

# Safety Annex for Architecture Analysis and Design Language

Danielle Stewart<sup>1</sup>, Jing (Janet) Liu<sup>2</sup>, Michael W. Whalen<sup>1</sup>, and Darren Cofer<sup>2</sup>

<sup>1</sup> University of Minnesota

Department of Computer Science and Engineering

dkstewar, whalen@cs.umn.edu

<sup>2</sup> Rockwell Collins

Advanced Technology Center

Jing.Liu, darren.cofer@rockwellcollins.com

**Abstract.** This paper describes a new methodology with tool support for model based safety analysis. It is implemented as a new Safety Annex for the Architecture Analysis and Design Language (AADL). The Safety Annex provides the ability to describe faults and faulty component behaviors in AADL models. In contrast to previous AADL-based approaches, the Safety Annex leverages a formal description of the nominal system behavior to propagate faults in the system. This approach ensures consistency with the rest of the system development process and simplifies the work of safety engineers. The language for describing faults is extensible and allows safety engineers to weave various types of faults into the nominal system model. The Safety Annex supports the injection of faults into component level outputs, and the resulting behavior of the system can be analyzed using model checking through the Assume-Guarantee Reasoning Environment (AGREE).

**Keywords:** Model-based systems engineering, fault analysis, safety engineering

## 1 Introduction

System safety analysis techniques are well-established and are a required activity in the development of safety-critical systems. While model based development methods are widely used in the aerospace industry, these methods are only recently being applied to system safety analysis. Model-based systems engineering (MBSE) methods and tools based on formal methods now permit system-level requirements to be specified and analyzed early in the development process [5, 6]. These tools can also be used to perform safety analysis based on the system architecture and initial functional decomposition. Design models can be integrated into the safety analysis process to help guarantee accurate and consistent results. This integration is especially important as the amount of safety-critical hardware and software in various domains has drastically increased due to the demand for greater autonomy, capability, and connectedness.

We have developed a Safety Annex for the Architecture Analysis and Design Language (AADL) [9] that provides the ability to reason about faults and faulty component

behaviors in AADL models. In the Safety Annex approach, we use formal assume-guarantee contracts to define the behavior of system components. The nominal model is then verified using the Assume Guarantee Reasoning Environment (AGREE) [6]. The Safety Annex provides a way to weave faults into the nominal system model and analyze the behavior of the system in the presence of faults. The Safety Annex also provides a library of common fault node definitions that is customizable to the needs of system and safety engineers.

There are other tools purpose-built for safety analysis, including AltaRica [14], smartIFlow [12] and xSAP [4]. These notations are separate from the system development model. Other tools extend existing system models, such as HiP-HOPS [1] and the AADL Error Model Annex, Version 2 (EMV2) [7]. EMV2 uses enumeration of faults in each component and explicit propagation of faulty behavior to perform error analysis. The required propagation relationships must be manually added to the system model and can become complex, leading to mistakes in the analysis.

In contrast, the Safety Annex supports model checking and quantitative reasoning by attaching behavioral faults to components and then using the normal behavioral propagation and proof mechanisms built into the AGREE AADL annex. This allows users to reason about the evolution of faults over time, and produce counterexamples demonstrating how component faults lead to failures. Our approach adapts the work of Joshi et. al in [13] to the AADL modeling language. More information on the approach is available in [15], and the tool and relevant documentation can be found at: <https://github.com/loonwerks/AMASE/>.

## 2 Preliminaries

In this section, we describe the overall process flow and introduce some terminology associated with the certification context. We also describe the system architecture modeling and verification environment that we are using.

### 2.1 Safety Assessment Process

One of our goals is to transition the tools we have developed into use by the safety engineers who perform safety assessment on the avionics products. Therefore, we need to understand how the tools and the models will fit into the safety assessment and certification process.

ARP4754A, the Guidelines for Development of Civil Aircraft and Systems [ref. ARP4754A], has been recognized by the Federal Aviation Administration (FAA) as an "acceptable method for establishing a development assurance process" [ref. AC 20-174]. Figure 2 from [ref. ARP4754A] demonstrates the ARP4754A process flow. The safety assessment process is a starting point of the integral processes, and is tightly coupled with the system development and verification processes. It is used to show compliance with certification requirements, and meeting a company's internal safety standards [ref. ARP4754A]. ARP4761, the Guidelines and Methods for Conducting Safety Assessment Process on Civil Airborne Systems and Equipment [ref. ARP4761], identifies a systematic means to show compliance. The guidelines presented in ARP4761 include

The diagram illustrates the ARP4754A Process, which is a structured approach to aircraft development and verification. It is organized into four main columns representing different levels of abstraction: Aircraft, System, Item, and Software/Hardware. Each column contains a series of boxes representing specific activities, with diagonal arrows indicating the flow of requirements (top-down) and verification (bottom-up).

