FRETting about Requirements: Formalised Requirements for an Aircraft Engine Controller*

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Abstract

[Context & motivation] Eliciting requirements that are detailed and logical enough to be amenable to formal verification is a difficult task. Multiple tools exist for requirements elicitation and some of these also support formalisation of requirements in a way that is useful for formal methods.

[Question/problem] This paper reports on our experience of using the Formal Requirements Elicitation Tool (FRET) alongside our industrial partner. The use case that we investigate is an aircraft engine controller. In this context, we evaluate the use of FRET to bridge the communication gap between formal methods experts and aerospace industry specialists. [Principal ideas/results] We describe our journey from ambiguous, natural-language requirements to concise, formalised FRET requirements. We include our analysis of the formalised requirements from the perspective of patterns, translation into other formal methods and the relationship between parent-child requirements in this set. We also provide insight into lessons learned throughout this process and identify future improvements to FRET. [Contribution] Previous experience reports have been published by the FRET team, but this is the first such report of an industrial use case that was written by researchers that have not been involved FRET's development.

1 Introduction

Formal verification uses mathematically-based techniques to guarantee that a system obeys certain properties, which is particularly useful when developing safety-critical systems like those used in the aerospace domain. Developing a correct set of requirements necessitates discussion with people who have expertise in the system under development, who may not have skills in formal methods. In which case, it can be beneficial to the requirements elicitation process to write the requirements in an intermediate language. Tools like NASA’s Formal Requirements Elicitation Tool (FRET) provide a gateway for developing formal requirements with developers who are not familiar with formal languages.

In this paper, we examine how FRET can be used in an industrial case study of an aircraft engine controller that has been supplied by our industrial partner, United Technologies Research Center (Ireland). FRET has previously been used to formalise the requirements for the 10 Lockheed Martin Cyber-Physical Challenges. However, to the best of our knowledge this paper provides the first experience report on FRET’s use on an industrial case study, by a team not involved in FRET’s development.

Our approach provides external and internal traceability. Using a tool like FRET to develop the requirements provides a link between natural-language requirements and formally verified artefacts. FRET also enables the user to describe a link between requirements at different levels of abstraction, which means that this traceability is maintained within the developing set of requirements. We also use FRET to collect information about the rationale behind a requirement, further improving the traceability; either back to a natural-language requirement, or forward to a more concrete requirement. These

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traceability features encourage better explainability of a requirement’s source, and the intermediate language improves the explainability of the requirements themselves.

The rest of the paper is laid out as follows. §2 outlines the relevant background material pertaining to FRET and the aircraft engine controller use case. Then, we describe our requirements elicitation process and present detailed requirements in §3. These requirements are analysed in §4. We discuss the lessons that were learned through this work in §5 and §6 concludes. We also provide a detailed appendix showing the full set of requirements, test cases, Simulink model and FRETISH requirements.

2 Background

This section provides an overview of FRET and the aircraft engine controller use case for which we were developing requirements.

FRET: is an open-source tool that enables developers to write and formalise system requirements [1]. FRET accepts requirements written in a structured natural-language called fretish, in which requirements take the form:

```
scope condition component shall timing response
```

The condition, component, and response fields are mandatory; scope and timing are optional fields. This allows responses that are tied to a scope, are triggered by conditions, relate to a system component, and may have timing constraints.

The underlying semantics of a fretish requirement is determined by the scope, condition, timing, and response fields. There is a template for each possible combination of a requirement’s fields, currently FRET provides 160 such templates [8]. The selected template is used to generate formalisations of the associated requirement in both past- and future-time metric Linear-time Temporal Logic (LTL). FRET displays a diagrammatic semantics for each requirement, which shows: the time interval where it should hold, and its triggering and stopping conditions (if they exist). Both versions of the requirements are helpful for sanity-checking what has been written in fretish.

The user must give each fretish requirement an ID, which can be used to create a many-to-many, hierarchical link between requirements: a parent requirement may have many child requirements, and one child may have many parents. While this link facilitates traceability, FRET does not define this relationship (formally or otherwise). For example, a child requirement does not inherit definitions from its parent. We discuss possible improvements to this link in §4.2. FRET also allows the user to enter ‘Rationale’ and ‘Comments’ for a requirement, which further supports traceability and encourages explainability of requirements.

FRET can automatically translate requirements into contracts for a Simulink diagram, written in CoCoSpec, which are checked during Simulink simulations by the CoCoSim tool, using the Kind2 model checker [4]. FRET can also generate runtime monitors for the Copilot framework [6].

Aircraft Engine Controller: Our use case is a software controller for a high-bypass civilian aircraft turbofan engine, provided by our industrial partner on the VALU3S [2] project, based on existing controller designs [13, 14]. It is an example of a Full Authority Digital Engine Control (FADEC) system, which monitors and controls everything about the engine, using input from a variety of sensors. The engine itself contains two compressors (high-pressure and low-pressure) turning a central spool, which drives the engine.

As described in our prior work [9], the controller’s high-level objectives are to manage the engine thrust, regulate the compressor pressure and speeds, and limit engine parameters to safe values. It should continue to operate, keeping settling time, overshoot, and steady state errors within acceptable limits, while respecting the engine’s operating limits (e.g. the spool’s speed limit), in the presence of:

- sensor faults (a sensor value deviating too far from its nominal value, or being unavailable),
- perturbation of system parameters (a system parameter deviating too far from its nominal value), and
- other low-probability hazards (e.g. abrupt changes in outside air pressure).

The controller is also required to detect engine surge or stall and change mode to prevent these hazardous situations.

Our industrial partner has supplied us with 14 English-language requirements (Table 1) and 20 abstract test cases, which provide more detail about the controller’s required behaviour. The naming
convention for requirements is:
\[ \text{use case id}_R \cdot \text{parent requirement id}_R \cdot \text{child requirement id}_R \]

For example, because this is Use Case 5 in the VALU3S project\(^1\), requirement one is named UC5_R.1. Note, we use a similar naming convention for test cases. Table 2 shows the abstract test cases for UC5_R.1. Our industrial partner also designed the controller in Simulink\(^2\), shown in the extended version of this paper\(^3\).

For our Use Case, we collaborated with scientists in the System Analysis and Assurance division of an aerospace systems company. The hour-long requirements elicitation meetings were held monthly, over a period of 10 months, with additional meetings as needed. In these meetings, our collaborators reviewed the FRETISH versions of their natural-language requirements, validating our formalisation and clarifying ambiguities for us. Since our collaborators were already familiar with other formal tools we were able to introduce them to FRET quite quickly. However, we produced a training video for other members of the project consortium\(^4\).

