which can be detected by either the ERU or the call centre itself. Finally, if no detection and recovery take place, the error propagates to a failure visible at the external boundary of the SoS as a failure to attend the target casualty.

### B. Fault Tolerance Connections view

In [3] a nominal ‘connections view’ was presented for the SoS, in which:

- A Phone System provides a connection to the external environment (the Caller) and the Call Centre, permitting the two to communicate.
- A Radio System supplies interfaces to, and requires interfaces from, the ERU and the Call Centre, permitting these two CSs to communicate.
- The ERU provides a connection to the external environment in the form of the target casualty that the ERU attends.

The caller and the target are modelled separately because they may not be in the same location. The Phone System and Radio System are modelled explicitly because they are key systems upon which the SoS depends, but are associated with some known risks (e.g., radio reception is not possible in some mountainous or remote areas). Their inclusion permits us to model our reliance on them explicitly. The Phone System provides two possible connections; one for the use of external entities, and a separate one for the use of CSs inside the SoS.
The FMAF Fault Tolerance Connections View (FTCV) shows the internal and external SoS connections which may be necessary for fault tolerance. We present an FPCV in Figure 5 depicting the same SoS internal and external connections described above and in [3], but adapted to cope with Fault 3.1. In this scenario, the original caller provides poor quality location information. In some cases, after acquiring better information, the caller wishes to recontact the call centre. This may require consideration to be paid to connections between the SoS and the original caller, in order to allow the caller to phone back with new details. For example, the caller may be provided with details of the specific dispatch office that is dealing with the emergency, or perhaps the Phone System can recognise an incoming call from a number already associated with an ongoing emergency, and pre-populate the operator’s screen with known details.

Alternatively, in some situations it is possible that the caller does not provide quality location information and does not recontact the call centre (e.g., they may hang up or be cut off before the operator can reconfirm address details or may be too distracted to provide a quality address) and although it may be possible to ascertain the location of many callers from their phone number this is not always the case (e.g., the caller may not be in the same location as the target, or may be in a moving vehicle). In a situation like this, responsibility for detecting the error falls upon the ERU, which will realise the problem on arrival at the incorrect location, and then will contact the call centre for advice. After confirming the location of the ERU matches the location that was provided by the caller, the call centre operator needs further information about the correctness of the information they provided. Sometimes the operator may need to re-contact the caller to confirm the correct location. For this reason, the FTCV model for Fault 3.1 shows an additional connection that allows the call centre operator to phone the original caller back. Other variations of Fault 3 may also require modified or additional connections within the SoS. For example, Figure 3 does not include the Mobile Phone System which can be used as a backup in the event of a Radio System failure, but the connections with the Mobile Phone system become important when modelling Fault 3.3 (the radio quality is too poor to hear the location clearly).

C. Fault Activation Views

Fault Activation Views (FAVs) are behaviour models which identify where, within the nominal behaviour, a fault can arise and which CS(s) will detect the fault. Figure 4 presents a Fault Activation View (FAV) for Fault 3.2 (the call centre operator introduces the fault by providing incorrect details to the ERU). The fault’s activation, detection and recovery are represented using interruptible regions. There are three interruptible regions in this FAV; one to represent the activation of the fault (within the call centre), and two representing opportunities to detect the resulting erroneous state and initiate recovery. Two CSs are capable of detecting the error: the operator may detect this themselves (e.g., by checking recordings of the call) and recontacting the ERU; or alternatively the ERU may detect the erroneous state after arriving at an incorrect address. Each detection event prompts the beginning of the recovery process; for example, in Figure 4 the error detection leads to the process ‘Start Recovery 3.2a (CC)’ or ‘Start Recovery 3.2b (ERU)’. These recovery processes differ very slightly; for example, if the ERU detects the fault, then the ERU will need to contact the call centre for advice. However, both recovery processes involve the operator clarifying the genuine emergency location (e.g., via recordings of the original call) and transmitting it to the ERU, or selecting an alternative ERU if it is closer (omitted here).

D. Erroneous/Recovery Processes and Scenarios

Analysis of Fault 3 has identified some new recovery procedures to be designed and enacted when specific faults are uncovered. For example, we can see that procedures need to be designed for: the call centre operator, for situations when more information about location is required or where the original caller phones back with extra location details; and for the ERU, when arriving at an incorrect location. We model these using the FMAF Erroneous/Recovery Processes and Erroneous/Recovery Scenarios (omitted due to space limitations).

VI. FAULT 2: ERU BREAKS DOWN OR CRASHES

Fault 2 arises when an ERU has broken down or crashed.

A. Fault Activation View and Recovery View

An FAV for Fault 2 is presented in Figure 5. In trying to answer the question of which activity is interrupted, we find that the fault may arise in one of several different stages of ERU behaviour. The possibilities are:

- **Fault 2.1:** the ERU is currently travelling to a target
- **Fault 2.2:** the ERU is currently transporting a patient to a hospital
- **Fault 2.3:** the ERU is not currently on assignment

Recovery processes may differ for each of these scenarios, so we partition them (they can be amalgamated later if we discover that detection and recovery do not differ). For some of these scenarios, recovery simply consists of providing the medical crew with transport and removing or repairing the original vehicle. However, if the ERU is travelling to or transporting a patient, then in addition to these steps an alternative
ERU must be directed to take over patient transportation, because waiting for repair or a replacement vehicle introduces unacceptable delay. Figure 5 presents an FAV for Fault 2.1 (FAVs of Faults 2.2 and 2.3 omitted due to space limitations). The fault is depicted as activating during the ERU nominal process ‘ServiceRescue’.