**Top-Down Requirements Development and Validation:**

- Aircraft Level:** Aircraft Requirements Identification (4.1.4) leads to Aircraft FHA, PASA, and Aircraft CCA. A diagonal arrow labeled "Top Down Safety Requirements Development & Validation" points from the top-left towards the bottom-right.
- System Level:** System Requirements Identification (4.1.5 & 4.3) leads to System FHA, PSSA, and System CCA. A diagonal arrow labeled "Validation of requirements at the next highest level" points from the top-left towards the bottom-right.
- Item Level:** Item Requirements Identification (4.1.7 & 4.5) leads to System FTA and System CMA. A diagonal arrow labeled "Validation of requirements at the next highest level" points from the top-left towards the bottom-right.
- Software/Hardware Level:** Software Design and Hardware Design are shown at the bottom.

**Bottom-Up Requirements Verification:**

- Software/Hardware Level:** Software Design and Hardware Design lead to System FTA, System CMA, and System FMEA/FMES.
- Item Level:** Item Design (4.6.2 & 4.6.3) leads to Item Verification (5.5). A diagonal arrow labeled "Bottom Up Safety Requirements Verification" points from the bottom-left towards the top-right.
- System Level:** System FHA, PSSA, and System CCA lead to System SSA, System CCA, and System FMEA/FMES. A diagonal arrow labeled "System Integration" points from the bottom-left towards the top-right.
- Aircraft Level:** Aircraft FHA, PASA, and Aircraft CCA lead to Aircraft Verification (5.5). A diagonal arrow labeled "System Integration" points from the bottom-left towards the top-right.

**Central Verification Phases:**

- Item Verification:** Connects Item Design to Item Verification.
- Systems Verification:** Connects System Requirements Identification to System Verification.
- Aircraft Verification:** Connects Aircraft Requirements Identification to Aircraft Verification.

**References:**

- DO-178B/DO-254 Process
- ED-12B/ED-80 Process

A prerequisite of performing the safety assessment of a system design is to understand how the system works, primarily focusing on the integrity of the outputs and the availability of the product. The safety engineers then use the acquired understanding to construct the safety analysis artifacts, conduct safety analysis, and compare the analysis results with established safety objectives and safety related requirements.

In practice, prior to performing the safety assessment of a system, the safety engineers are often equipped with fair amount of knowledge on how system works in general, but not necessarily with the specific system. Acquiring the knowledge on the content and behavior of a specific system has shown to be time consuming to get it right. For example, it took a safety engineer two solid days to understand how the software works in a Stall Warning System (a small system in comparison to a flight control computer). The primary task includes threading the signal and function flows to relate the input and output signals from end-to-end, and understanding the causal effect between them. This is the same amount of time, if not more, as constructing the analysis artifacts and performing the analysis itself. In another example, it took a safety engineer more than a month to develop the PSSA document for a Horizontal Stabilizer Control System

(a medium system in comparison to a flight control computer), and multiple rounds of reviews including system, hardware, and software engineers.

Capturing failure mode in models and generating safety analysis artifacts directly from models can enhance communication and synchronization between system design process and safety assessment process, and the ability to analyze complex systems. Industry practitioners have come to realize the benefits and importance of using models to assist the safety assessment process (either by augmenting the existing system design model, or by building a separate safety model), and a revision of the ARP4761 with model based safety analysis appendix is under way.

Using the same system design model to conduct both system design and safety analysis can help reduce the gap in comprehending the system behavior and transferring the knowledge between the design model to the safety analysis model. It maintains a living model that captures the latest state of the system design as the process flows per Figure 2. It also allows all participants of the ARP4754A process to be able to communicate and review the system design using the "single source of truth".

Figure(added figure) adapted from [ref. ARP4754A] demonstrates our proposed process flow.

In order to allow performing system design and safety analysis on the same model, the system design model will need to be augmented to include both the system design information (e.g., system architecture, functional behavior) and safety-relevant information (e.g., failure mode, failure rate), at the same time keeping the two types of information distinguishable yet interactable from each other.

The next subsection describes the foundation of the modeling in more details.

## 2.2 Architecture Description and Design Contracts

The Architecture Analysis and Design Language(AADL) [ref AADL] is an architecture modeling language

It comes with associated annexes and tool extensions (see Section) in the Open Source AADL Tool Environment (OSATE) and allows for a wide range of system modeling and analysis capabilities (e.g., latency, throughput, behaviors).