### 3 Our Requirements Elicitation Process Using FRET

In this section we describe our requirements elicitation process. We begin by outlining how this fits into our larger approach to verification for the aircraft engine controller use case. We then describe our journey from natural-language requirements to formalised FRETISH requirements.

#### 3.1 Requirements-Driven Methodology

As part of the three-phase verification methodology outlined in our prior work\(^9\), we used FRET to elicit and formalise requirements for the aircraft engine controller. Focussing on Phase 1, this paper includes the full set of FRETISH requirements and presents lessons learnt, which were not discussed in\(^9\). Fig. 1 shows a high-level flowchart of our methodology, with an exploded view of the relationship between the artefacts involved in Phase 1. The methodology takes the natural-language requirements (Table 1), test cases, and Simulink diagram of the engine controller as input, and enables the formal verification of the system’s design against the requirements.

Phase 1 of our methodology involves formalising natural-language requirements using FRET, eliciting further detail as we progress. Phase 2 consists of two, potentially parallel, phases. Phase 2A uses FRET’s built-in support for generating CoCoSpec contracts that can be incorporated into a Simulink diagram for verification with the Kind2 model-checker. In Phase 2B, the formalised requirements drive a (manual) translation into other formal methods, as chosen by the verifier. These tools typically require the construction of a formal model of the system, which is verified against the translated requirements. This step requires translation of the FRETISH requirements into the formalism of the chosen verification tool. Finally, Phase 3 produces a report collecting the verification results and other useful artefacts, such as formal models, Simulink diagrams, various versions of the requirements, counter-examples, proofs, etc. This supports tracing the requirements through the system’s development lifecycle.

The following subsections describe the requirements elicitation process (Phase 1) in more detail. Figure 1’s exploded view, shows how natural-language requirements are translated into FRETISH parent requirements (solid arrow), and the test cases are translated into child requirements. Since we view the test cases as implementations of the natural-language requirements (dashed arrow), the child requirements are similarly viewed as implementations of their corresponding parent requirements. The left-hand side of Fig. 1 shows how the work in this paper fits within our development and verification methodology: the solid arrows from the FRETISH parent and child requirements, to Phases 2A and 2B, show how the output of this work is consumed by the next phase.

#### 3.2 Speaking FRETISH: Parent Requirements

The inputs to our requirements elicitation process were the Simulink diagram, 14 natural-language requirements (Table 1), and 20 abstract test cases that were supplied by our industrial partner. We

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1. The VALU3S project: [https://valu3s.eu](https://valu3s.eu)
2. Simulink: [https://mathworks.com/products/simulink.html](https://mathworks.com/products/simulink.html)
3. This Paper Extended Version: [https://arxiv.org/abs/2112.04251](https://arxiv.org/abs/2112.04251)
4. “Formalising Verifiable Requirements” Presentation: [https://www.youtube.com/watch?v=FQKbYChxPY&list=PLG1cM9eue6A6ceqBywXGjVoRFXOHp-uf7&index=9](https://www.youtube.com/watch?v=FQKbYChxPY&list=PLG1cM9eue6A6ceqBywXGjVoRFXOHp-uf7&index=9)

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| ID   | Description                                                                                                                                                                                                 |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| UC5_R_1 | Under sensor faults, while tracking pilot commands, control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_2 | Under sensor faults, during regulation of nominal system operation (no change in pilot input), control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_3 | Under sensor faults, while tracking pilot commands, operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed)                                                                 |
| UC5_R_4 | Under sensor faults, during regulation of nominal system operation (no change in pilot input), operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed) |
| UC5_R_5 | Under mechanical fatigue conditions, while tracking pilot commands, control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_6 | Under mechanical fatigue conditions, during regulation of nominal system operation (no change in pilot input), control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_7 | Under mechanical fatigue conditions, while tracking pilot commands, operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed)                                                    |
| UC5_R_8 | Under mechanical fatigue conditions, during regulation of nominal system operation (no change in pilot input), operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed) |
| UC5_R_9 | Under low probability hazardous events, while tracking pilot commands, control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_10 | Under low probability hazardous events, during regulation of nominal system operation (no change in pilot input), control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits) |
| UC5_R_11 | Under low probability hazardous events, while tracking pilot commands, operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed)                                                      |
| UC5_R_12 | Under low probability hazardous events, during regulation of nominal system operation (no change in pilot input), operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed) |
| UC5_R_13 | While tracking pilot commands, controller operating mode shall appropriately switch between nominal and surge / stall prevention operating state                                                                 |
| UC5_R_14 | During regulation of nominal system operation (no change in pilot input), controller operating mode shall appropriately switch between nominal and surge / stall prevention operating state |

Table 1: Natural-language requirements for the aircraft engine controller as produced by the aerospace use case in the VALU3S project. These 14 requirements are mainly concerned with continued operation of the controller in the presence of sensor faults (UC5_R_1–UC5_R_4), perturbation of system parameters (UC5_R_5–UC5_R_8) and low probability hazards (UC5_R_9–UC5_R_12). There are also requirements for switching between modes if engine surge/stall is detected (UC5_R_13–UC5_R_14).
elicited further information about the requirements through regular team discussions with our industrial partner. We started by translating the natural-language requirements into FRETISH, producing the set of 14 FRETISH requirements in Table 3. The correspondence between the FRETISH requirements and their natural-language counterparts is clear. For example, requirement UC5_R1 states that:

**Under sensor faults, while tracking pilot commands, control objectives shall be satisfied (e.g., settling time, overshoot, and steady state error will be within predefined, acceptable limits).**

This became the corresponding FRETISH requirement:

```java
if ((sensorfaults) & (trackingPilotCommands)) Controller shall satisfy (controlObjectives)
```

Producing this initial set of requirements enabled us to identify the ambiguous parts of the natural-language requirements. For example, the phrase “sensor faults” simply becomes a boolean in our FRETISH requirements, highlighting that we need to elicit more details. We captured these additional details as child requirements, as described in §3.3.

### 3.3 Adding Detail: Child Requirements

Once the FRETISH parent requirements (Table 3) were complete, we added more detail to make the requirements set more concrete. We paid particular attention to ambiguous phrases translated from the natural-language requirements. These extra details were drawn from the abstract test cases and from detailed discussions with our industrial collaborators, who clarified specific ambiguities.

We captured the extra details in 28 child requirements. As mentioned in §2, a child requirement does not inherit definitions from its parent(s). However, we use this hierarchical link to group the detail in the child requirements under a common parent, which enables the detailed child requirements to be traced back to the more abstract parent requirements.

