Why just FRET when you can Refactor?
Retuning FRETISH Requirements *

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Abstract
Formal verification of a software system relies on formalising the requirements to which it should adhere, which can be challenging. While formalising requirements from natural-language, we have dependencies that lead to duplication of information across many requirements, meaning that a change to one requirement causes updates in several places. We propose to adapt code refactorings for NASA’s Formal Requirements Elicitation Tool (FRET), our tool-of-choice. Refactoring is the process of reorganising software to improve its internal structure without altering its external behaviour; it can also be applied to requirements, to make them more manageable by reducing repetition. FRET automatically translates requirements (written in its input language fretish) into Temporal Logic, which enables us to formally verify that refactoring has preserved the requirements’ underlying meaning. In this paper, we present four refactorings for fretish requirements and explain their utility. We describe the application of one of these refactorings to the requirements of a civilian aircraft engine software controller, to decouple the dependencies from the duplication, and analyse how this changes the number of requirements and the number of repetitions. We evaluate our approach using Spot, a tool for checking equivalence of Temporal Logic specifications.

1 Introduction

Developing a valid set of system requirements necessitates discussion with people who have expertise in the system under development, who may not be experts in formal methods. Requirements elicitation discussions can be helped by writing the requirements in an intermediate, semi-formal language before fully formalising them. We use NASA’s Formal Requirements Elicitation Tool (FRET) as a gateway for developing formal requirements alongside an industrial partner. FRET integrates a semi-formal requirements language and temporal logic [12].

Refactoring is applied to software to improve its structure and is defined as:
“...the process of changing a software system in such a way that it does not alter the external behaviour of the code yet improves its internal structure” [10].

The cleaner code produced by refactoring is easier to maintain, examine, understand, and update. Like software, requirements often go through several iterations before they are complete. Even then, they may need updating, if an error is found or a new feature is added. This means that their structure is almost as important as that of the software that they specify.

While eliciting the requirements for a civilian aircraft engine software controller, as part of the VALU3S project, we found dependencies that lead to many repeated definitions, meaning that one change required updates in multiple places – a classic bad smell in software engineering [10] – which makes the requirements much more difficult to maintain.

In this paper, we adapt code refactorings to requirements written in FRET’s input language, fretish. We then present our refactoring of the requirements for our example application. Our industrial partner supplied 14 abstract requirements, which we mapped one-to-one into fretish. Elicitation discussions with our industrial partner produced 42 fretish requirements in total [7].

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1The VALU3S project: https://valu3s.eu/
Our refactoring approach was driven by the need to reorganise the requirements set. Refactoring the requirements slightly reduced the total number of requirements, and markedly reduced the number of repeated definitions. We check that the refactoring steps have not changed the behaviour of the requirements by using an external library to compare their temporal logic translations. Our previous work explores the motivation for refactoring FRETISH requirements [8], and in this paper we introduce the refactoring steps and present a worked example.

This paper is laid out as follows. §2 presents the background of FRET (§2.1) and requirements refactoring (§2.2). §3 describes our adaptation of code refactorings to FRETISH requirements, and §4 describes how we refactored our requirements set. In §5, we analyse how refactoring has changed our requirements set. §6 discusses how to introduce refactoring into FRET and what impact that might have. Finally, §7 concludes the paper.

2 Background

This section provides an overview of FRET and refactoring for requirements.

2.1 FRET

FRET is an open-source tool that enables developers to write and formalise system requirements in a structured natural-language called FRETISH [12]. Requirements in FRET take the form:

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

Here, the scope and timing fields are optional. Intuitively, this structure defines requirements that, in a particular scope and under a given condition then a particular component shall obey the response under specific timing constraints.

FRET formalises each requirement in both past- and future-time Metric Temporal Logic (MTL). For each requirement, FRET also produces a structured text description of the requirement’s behaviour, and a diagrammatic semantics (Fig.1) that shows the time interval where the requirement should hold and the requirement’s triggering and stopping conditions (if they exist). These are helpful for sanity-checking what has been written in FRETISH.

FRET supports a hierarchical link between requirements. In this many-to-many relationship, parent requirements may have many children, and a child requirement may have many parents. Linking parent and child requirements based on their IDs supports traceability, but the parent-child relationship does not include inheritance or any other functional link between the 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 [3]. FRET can also generate runtime monitors for the stream-based Copilot framework [6].

2.2 Refactoring Requirements

Refactoring is a software engineering process where program code is reorganised to improve its internal structure, without altering its external behaviour [10]. Refactoring has been adapted for software requirements, for example Ramos et al. [18] present refactoring approaches for requirements, directly based on the code refactorings described by Fowler et al. [10]. Both of these works have been particularly influential on this paper.