Talk about AGREE

Following the motivation/discussion in the process subsection, talk about why we choose to extend AGREE in safety annex, instead of using a separate safety model, or a semi-separate safety model like EMV2.

## 3 Detailed Approach

### 3.1 Functionality

In this section, we describe the main features and functionality of the Safety Annex. An AADL model of the nominal system behavior specifies the hardware and software components of the system and their interconnections. This nominal model is then annotated with assume-guarantee contracts using the AGREE annex [6] for AADL. The nominal model requirements are verified using compositional verification techniques based on  $k$ -induction model checking [10].

Once the nominal model behavior is defined and verified, the Safety Annex can be used to specify possible faulty behaviors for each component. The faults are defined on each of the relevant components using a customizable library of fault nodes and the faults are assigned a probability of occurrence. A probability threshold is also defined at the system level. This extended model can be analyzed to verify the behavior of the system in the presence of faults. Verification of the nominal model with or without the fault model is controlled through the safety analysis option during AGREE verification.

To illustrate the syntax of the Safety Annex, we use an example based on the Wheel Brake System (WBS) described in [2] and used in our previous work [15]. The fault library contains commonly used fault node definitions. An example of a fault node is shown below:

```
node fail_to(val_in: real, alt_val: real, trigger: bool) returns (val_out: real);
let
  val_out = if (trigger) then alt_val else val_in;
tel;
```

The *fail\_to* node provides a way to inject a faulty input value. When the *trigger* condition is satisfied, the nominal component output value is overridden by the *fail\_to* failure value. In the WBS, the pump component generates an expected amount of pressure to a hydraulic line. Declaration of a non-deterministic fault in the pump component is shown below:

```
annex safety {**
  fault "In pump: pressure_output failed to non-deterministic value.": faults.fail_to {
    eq alt_value :real;
    inputs: val_in <- pressure_output,
            alt_val <- alt_value;
    outputs: pressure_output.val <- val_out ;
    probability: 1.0E-5 ;
    duration: permanent;
  }
**};
```

The *fault statement* consists of a unique description string, the fault node definition name, and a series of *fault subcomponent* statements.

**Inputs** in a fault statement are the parameters of the fault node definition. In the example above, *val\_in* and *alt\_val* are the two input parameters of the fault node. These are linked to the output from the Pump component (*pressure\_output.val*), and *alt\_value*, a nondeterministic value defined within the Safety Annex. When the analysis is run, these values are passed into the fault node definition.

**Outputs** of the fault definition correspond to the outputs of the fault node. The fault output statement links the component output (*pressure\_output.val*) with the fault node output (*val\_out*). If the fault is triggered, the nominal value of *pressure\_output.val* is overridden by the failure value output by the fault node. Faulty outputs can take deterministic or non-deterministic values.

**Probability** (optional) describes the probability of a fault occurrence.

**Duration** describes the duration of the fault; currently the Safety Annex supports transient and permanent faults.

To-add: HW fault and dependent fault:

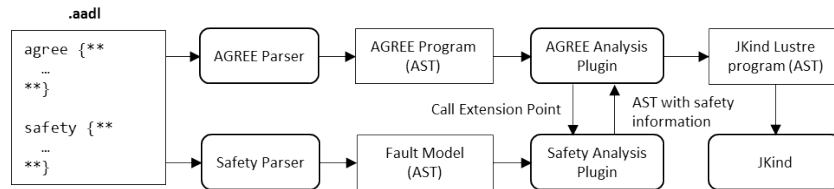
Fault propagations: it resides outside of fault statements and inside safety annex. This is because fault propagations are typically tied to the way components are connected or bound together; this information may not be available when faults are being specified for individual components. In addition, having fault propagations specified outside of a components fault statements makes it easier to reuse the component in different systems.

HW fault: no behavioral aspects.

Dependent fault modeling: With the introduction of dependent faults, active faults are divided into two categories: independently active (activated by its own triggering event) and dependently active (activated when the faults they depend on become active). Top level fault hypothesis (e.g., maximum number of faults that can be active, or probability threshold for occurrences of faults) now applies to independently active faults. Faulty behaviors augment nominal behaviors whenever their corresponding faults are active (either independently active or dependently active).

### 3.2 Architecture and Implementation


The architecture of the Safety Annex is shown in Figure 2. It is written in Java as a plug-in for the OSATE AADL toolset, which is built on Eclipse. It is not designed as a stand-alone extension of the language, but works with behavioral contracts specified AGREE AADL annex and associated tools [6]. AGREE allows *assume-guarantee* behavioral contracts to be added to AADL components. The language used for contract specification is based on the Lustre dataflow language [11]. AGREE improves scalability of formal verification to large systems by decomposing the analysis of a complex system architecture into a collection of smaller verification tasks that correspond to the structure of the architecture.