For example, UC5_R1 was distilled into three requirements (UC5_R1.1, UC5_R1.2 and UC5_R1.3), shown in Table 4. These three child requirements each have the same condition and component, but differ in their responses. Each child requirement specifies one of the “control objectives” (settling time, overshoot and steady state error) mentioned in the natural-language version of UC5_R1. During elicitation discussions, it was revealed that these were actually the only control objectives that were
| Test Case ID | Requirement ID | Description |
|--------------|----------------|-------------|
| UC5_TC_1     | UC5_R_1        | **Preconditions**: Aircraft is in operating mode M and sensor S value deviates at most +/- R % from nominal value  
**Input conditions/steps**: Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results**: Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_2     | UC5_R_1        | **Preconditions**: Aircraft is in operating mode M and sensor S value is not available (sensor is out of order)  
**Input conditions/steps**: Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results**: Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |

Table 2: Abstract test cases corresponding to requirement UC5_R_1. Each specifies the preconditions for the test case, the input conditions/steps and the expected results.

of concern for this use case. Here, using FRET encouraged us to question exactly what the phrase “control objectives” meant.

Each of these requirements includes the condition when \( \text{diff}(r(i),y(i)) > E \) and the timing constraint until \( \text{diff}(r(i),y(i)) < e \), which were initially overlooked in the natural-language requirements but revealed during elicitation discussions with our industrial partner. The response must hold when the difference between the reference sensor value, \( r(i) \), and the observed sensor value, \( y(i) \), falls between specific bounds \( (E \text{ and } e) \). This important detail was missing from the parent requirement but was uncovered during our requirements elicitation.

The “Preconditions” of test cases UC5_TC_1 and UC5_TC_2 (Table 2) showed us that the phrase “Under sensor faults” meant a period where a sensor value deviates by ±R% from its nominal value or returns a null value. To represent this, the child requirements use the function \( \text{sensorValue}(S) \) where \( S \) is a parameter representing each of the 4 sensors for the engine controller. These requirements are thus applied to all of the sensors in the model.

In UC5_TC_1 and UC5_TC_2, the “Input conditions/steps” refer to the aircraft thrust and a change in the pilot’s input. We encoded this as the condition and response pair \( (\text{pilotInput} = \rightarrow \text{setThrust} = V2) \ \& \ (\text{observedThrust} = V1) \) and satisfy \( (\text{observedThrust} = V2) \), where \( V1 \) and \( V2 \) are thrust variables and \( =\rightarrow \) is logical implication. During elicitation discussions we found that this pair corresponds to the condition \( \text{trackingPilotCommands} \). This was a particularly important clarification because \( \text{trackingPilotCommands} \) models the phrase “while tracking pilot commands”, which the natural-language requirements use extensively. This underlines that it is possible for an ambiguous statement to have a very precise meaning that was lost while drafting the requirements.

The thrust variables \( V1 \) and \( V2 \) in our FRETISH requirements correspond to variables \( V1, V2, A1, \) and \( A2 \) in the test cases. During elicitation discussions, we found that \( V1 \) and \( V2 \) alone were sufficient to capture the requirement. \( V1 \) and \( A1 \) are used interchangeably as the initial thrust value, which we label \( V1 \). Similarly, \( V2 \) and \( A2 \) refer to the updated thrust value, which we label \( V2 \) for consistency. This is another ambiguity that our translation from natural-language to FRETISH helped to clarify.

Our industrial partner checked the child requirements to ensure that there were no errors or omissions. The intuitive meaning of FRETISH constructs simplified this check, and features like the requirements’ diagrammatic semantics provided quick feedback when we edited the requirements during elicitation discussions. The act of formalising the requirements helped us to identify ambiguities in the requirements, prompting elicitation of further detail from our industrial partner.
| ID    | FRETISH                                                                 | Controller shall satisfy (controlObjectives) | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives) | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
|-------|------------------------------------------------------------------------|------------------------------------------------|------------------------------------------------------|------------------------------------------------|------------------------------------------------------|------------------------------------------------|----------------------------------------------------------|
| UC5_R_1 | if ((sensorfaults) & (trackingPilotCommands))                         | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_2 | if ((sensorfaults) & (!trackingPilotCommands))                        | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_3 | if ((sensorfaults) & (trackingPilotCommands))                         | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_4 | if ((sensorfaults) & (!trackingPilotCommands))                        | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_5 | if ((mechanicalFatigue) & (trackingPilotCommands))                    | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_6 | if ((mechanicalFatigue) & (!trackingPilotCommands))                   | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_7 | if ((mechanicalFatigue) & (trackingPilotCommands))                    | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_8 | if ((mechanicalFatigue) & (!trackingPilotCommands))                   | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_9 | if ((lowProbabilityHazardousEvents) & (trackingPilotCommands))        | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_10 | if ((lowProbabilityHazardousEvents) & (!trackingPilotCommands))      | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_11 | if ((lowProbabilityHazardousEvents) & (trackingPilotCommands))        | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_12 | if ((lowProbabilityHazardousEvents) & (!trackingPilotCommands))      | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (controlObjectives)  | Controller shall satisfy (operatingLimitObjectives) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_13 | if (trackingPilotCommands)                                           | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |
| UC5_R_14 | if (!trackingPilotCommands)                                          | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) | Controller shall satisfy (changeMode(nominal)) | Controller shall satisfy (changeMode(surgeStallPrevention)) |

Table 3: FRETISH parent requirements corresponding to the natural-language requirements outlined in Table 1. The correspondence is clear to see and we have used booleans to represent the ambiguous terms from the natural-language requirements.

### 4 An Analysis of Elicited Requirements

This section provides an analysis of the FRETISH requirements that we produced for the aircraft engine controller use case. We note that the requirements only refer to one component, the Controller, but this could be decomposed to refer to specific blocks in the use case Simulink design.

#### 4.1 Requirement Templates

Each of the 14 FRETISH parent requirements (Table 3) uses the same pattern: condition component shall response. As described in §2, FRET maps each requirement into a semantic template so that it can generate the associated LTL specification. Our parent requirements all correspond to the template [null, regular, eventually], which specifies the scope-option, condition-option and timing-option, respectively (if the timing-option is omitted, then eventually is the default). Specific details about templates in FRET are given in [8].

We introduced until clauses into all of the 28 child requirements, although with different timing constraints. The introduction of the until clauses was identified through a combination of the information in the test cases and from extensive discussions with our industrial partner. However, the specific timing constraints required in-depth discussion with our industrial partner to identify. Most of the child requirements correspond to the template [null, regular, until]. However, some child requirements differed slightly as outlined below.