Initially for Fault 2 we assume that the ERU crew will be the first to detect the problem. However in some situations the ERU crew may be incapacitated and unable to communicate with the SoS (e.g., they are injured themselves, or the radio equipment is damaged). In this case, detection falls to the call centre operator. The operator may be alerted to the problem, e.g., via phone calls from members of the public. Or the operator may raise the alarm after being unable to contact the ERU within a reasonable timeframe. For this reason, Figure 5 presents two possible detection events, each resulting in a separate recovery process; one recovery process is initiated if the ERU themselves detect and report the fault, and the other recovery strategy is initiated by the call centre operator.

Figure 6 presents a recovery view for Recovery Process 2.1a. This recovery is appropriate for Fault 2.1, and is initiated by the call centre (as shown in Figure 5). An FMAF recovery view shows what action is taken by each CS as the SoS recovers from the fault. In this case, Fault 2 was activated before the ERU reached the target, so recovery involves finding a new ERU, (‘ERU 2’), to attend the original target, (possibly diverting an ERU on a lower priority assignment). In addition, the original vehicle and its crew must also be dealt with, which may involve dispatching repair teams, or initiating a new rescue event if the ERU themselves detect and report the fault, and the other recovery strategy is initiated by the call centre operator.

The question still arises of what the operator should do if they suspect there is a problem (e.g., because the ERU has been uncontactable for some time) but does not have details of the nature of the problem (e.g., it’s unknown whether there is a break down or an accident). One possible strategy is to assume the worse case scenario immediately: the call centre operator could dispatch a vehicle with aid if the ERU is uncontactable for some predetermined period of time. This will lead to crashed and broken down ERUs being recovered much more quickly than otherwise, but it risks wasting resources if - for example - the ERU is in a radio-shadowed area and not suffering any vehicle problems. Alternatively, the ERU suppliers can elect to take some other action - e.g., installing devices that can self-report some types of vehicle problems; this requires a business case to consider the probable cost benefits to each CS affected by the activation of the fault and initiation of recovery. There is a need to model and agree upon the correct recovery procedure in advance, because in this case the behaviour and installed devices of one CS (the ERU) need to be well understood by another CS (the call centre) in order to diagnose a problem; and because the call centre will need to take responsibility for initiating recovery action (with an
associated cost) based on the expected behaviour of the ERU crew and/or hardware. The FMAF models can be useful here for identifying different activities that can be affected by a fault (thereby aiding with partitioning faults which have similar causes but different recoveries, as is the case for Faults 2.1, 2.2, and 2.3) and clearly showing which CS can detect the problem and will be initiating recovery.

The FAV is also helpful for identifying where nominal procedures may need to be modified as a result of designing recovery procedures. For example, after considering options for recovering from Fault 2.1, the reliability engineer may decide that the call centre should monitor the ERU’s response times. There is a concept of a timer in the call centre’s nominal behaviour, visible in [3]; the reliability engineers can return to this nominal behaviour model and modify or extend as necessary to permit the appropriate recovery.

VII. CONCLUSIONS AND FUTURE WORK

In this paper we have briefly demonstrated the use of the COMPASS-developed FMAF approach for modelling fault tolerance in an SoS at the architectural level. We have built further on a case study which was previously published with a single fault modelled; our contribution here goes further by demonstrating the modelling of two quite different faults in the same SoS.

In this paper we present two faults which may be detected by more than one CS. For example, Fault 2.1 (ERU crashes or breaks down en route to target) may be detected by the ERU crew, or alternatively by the call centre. Fault 3.2 (call centre transmits incorrect location) presents an example of a fault which may be detected by two different CSs, and also where the fault activation and detection/recovery may be allocated to different CSs. The identity of the detector is significant, because this dictates which recovery processes are needed. For example, for Fault 2, in cases where the ERU detects the fault, details on ERU status and needs are available and narrow down the necessary recovery actions. However, if the call centre acts as the detector and the ERU is uncontrollable, the call centre does not necessarily have access to these details and must make some assumptions.

We have employed two different methods of presenting the multiple detector roles in our FAV diagrams for Faults 2 and 3. In Figure 5 we have employed an interruptible region for the detection of Fault 2, and initiation of recovery by the ERU, and in the same diagram a separate interruptible region for the detection of Fault 2 and initiation of recovery by the call centre. However, in Figure 4 we have employed a single interruptible region to depict detection of Fault 3 and initiation of recovery by either the ERU or the call centre. There are advantages and disadvantages for each method. Employing separate interruptible regions for the two different ‘detector’ roles (as in Figure 5) allows us to demonstrate clearly where the responsibility for the detection and recovery lies. This is particularly pertinent for an SoS, where the separate constituent systems are independent and autonomous. Representing the initiation of similar recovery processes together (e.g., Figure 4) is useful for situations where separate recoveries need to be considered together, and ensures that the ‘flow’ of processes is easily followed. This is important for an SoS, where there may be events arising in different constituent systems in parallel. The FMAF modelling approach is a useful tool for reliability engineers, who may need to initiate some negotiations and agreements between independently managed and funded CSs, particularly in cases where one CS may need to accept responsibility for detecting and recovering from faults introduced by others.

There are several areas for future and ongoing work in this area of SoS fault tolerance, including: modelling remaining faults in the TMS case study; including additional concepts from the dependability taxonomy [10]; incorporating the newly identified extensions into the FMAF framework definition; and the development of tools and techniques to support linking between architectural models and fault analysis tools (such as HiP-HOPS[3] and formal verification techniques.

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