**Fig. 2.** Safety Annex Plug-in Architecture

AGREE contracts are used to define the nominal behaviors of system components as *guarantees* that hold when *assumptions* about the values the component's environment are met. The Safety Annex extends these contracts to allow faults to modify the behavior of component inputs and outputs. To support these extensions, AGREE implements an Eclipse extension point interface that allows other plug-ins to modify the generated abstract syntax tree (AST) prior to its submission to the solver. If the Safety Annex is enabled, these faults are added to the AGREE contract and, when triggered, override the nominal guarantees provided by the component. An example of a portion of an initial

AGREE node and its extended contract is shown in Figure 3. The `__fault` variables and declarations are added to allow the contract to override the nominal behavioral constraints (provided by guarantees) on outputs. In the Lustre language, assertions are constraints that are assumed to hold in the transition system.



```

agree node green_pump(
  time : real
) returns (
  pressure_output : common__pressure__i
);
let
  guarantees {
    "Pump always outputs something" :
      (pressure_output.val > 0.0)
  }
tel;

agree node green_pump(
  time : real;
  __fault__nominal__pressure_output : common__pressure__i;
  fault__trigger__green_pump__fault_22 : bool;
  green_pump__fault_22__alt_value : real
) returns (
  pressure_output : common__pressure__i
);
var
  green_pump__fault_22__node__val_out : common__pressure__i;
let
  assertions {
    (green_pump__fault_22__node__val_out = pressure_output)
  }
  guarantees {
    "Pump always outputs something" :
      (__fault__nominal__pressure_output.val > 0.0)
  }
  green_pump__fault_22__node__val_out =
    faults__fail_to(
      __fault__nominal__pressure_output,
      green_pump__fault_22__alt_value,
      fault__trigger__green_pump__fault_22);
tel;

```

**Fig. 3.** Nominal AGREE node and its extension with faults

An annotation in the AADL model determines the fault hypothesis. This may specify either a maximum number of faults that can be active at any point in execution (typically one or two), or that only faults whose probability of simultaneous occurrence is above some probability threshold should be considered. In the former case, we assert that the sum of the true *fault\_trigger* variables is below some integer threshold. In the latter, we determine all combinations of faults whose probabilities are above the specified probability threshold, and describe this as a proposition over *fault\_trigger* variables.

Once augmented with fault information, the AGREE model follows the standard AGREE translation path to the model checker JKind [10], an infinite-state model checker for safety properties. The augmentation includes traceability information so that when counterexamples are displayed to users, the active faults for each component are visualized.

## 4 Case Studies

To evaluate the effectiveness of the Safety Annex, we updated the WBS model [15] to specify faulty component behaviors. The components' nominal and faulty behaviors are modeled separately. At the top-level AADL component, the fault hypothesis was specified as the maximum number of faults that can be active at any time. The AGREE contracts at the top-level component were verified using AGREE, with the "Perform Safety Analysis" option selected. This signals the tool to weave the nominal and faulty behaviors into one augmented AGREE model before feeding to the model checker.

In this example, the top level contract “Pedal pressed and no skid implies brake pressure applied” was verified in the presence of at most one fault active during execution. However, it was shown to be invalid when more than one fault was allowed. The counterexample indicated that both Selector’s outputs failed to non-deterministic values due to the faults introduced.

We also applied the Safety Annex to the Quad-Redundant Flight Control System (QFCS) model [3]. We introduced faulty behaviors to see the response of the system to several faults, and to evaluate fault mitigation logic in the model. The QFCS system-level properties failed when unhandled faulty behaviors were introduced.

We also used the Safety Annex to explore more complicated faults at the system level on a simplified QFCS model with cross-channel communication between its Flight Control Computers.

- Byzantine faults [8] were simulated by creating one-to-one connections from the source to multiple observers so that disagreements could be introduced by injecting faults on individual outputs. A system-level property failed due to the fault on the baseline model, but did not fail on the model with Byzantine fault handling protocol added. Using the Safety Annex like this can test a system’s vulnerability to Byzantine faults and verify mitigation mechanisms.
- Dependent faults in hardware were simulated by injecting faults to hardware components (physical layer) to affect their data outputs (logical layer), and consequently failing the software components bound to the hardware components. The relationship between the hardware components’ outputs and the software components’ inputs were specified in AGREE as part of the system’s nominal behavior.