UC5_R_13 and UC5_R_14 generated a lot of discussion, because they differ so much from the other requirements; here, the system changes between modes of operation, so we use the scope clause. This

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Table 4: We have three distinct child requirements for UC5_R_1 that capture the correct behaviour with respect to each of settling time, overshoot and steady state error.

\[
\text{in surgeStallPrevention mode when } (\text{diff(setNL, observedNL)} < \text{NLmax}) \text{ if } (\text{pilotInput} \Rightarrow \text{!surgeStallAvoidance}) \text{ Controller shall until } (\text{diff(setNL, observedNL)} > \text{NLmin}) \text{ satisfy (changeMode(nominal))}
\]

Figure 2: FRETISH and semantics diagram generated for UC5_R_14.2. Here, ‘M’ indicates the mode, ‘TC’ the triggering condition, and ‘SC’ the stopping condition.

produced the child requirements shown in Table 5. The when and until clauses differ from the other requirements, because here the mode change is triggered by comparing the set value of the low-pressure compressor’s spool speed (setNL) to the value produced by the sensor (observedNL). It is necessary to differentiate between the cause of the difference, i.e. whether it was directly caused by pilotInput or by external factors (!pilotInput). In either case the system must change modes, but our industrial partner felt that it was important that the requirements distinguish the difference.

Fig. 2 contains the semantics diagram produced by FRET for UC5_R_14.2. The semantic template that was used is [in, regular, until]. In a recent study using FRET to formalise the 10 Lockheed Martin Cyber Physical Challenge problems, the most commonly used semantic template was [null, null, always] \[11\]. Of these 10 problems, the autopilot system is the closest to our case study, and it was the only requirement set to use the in scope-option. The timing-option in their requirements was different to ours; but we use until, which was introduced into FRETISH after that study.

We used all of the fields available in FRETISH in our use case, although a lot of our individual requirements used a subset of them. We only used scope in the four child requirements of UC5_R_13 and UC5_R_14. FRET provides many ways of specifying modes, but we only used in mode for this; there are many ways to specify a condition, but we only used when and if. There are also multiple
Table 5: Child requirements corresponding to UC5_R_13 and UC5_R_14. These differ from the previous requirements because we use the scope field to assert which mode of operation the controller is in.

Table 6: Child requirement of UC5_R_11 which has timing implicit through the use of the timestamp variables $T_1$ and $T_2$.

ways to specify timing, but in this case study we only used until clauses.

Despite until providing timing constraints, we did not use explicit times (e.g. ticks/timesteps/seconds) in our requirements. This is because the natural-language requirements (Table 1) do not mention timing, and our introduction of timing constraints came from elicitation discussions. However, time points are implicit in some of the child requirements, e.g. comparing $r(i)$ and $y(i)$ in the child requirements of UC5_R_1 (Table 4), or the $T_1$ and $T_2$ variables in UC5_R_11.1 (Table 6). The timing clause was not intentionally avoided, but we felt that the implicit time constraints better suited the requirements and was closer to the description agreed with our industrial partner.

4.2 Parent-Child Relationship in our Use Case

As previously mentioned, FRET allows a requirement to be related to another as a ‘parent’ or a ‘child’, but this relationship is not well defined, formally or otherwise. The parent-child relationship in FRET could be viewed as formal refinement: a concept supported by a variety of formal methods that enable formal specifications to be gradually made more concrete, while proving that they still obey a more abstract version of the specification. Similar approaches exist in the literature on refactoring goal-driven requirements.

If viewed through the lens of refinement, we would need to introduce abstraction invariants to relate the abstract and concrete specifications. These invariants facilitate the proof that the concrete specification does not permit any behaviours that the abstract specification forbids.

Here, we investigate whether FRET’s parent-child relationship can be expressed as formal refinement. In particular, it is possible to formalise the following abstraction invariant in relation to sensorfaults:

$$\text{sensorfaults} \iff (\text{sensorValue}(S) > \text{nominalValue} + R) \lor (\text{sensorValue}(S) < \text{nominalValue} - R) \lor (\text{sensorValue}(S) = \text{null})$$
Intuitively this means that the boolean \texttt{sensorfaults} (from the parent requirement) corresponds to the condition on the right of the \( \iff \) (from the child requirement). This kind of refinement is referred to as \textit{data refinement}.

Similarly, the abstraction invariant between \texttt{trackingPilotCommands} and the condition and response pair \((\text{pilotInput} \implies \text{setThrust} = \text{V2}) \& \text{and} \text{observeThrust} = \text{V1})\) and satisfy \((\text{observeThrust} = \text{V2})\) could be specified as:

\[
\text{trackingPilotCommands} \iff \text{pilotInput}
\]

The remainder of the condition-response pair above is then treated as \textit{superposition} refinement, which adds detail during refinement. This approach is used because of the update of the \texttt{observeThrust} variable which is difficult to express in an abstraction invariant because it provides a behavioural update rather than a simple match between booleans. The additional \texttt{when} and \texttt{until} clauses in the child requirement are also superposition refinements.

The parent-child relationship in FRET appears to us to be formal refinement, at least for our set of requirements. In which case UC5_R1 is refined by its three child requirements (UC5_R1.1, UC5_R1.2, UC5_R1.3). We will examine this further in future work, where we will seek to translate these requirements into a formalism that supports refinement, and then examine whether the appropriate proof obligations can be discharged by theorem provers.

### 4.3 Translatable Requirements

As mentioned in §1, our aim is to formally verify the aircraft engine controller system described in §2. It is often difficult to identify what properties a system should obey, for example what does it mean for the system to operate ‘correctly’. Identifying the properties to verify often causes difficulties for non-domain experts. FRET helped to guide conversations with the domain experts to facilitate the formalisation of the requirements.

FRET currently supports translation to the CoCoSim \cite{4} and Copilot \cite{12} verification tools. We are particularly interested in using CoCoSim since it works directly on Simulink diagrams. Thus, we have started to generate CoCoSim contracts for these requirements automatically using FRET \cite{10}. This is described in \cite{9} and corresponds to Phase 2A of the methodology outlined in Fig. 1.

As described in §4.1, we didn’t rely heavily on \texttt{timing} constraints that specified specific time steps, rather we used \texttt{until} constraints that could potentially be translated into boolean flags in other formalisms. As such, we believe that the vast majority of the requirements that we formalised in FRET could be used by other formal methods. For example, we may need to model the aircraft engine controller in an alternative formalism if some of these properties fail to verify using CoCoSim due to the state space explosion. This approach has been taken, manually, in previous work \cite{3}.

### 5 Lessons Learnt and Future Improvements

This section summarises some of the lessons that we learnt from this case study.

\textit{Communication Barrier:} We found that FRET and \texttt{fretish} provided a useful conduit for conversation with our industrial partner. Formalising natural-language requirements is often time-consuming because of contradictions and ambiguities. \texttt{fretish} provides a stepping-stone between readable natural-language requirements and their fully-formal counterparts, and helped us to step-wise reduce ambiguity. This process produced requirements that are easier to read than if they had been fully-formal, but which FRET can still automatically formalise.

We used FRET during elicitation discussions to explain and update our requirements, alongside our industrial partner. The diagramatic semantics gave a useful visualisation of the requirements, helping both us and our industrial partner to sanity-check updates. FRET also enabled our documentation of information for each natural-language requirement, recording the reasoning for any changes, alongside each \texttt{fretish} requirement, thus facilitating requirements explainability.

\textit{Parent-Child Relationship:} While not a formal relationship, the link between parent and child requirements enabled us to gradually make the requirements more concrete, by adding details and removing ambiguities. For example, the term \texttt{sensorfaults} in UC5_R1 was replaced with \((\text{sensorValue}(S) > \text{nominalValue} + R) \lor (\text{sensorValue}(S) < \text{nominalValue} - R) \lor (\text{sensorValue}(S) = \text{null})\) in its child requirements (Table 4). Documenting these links, via the ‘Parent ID’ and ‘Rationale’ fields in FRET,
provides a structuring mechanism that enables traceability within the requirement set. However, a more concrete definition of this link would be beneficial. We have suggested a definition using formal refinement, but an object-oriented inheritance relationship could also provide structure here.

**Limitations of FRETISH:** While a useful language, we note some limitations of FRETISH. Logical quantifiers ($\forall$, $\exists$) would be a welcome addition to FRETISH. For example, in UC5_R_1.1, we used `sensorValue(S)`, where the parameter $S$ indicates that this condition applies to all sensors. This is slight abuse of notation, it would have been more accurate to use a $\forall$ quantifier.

We also suggest that highlighting assignments to variables (which hold after the requirement is triggered) would be beneficial. For example, in UC5_R_1.1 we use the `observedThrust` variable in both the condition and the response. We expect that `observedThrust` has been updated by the response but this is not obvious, and may have implications when translating to other verification tools.

**An Industrial Perspective:** Our industrial partner had not used FRET before, so we asked them about their experience with it. They felt that the FRETISH requirements were ‘much more clear’ than the natural-language requirements, and that using a ‘controlled-natural language with precise semantics is always better than natural-language’. When asked if FRET was difficult to use or understand they said that FRET was ‘very easy to use; interface is intuitive; formal language is adequately documented inside the tool (along with usage examples)’. Overall, they found that FRET was useful ‘because it forces you to think about the actual meaning behind the natural-language requirements’.

Having installed FRET, our industrial partner found some usability improvements that could be made. Some were problems with the GUI, which have a low impact but happen very frequently. Other issues related to FRETISH; for example, they would like to be able to add user-defined templates and patterns, such as specifying timing within the condition component. Finally, to aid interoperability they ‘would like to be able to export to a format where the formalised requirements are machine readable (e.g. parse tree)’.

**Impact:** Formalising the requirements made them more detailed and less ambiguous; crucially much of the detail came from elicitation discussions, not from existing documents. FRET captures the links between requirements, and explanations of their intent (which was often more detailed than what already existed). These two things mean that the FRET requirements are a valuable development artefact. We are currently pursuing Phase 2 of our methodology (Fig. 1), in which we will assess the impact of the FRETISH requirements on verification.

We believe that FRET can scale to larger requirements sets, with the parent-child relationship providing a grouping function. However, for large sets of requirements it might be necessary to modularise or refactor the requirements so that they are easier to maintain. We are currently examining how FRETISH requirements can be refactored for our use case.

## 6 Conclusions and Future Work

This paper provides an experience report of requirements elicitation and formalisation of an aircraft engine controller in FRET. Our industrial partner provided a set of natural-language requirements, test cases, and a Simulink diagram. In close collaboration with our industrial partner, we clarified ambiguous text in the requirements and test cases. This was essential, as we had originally misunderstood some of the text. This iterative process produced a set of detailed FRETISH requirements that we, and our industrial partner, are confident correspond to the intent of the natural-language requirements. The FRETISH requirements are now ready for use in formal verification activities.

During this work we identified improvements that could be made to FRET, which we plan to investigate in future work. First, our FRETISH requirements contain quite a lot of repetition, so if changes were needed we often had to make the change manually in several places. This was very time-consuming, so we propose adding automatic requirement refactoring. Second, we plan to investigate how to introduce globally-declared variable types. This would improve the readability of requirements; clarifying what operations are valid for a particular variable, while encapsulating definitions that might change in the future. This could be made optional, to retain the ability to write very abstract initial requirements. Finally, we would like to improve the interoperability of FRET with other formal verification tools. For example, adding a translator to the input language of a theorem prover to avoid the state-explosion faced by model checkers (like Kind2, which is used to verify CoCoSpec contracts); or outputting the requirement to a parse tree, as suggested by our industrial partner.
References

[1] R.-J. Back and J. von Wright. *Refinement Calculus: A Systematic Introduction*. Springer, 1998.

[2] R. Barbosa, S. Basagiannis, G. Giantamidis, H. Becker, E. Ferrari, J. Jahic, A. Kanak, M. L. Eshaola, V. Orani, D. Pereira, et al. The VALU3S ECSEL Project: Verification and Validation of Automated Systems Safety and Security. In *Euromicro Conference on Digital System Design*, pages 352–359. IEEE, 2020.

[3] H. Bourbouh, M. Farrell, A. Mavridou, I. Slijivo, G. Brat, L. A. Dennis, and M. Fisher. Integrating Formal Verification and Assurance: An Inspection Rover Case Study. In *NASA Formal Methods Symposium*, pages 53–71. Springer, 2021.

[4] H. Bourbouh, P.-L. Garoche, T. Loquen, É. Noulard, and C. Pagetti. CoCoSim, a code generation framework for control/command applications An overview of CoCoSim for multi-periodic discrete Simulink models. In *European Congress on Embedded Real Time Software and Systems*, 2020.

[5] R. Darimont and A. Van Lamsweerde. Formal Refinement Patterns for Goal-Driven Requirements Elaboration. *ACM SIGSOFT Software Engineering Notes*, 21(6):179–190, 1996.

[6] A. Dutle, C. Muñoz, E. Conrad, A. Goodloe, I. Perez, S. Balachandran, D. Giannakopoulou, A. Mavridou, T. Pressburger, et al. From Requirements to Autonomous Flight: An Overview of the Monitoring ICAROUS Project. In *Workshop on Formal Methods for Autonomous Systems*, pages 23–30. EPTCS, 2020.

[7] D. Giannakopoulou, A. Mavridou, J. Rhein, T. Pressburger, J. Schumann, and N. Shi. Formal Requirements Elicitation with FRET. In *International Conference on Requirements Engineering: Foundation for Software Quality*, 2020.