#### **4.1 Safety Process Related Case Study**

value added to traditional safety assessment

#### **4.2 Scalability Related Case Study**

Talk about the findings from translating WBS LTL properties into AGREE/Safety Annex, e.g., missing including power in the system validity assessment that caused the compositional verification to fail?

### **5 Related Work**

Address NFM review comments

### **6 Conclusion**

We have developed an extension to the AADL language with tool support for formal analysis of system safety properties in the presence of faults. Faulty behavior is specified as an extension of the nominal model, allowing safety analysis and system implementation to be driven from a single common model. This new Safety Annex leverages



the AADL structural model and nominal behavioral specification (using the AGREE annex) to propagate faulty component behaviors without the need to add separate propagation specifications to the model. Next steps will include extensions to automate injection of Byzantine faults as well as the ability to specify dependent faults.

**Acknowledgements.** This research was funded by NASA contract NNL16AB07T and the University of Minnesota College of Science and Engineering Graduate Fellowship.

## References

1. Systems Modeling with EAST-ADL for Fault Tree Analysis through HiP-HOPS\*. *IFAC Proceedings Volumes*, 46(22):91 – 96, 2013.
2. AIR 6110. Contiguous Aircraft/System Development Process Example, Dec. 2011.
3. J. Backes, D. Cofer, S. Miller, and M. W. Whalen. Requirements Analysis of a Quad-Redundant Flight Control System. In K. Havelund, G. Holzmann, and R. Joshi, editors, *NASA Formal Methods*, volume 9058 of *Lecture Notes in Computer Science*, pages 82–96. Springer International Publishing, 2015.
4. B. Bittner, M. Bozzano, R. Cavada, A. Cimatti, M. Gario, A. Griggio, C. Mattarei, A. Micheli, and G. Zampedri. The xSAP Safety Analysis Platform. In *Tools and Algorithms for the Construction and Analysis of Systems - 22nd International Conference, TACAS 2016, April 2-8, 2016, Proceedings*, pages 533–539, 2016.
5. M. Bozzano, A. Cimatti, A. Griggio, and C. Mattarei. Efficient Anytime Techniques for Model-Based Safety Analysis. In *Computer Aided Verification (CAV '11)*, 2015.
6. D. D. Cofer, A. Gacek, S. P. Miller, M. W. Whalen, B. LaValley, and L. Sha. Compositional Verification of Architectural Models. In A. E. Goodloe and S. Person, editors, *Proceedings of the 4th NASA Formal Methods Symposium (NFM 2012)*, volume 7226, pages 126–140, Berlin, Heidelberg, April 2012. Springer-Verlag.
7. J. Delange, P. Feiler, J. Hudak, and D. Gluch. Architecture fault modeling and analysis with the error model annex, version 2, 06 2016.
8. K. Driscoll, H. Sivencrona, and P. Zumsteg. Byzantine Fault Tolerance, from Theory to Reality. In *SAFECOMP*, volume 2788 of *LNCS*, pages 235–248, 2003.
9. P. Feiler and D. Gluch. *Model-Based Engineering with AADL: An Introduction to the SAE Architecture Analysis & Design Language*. Addison-Wesley Professional, 2012.
10. A. Gacek, J. Backes, M. Whalen, L. Wagner, and E. Ghasabani. The JKind Model Checker. *ArXiv e-prints*, Dec. 2017.
11. N. Halbwachs, P. Caspi, P. Raymond, and D. Pilaud. The Synchronous Dataflow Programming Language Lustre. In *In Proceedings of the IEEE*, volume 79(9), pages 1305–1320, 1991.
12. P. Hönig, R. Lunde, and F. Holzapfel. Model Based Safety Analysis with smartIfFlow. *Information*, 8(1), 2017.
13. A. Joshi, S. P. Miller, M. Whalen, and M. P. Heimdahl. A Proposal for Model-Based Safety Analysis. In *In Proceedings of 24th Digital Avionics Systems Conference (Awarded Best Paper of Track)*, 2005.
14. T. Prosvirnova, M. Batteux, P.-A. Brameret, A. Cherfi, T. Friedlhuber, J.-M. Roussel, and A. Rauzy. The AltaRica 3.0 Project for Model-Based Safety Assessment. *IFAC Proceedings Volumes*, 46(22):127 – 132, 2013.
15. D. Stewart, M. Whalen, D. Cofer, and M. P. Heimdahl. Architectural Modeling and Analysis for Safety Engineering. In *In Proceedings of IMBSA2017: 5th International Symposium on Model Based Safety and Assessment*, 2017.