[8] D. Giannakopoulou, T. Pressburger, A. Mavridou, and J. Schumann. Automated formalization of structured natural language requirements. *Information and Software Technology*, 137, 2021.

[9] M. Luckcuck, M. Farrell, O. Sheridan, and R. Monahan. A Methodology for Developing a Verifiable Aircraft Engine Controller from Formal Requirements. In *IEEE Aerospace Conference*, 2022.

[10] A. Mavridou, H. Bourbouh, P. L. Garoche, D. Giannakopoulou, T. Pressburger, and J. Schumann. Bridging the Gap Between Requirements and Simulink Model Analysis. In *International Conference on Requirements Engineering: Foundation for Software Quality*, 2020.

[11] A. Mavridou, H. Bourbouh, D. Giannakopoulou, T. Pressburger, M. Hejase, P.-L. Garoche, and J. Schumann. The Ten Lockheed Martin Cyber-Physical Challenges: Formalized, Analyzed, and Explained. In *International Requirements Engineering Conference*, pages 300–310. IEEE, 2020.

[12] I. Perez, F. Dedden, and A. Goodloe. Copilot 3. Technical report, NASA/TM-2020-220587, National Aeronautics and Space Administration, 2020.

[13] I. Postlethwaite, R. Samar, B. Choi, and D. Gu. A Digital Multimode H∞ Controller for the Spey Turbofan Engine. In *European Control Conference*, 1995.

[14] R. Samar and I. Postlethwaite. Design and Implementation of a Digital Multimode H∞ Controller for the Spey Turbofan Engine. *Journal of Dynamic Systems, Measurement, and Control*, 132(1):011010, 2010.

[15] P. Zave and M. Jackson. Four Dark Corners of Requirements Engineering. *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 6(1):1–30, 1997.
Appendix Appendix A  Simulink Diagram

This appendix contains a high-level view of the Simulink diagram of the aircraft engine controller that we described in Sect. 2.

Figure 3: High-level view of the Simulink diagram that our industrial partner constructed to model the controller for this use case.
## Appendix B  Test Cases

This appendix contains all of the test cases for the aircraft engine controller, provided by our industry partners. There are 20 test cases in total and these are shown in Tables 7 – 10.

| Test Case ID | Req. ID | Description |
|--------------|---------|-------------|
| UC5_TC_1     | UC5_R_1 | **Preconditions:** Aircraft is in operating mode M and sensor S value deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_2     | UC5_R_1 | **Preconditions:** Aircraft is in operating mode M and sensor S value is not available (sensor is out of order)  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_3     | UC5_R_2 | **Preconditions:** Aircraft is in operating mode M and sensor S value deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  
**Expected results:** Observed aircraft thrust returns to value V1, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_4     | UC5_R_2 | **Preconditions:** Aircraft is in operating mode M and sensor S value is not available (sensor is out of order)  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  
**Expected results:** Observed aircraft thrust returns to value V1, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_5     | UC5_R_3 | **Preconditions:** Aircraft is in operating mode M and sensor S value deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting operating limit objectives (e.g. upper limit in shaft speed) |
| UC5_TC_6     | UC5_R_3 | **Preconditions:** Aircraft is in operating mode M and sensor S value is not available (sensor is out of order)  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting operating limit objectives (e.g. upper limit in shaft speed) |

Table 7: The test cases for the aircraft engine controller, provided by our industrial partner corresponding to requirements UC5_R_1, UC5_R_2 and UC5_R_3.
| Test Case ID | Req. ID | Description |
|-------------|---------|-------------|
| UC5_TC_7    | UC5_R.4 | **Preconditions:** Aircraft is in operating mode M and sensor S value deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  
**Expected results:** Observed aircraft thrust returns to value V1, respecting operating limit objectives (e.g. upper limit in shaft speed) |
| UC5_TC_8    | UC5_R.4 | **Preconditions:** Aircraft is in operating mode M and sensor S value is not available (sensor is out of order)  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  
**Expected results:** Observed aircraft thrust returns to value V1, respecting operating limit objectives (e.g. upper limit in shaft speed) |
| UC5_TC_9    | UC5_R.5 | **Preconditions:** Aircraft is in operating mode M and system parameter P deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_10   | UC5_R.6 | **Preconditions:** Aircraft is in operating mode M and system parameter P deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  
**Expected results:** Observed aircraft thrust returns to value V1, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_11   | UC5_R.7 | **Preconditions:** Aircraft is in operating mode M and system parameter P deviates at most +/- R % from nominal value  
**Input conditions / steps:** Observed aircraft thrust is at value V1 and pilot input changes from A1 to A2  
**Expected results:** Observed aircraft thrust changes and settles to value V2, respecting operating limit objectives (e.g. upper limit in shaft speed) |

Table 8: The test cases for the aircraft engine controller, provided by our industrial partner corresponding to requirements UC5_R.4, UC5_R.5, UC5_R.6 and UC5_R.7.
| Test Case ID | Req. ID   | Description                                                                                                                                 |
|-------------|----------|---------------------------------------------------------------------------------------------------------------------------------------------|
| UC5_TC_12   | UC5_R_8  | **Preconditions:** Aircraft is in operating mode M and system parameter P deviates at most +/\ R % from nominal value  |
|             |          | **Input conditions / steps:** Observed aircraft thrust is at value V1 and perturbations in nonpilot input cause it to change to V2  |
|             |          | **Expected results:** Observed aircraft thrust returns to value V1, respecting operating limit objectives (e.g. upper limit in shaft speed) |
| UC5_TC_13   | UC5_R_9  | **Preconditions:** Aircraft is in operating mode M                                                                                           |
|             |          | **Input conditions / steps:** Observed aircraft thrust is at value V1, pilot input changes from A1 to A2, and outside air pressure abruptly changes from P1 to P2 |
|             |          | **Expected results:** Observed aircraft thrust changes and settles to value V2, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_14   | UC5_R_10 | **Preconditions:** Aircraft is in operating mode M                                                                                           |
|             |          | **Input conditions / steps:** Observed aircraft thrust is at value V1, small perturbations in nonpilot input cause it to change to V2, and outside air pressure abruptly changes from P1 to P2 |
|             |          | **Expected results:** Observed aircraft thrust returns to value V1, respecting control objectives (settling time, overshoot, steady state error) |
| UC5_TC_15   | UC5_R_11 | **Preconditions:** Aircraft is in operating mode M                                                                                           |
|             |          | **Input conditions / steps:** Observed aircraft thrust is at value V1, pilot input changes from A1 to A2, and outside air pressure abruptly changes from P1 to P2 |
|             |          | **Expected results:** Observed aircraft thrust changes and settles to value V2, respecting operating limit objectives (e.g. upper limit in shaft speed) |
| UC5_TC_16   | UC5_R_12 | **Preconditions:** Aircraft is in operating mode M                                                                                           |
|             |          | **Input conditions / steps:** Observed aircraft thrust is at value V1, small perturbations in nonpilot input cause it to change to V2, and outside air pressure abruptly changes from P1 to P2 |
|             |          | **Expected results:** Observed aircraft thrust returns to value V1, respecting operating limit objectives (e.g. upper limit in shaft speed) |

Table 9: The test cases for the aircraft engine controller, provided by our industrial partner corresponding to requirements UC5_R_8, UC5_R_9, UC5_R_10, UC5_R_11 and UC5_R_12.
### Test Case ID | Req. ID | Description
---|---|---
UC5_TC_17 | UC5_R_13 | **Preconditions:** Aircraft is in nominal operating mode  
**Input conditions / steps:** Pilot input changes from A1 to A2, causing surge / stall avoidance indicator signal to be set  
**Expected results:** Aircraft switches to surge / stall prevention operating mode

UC5_TC_18 | UC5_R_13 | **Preconditions:** Aircraft is in surge / stall prevention operating mode  
**Input conditions / steps:** Pilot input changes from A1 to A2, causing surge / stall avoidance indicator signal to be cleared  
**Expected results:** Aircraft switches to nominal operating mode

UC5_TC_19 | UC5_R_14 | **Preconditions:** Aircraft is in nominal operating mode  
**Input conditions / steps:** Perturbations in nonpilot input cause surge / stall avoidance indicator signal to be set  
**Expected results:** Aircraft switches to surge / stall prevention operating mode

UC5_TC_20 | UC5_R_14 | **Preconditions:** Aircraft is in surge / stall prevention operating mode  
**Input conditions / steps:** Perturbations in nonpilot input cause surge / stall avoidance indicator signal to be cleared  
**Expected results:** Aircraft switches to nominal operating mode

Table 10: The test cases for the aircraft engine controller, provided by our industrial partner corresponding to requirements UC5_R.13, and UC5_R.14.
## Appendix C  Child Requirements

This appendix contains the complete set of FRETISH child requirements for the aircraft engine controller use case. These requirements are contained in Tables 11-15.

| ID       | Parent   | FRETISH                                                                 |
|----------|----------|-------------------------------------------------------------------------|
| UC5_R_1.1| UC5_R_1  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (pilotInput => setThrust = V2) & (observedThrust = V1)) Controller shall until (diff(r(i),y(i)) < e) satisfy (settlingTime >= 0) & (settlingTime <= settlingTimeMax) & (observedThrust = V2) |
| UC5_R_1.2| UC5_R_1  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (pilotInput => setThrust = V2) & (observedThrust = V1)) Controller shall until (diff(r(i),y(i)) < e) satisfy (overshoot >= 0) & (overshoot <= overshootMax) & (observedThrust = V2) |
| UC5_R_1.3| UC5_R_1  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (!pilotInput => setThrust = V1) & (observedThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (settlingTime >= 0) & (settlingTime <= settlingTimeMax) & (observedThrust = V2) |
| UC5_R_2.1| UC5_R_2  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (!pilotInput => setThrust = V1) & (observedThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (overshoot >= 0) & (overshoot <= overshootMax) & (observedThrust = V2) |
| UC5_R_2.2| UC5_R_2  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (!pilotInput => setThrust = V1) & (observedThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (steadyStateError >= 0) & (steadyStateError <= steadyStateErrorMax) & (observedThrust = V2) |
| UC5_R_2.3| UC5_R_2  | when (diff(r(i),y(i)) > E) if((sensorValue(S) > nominalValue + R) | (sensorValue(S) < nominalValue - R) | (sensorValue(S) = null) & (!pilotInput => setThrust = V1) & (observedThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (steadyStateError >= 0) & (steadyStateError <= steadyStateErrorMax) & (observedThrust = V2) |

Table 11: Child requirements for UC5_R_1 and UC5_R_2.
Table 12: Child requirements for UC5_R_3, UC5_R_4 and UC5_R_5.
| ID       | Parent       | FRETISH                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|----------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| UC5_R_6.1| UC5_R_6      | when \( \text{diff}(r(i),y(i)) > E \) if\(((\text{systemParameter}(P) > \text{nominalValue} + R) \mid (\text{systemParameter}(P) < \text{nominalValue} - R) \mid (\text{systemParameter}(P) = \text{null}) \& (\text{observedThrust} = V2) \& (\text{pilotInput} \Rightarrow \text{setThrust} = V1)) \) Controller shall until \( \text{diff}(r(i),y(i)) < e \) satisfy \( (\text{settlingTime} >= 0) \& (\text{settlingTime} <= \text{settlingTimeMax}) \& (\text{observedThrust} = V1) \)                                                                                                                                                                                                                     |
| UC5_R_6.2| UC5_R_6      | when \( \text{diff}(r(i),y(i)) > E \) if\(((\text{systemParameter}(P) > \text{nominalValue} + R) \mid (\text{systemParameter}(P) < \text{nominalValue} - R) \mid (\text{systemParameter}(P) = \text{null}) \& (\text{observedThrust} = V2) \& (\text{pilotInput} \Rightarrow \text{setThrust} = V1)) \) Controller shall until \( \text{diff}(r(i),y(i)) < e \) satisfy \( (\text{overshoot} >= 0) \& (\text{overshoot} <= \text{overshootMax}) \& (\text{observedThrust} = V1) \)                                                                                                                                                                                             |
| UC5_R_6.3| UC5_R_6      | when \( \text{diff}(r(i),y(i)) > E \) if\(((\text{systemParameter}(P) > \text{nominalValue} + R) \mid (\text{systemParameter}(P) < \text{nominalValue} - R) \mid (\text{systemParameter}(P) = \text{null}) \& (\text{observedThrust} = V2) \& (\text{pilotInput} \Rightarrow \text{setThrust} = V1)) \) Controller shall until \( \text{diff}(r(i),y(i)) < e \) satisfy \( (\text{steadyStateError} >= 0) \& (\text{steadyStateError} <= \text{steadyStateErrorMax}) \& (\text{observedThrust} = V1) \)                                                                                                                                                                 |
| UC5_R_7.1| UC5_R_7      | when \( \text{diff}(r(i),y(i)) > E \) if\(((\text{systemParameter}(P) > \text{nominalValue} + R) \mid (\text{systemParameter}(P) < \text{nominalValue} - R) \mid (\text{systemParameter}(P) = \text{null}) \& (\text{observedThrust} = V1) \& (\text{pilotInput} \Rightarrow \text{setThrust} = V2)) \) Controller shall until \( \text{diff}(r(i),y(i)) < e \) satisfy \( (\text{shaftSpeed} >= \text{operatingLowerBound}) \& (\text{shaftSpeed} <= \text{operatingUpperBound}) \& (\text{observedThrust} = V2) \)                                                                                                                                                          |
| UC5_R_8.1| UC5_R_8      | when \( \text{diff}(r(i),y(i)) > E \) if\(((\text{systemParameter}(P) > \text{nominalValue} + R) \mid (\text{systemParameter}(P) < \text{nominalValue} - R) \mid (\text{systemParameter}(P) = \text{null}) \& (\text{pilotInput} \Rightarrow \text{setThrust} = V1) \& (\text{observedThrust} = V2)) \) Controller shall until \( \text{diff}(r(i),y(i)) < e \) satisfy \( (\text{shaftSpeed} >= \text{operatingLowerBound}) \& (\text{shaftSpeed} <= \text{operatingUpperBound}) \& (\text{observedThrust} = V1) \)                                                                                                                                 |

Table 13: Child requirements for UC5_R_6, UC5_R_7 and UC5_R_8.
| ID       | Parent   | FRETISH                                                                                                                                                                                                                                                                                                                                 |
|----------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| UC5_R_9.1| UC5_R_9  | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V1) & (pilotInput => setThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (settlingTime >= 0) & (settlingTime <= settlingTimeMax) & (observedThrust = V2) |
| UC5_R_9.2| UC5_R_9  | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V1) & (pilotInput => setThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (overshoot >= 0) & (overshoot <= overshootMax) & (observedThrust = V2) |
| UC5_R_9.3| UC5_R_9  | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V1) & (pilotInput => setThrust = V2)) Controller shall until (diff(r(i),y(i)) < e) satisfy (steadyStateError >= 0) & (steadyStateError <= steadyStateErrorMax) & (observedThrust = V2) |
| UC5_R_10.1| UC5_R_10 | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V2) & (!pilotInput => setThrust = V1)) Controller shall until (diff(r(i),y(i)) < e) satisfy (settlingTime >= 0) & (settlingTime <= settlingTimeMax) & (observedThrust = V1) |
| UC5_R_10.2| UC5_R_10 | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V2) & (!pilotInput => setThrust = V1)) Controller shall until (diff(r(i),y(i)) < e) satisfy (overshoot >= 0) & (overshoot <= overshootMax) & (observedThrust = V1) |
| UC5_R_10.3| UC5_R_10 | when (diff(r(i),y(i)) > E) if (outsideAirPressure(T1) != outsideAirPressure(T2) & (diff(t, t1) < threshold) & (abs(outsideAirPressure (T1) - outsideAirPressure(T2)) > pressureThreshold) & (observedThrust = V2) & (!pilotInput => setThrust = V1)) Controller shall until (diff(r(i),y(i)) < e) satisfy (steadyStateError >= 0) & (steadyStateError <= steadyStateErrorMax) & (observedThrust = V1) |

Table 14: Child requirements for UC5_R_9 and UC5_R_10.
| ID     | Parent   | FRETISH                                                                                                                                                                                                 |
|--------|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| UC5_R11.1 | UC5_R11  | when \((\text{diff}(r(i),y(i)) > E) \text{ if } ((\text{outsideAirPressure}(T1) \neq \text{outsideAirPressure}(T2)) \& (\text{diff}(t_2,t_1) < \text{threshold}) \& (\text{abs}(
\text{outsideAirPressure}(T1) - \text{outsideAirPressure}(T2)) > \text{pressureThreshold}) \& (\text{observedThrust} = V1) \&(\text{pilotInput} => \text{setThrust} = V2)) \)) \text{ Controller shall until } (\text{diff}(r(i),y(i)) < e) \text{ satisfy} \quad (\text{shaftSpeed} \geq \text{operatingLowerBound}) \& (\text{shaftSpeed} \leq \text{operatingUpperBound}) \& (\text{observedThrust} = V2)\)                                                                 |
| UC5_R12.1 | UC5_R12  | when \((\text{diff}(r(i),y(i)) > E) \text{ if } ((\text{outsideAirPressure}(T1) \neq \text{outsideAirPressure}(T2)) \& (\text{diff}(t_2,t_1) < \text{threshold}) \& (\text{abs}(
\text{outsideAirPressure}(T1) - \text{outsideAirPressure}(T2)) > \text{pressureThreshold}) \& (\text{observedThrust} = V2) \&(\text{pilotInput} => \text{setThrust} = V1)) \)) \text{ Controller shall until } (\text{diff}(r(i),y(i)) < e) \text{ satisfy} \quad (\text{shaftSpeed} \geq \text{operatingLowerBound}) \& (\text{shaftSpeed} \leq \text{operatingUpperBound}) \& (\text{observedThrust} = V1)\)                                                                 |
| UC5_R13.1 | UC5_R13  | in nominal mode when \((\text{diff}(\text{setNL}, \text{observedNL}) > \text{NLmax}) \) \text{ if } (\text{pilotInput} => \text{surgeStallAvoidance}) \text{ Controller shall until } (\text{diff}(\text{setNL}, \text{observedNL}) < \text{NLmin}) \text{ satisfy} \quad (\text{changeMode(surgeStallPrevention)})\)                                                                 |
| UC5_R13.2 | UC5_R13  | in surgeStallPrevention mode when \((\text{diff}(\text{setNL}, \text{observedNL}) < \text{NLmax}) \) \text{ if } (\text{pilotInput} => \text{!surgeStallAvoidance}) \text{ Controller shall until } (\text{diff}(\text{setNL}, \text{observedNL}) > \text{NLmin}) \text{ satisfy} \quad (\text{changeMode(nominal)})\)                                                                 |
| UC5_R14.1 | UC5_R14  | in nominal mode when \((\text{diff}(\text{setNL}, \text{observedNL}) > \text{NLmax}) \) \text{ if } (\text{!pilotInput} => \text{surgeStallAvoidance}) \text{ Controller shall until } (\text{diff}(\text{setNL}, \text{observedNL}) < \text{NLmin}) \text{ satisfy} \quad (\text{changeMode(surgeStallPrevention)})\)                                                                 |
| UC5_R14.2 | UC5_R14  | in surgeStallPrevention mode when \((\text{diff}(\text{setNL}, \text{observedNL}) < \text{NLmax}) \) \text{ if } (\text{!pilotInput} => \text{!surgeStallAvoidance}) \text{ Controller shall until } (\text{diff}(\text{setNL}, \text{observedNL}) > \text{NLmin}) \text{ satisfy} \quad (\text{changeMode(nominal)})\)                                                                 |

Table 15: Child requirements for UC5_R11, UC5_R12, UC5_R13 and UC5_R14.