Requirements are an abstraction of a system’s model which are, in turn, abstractions of its implementation. Refactoring can also be applied to (formal) system models [4,11,14]. Refactoring a system’s requirements has the potential to avoid modelling or implementing problems that already exist in the

\[ \text{FRET: } \text{https://github.com/NASA-SW-VnV/fret} \]
requirements. Some code refactorings may weaken traceability links back to the requirements [16].

Weakened traceability was shown when extracting code into a method, but moving a method between
classes had no effect on traceability; renaming software units had a positive effect on traceability.

Being able to refactor requirements enables us to deal with the, almost inevitable, likelihood that
requirements will need to change [5]. This can be because of new features being added to the system, or
requirements elicitation discussions identifying new requirements. For our requirements set, discussions
with our industrial partner identified concrete details about the requirements, but compounded the
problem of duplication: with many definitions, one change required updates in many requirements.

We discuss this in detail in §4.

Deshpande et al. found that identifying dependencies between requirements is important, and
that ignoring them can negatively impact a project’s success [5]. They used machine learning to
identify dependencies between natural-language requirements in the same set, including requires and
similar relationships. Their survey of practitioners revealed that, although important, over 90% of
participants did not use an automated tool to extract and maintain dependencies. In §4.1, we manually
identify dependencies within our own requirements set. As mentioned, FRET captures hierarchical
links between parent- and child-requirements, but does not yet enable requirement dependencies to be
captured, apart from textually as part of a requirement’s rationale.

FRET automatically generates a formal representation in temporal logic, which enables us to
formally verify that the refactoring has not changed the requirements’ behaviour. This is analogous to
the crucial ‘compile and test’ step for code refactoring [10]. This step is not possible in [18], because
they focus on textual requirements so there is no easy way to test that the meaning of the requirements
have not changed.

3 Refactoring FRETISH: Concepts

FRET translates fretish requirements into (past- and future-time metric) temporal logic, but the
fretish requirements themselves are simply structured text. This means that refactoring fretish
is very similar to refactoring natural-language requirements. This section describes the adaptation of
two of the requirements refactorings from [18], to fretish requirements. The fifth refactoring in [18]
(Extract Alternative Flows) is not applicable to fretish.

We propose that tool-supported refactoring should be included in FRET, which should include a
formal check that the temporal logic version of the requirements before the refactoring is the same as
after the refactoring (i.e. that the behaviour has not been changed). This can be achieved by checking
that the two temporal logic formulae are equivalent; or that the refactored requirement implies the
original, if the refactoring adds behaviour to the requirement but still includes the behaviours of the
original.

Even with tool support, refactoring is not a process that should be applied through blind automation
[18]. Users who are formalising requirements must decide which refactorings are appropriate for their
set of requirements.

3.1 Extract Requirement

Extract Requirement moves definitions from one requirement into a newly-created requirement.
In the original requirement, the extracted parts are replaced with a reference to the new require-
ment. This is an adaptation of Extract Requirement in [18] (itself based on Extract Method
from [10]) to fretish requirements. When refactoring software, Extract Method extracts a piece of
repeated code into its own method. Extract Requirement achieves similar modularity for fretish
requirements. Extract Requirement also serves the intent of the Extract Alternative Flows(refactoring [18], which is aimed at modularising Use Case descriptions and has no clear application in
fretish.

Using Extract Requirement to introduce a reference to the newly-created requirement can
improve readability, because it can be named to better inform the reader of its intent. This refactoring
is especially useful when the definition being extracted is repeated across several requirements, because
encapsulating it inside one requirement means that a change to the behaviour only requires updates
in one place. To perform the Extract Requirement refactoring in FRET, we propose the following
steps:
Step 1 Create a new requirement with a descriptive name for the definitions being extracted;
Step 2 Copy the definitions being extracted to the newly-created requirement;
Step 3 Replace the extracted definitions in the original requirement with a reference to the newly-created requirement;
Step 4 Verify that the behaviour of the original requirement combined with the newly-created requirement is the same as (or at least implies) the behaviour of the original requirement before refactoring.

Each extracted requirement follows the same pattern: the extracted definitions become its condition, and its response sets a boolean to True if the condition holds. This represents the extracted definition being satisfied. The original requirement’s reference to the extracted requirement is interpreted by FRET as a boolean variable. Since we know that the extracted requirement is True if the extracted definitions are True, we can intuitively say that the reference in the original requirement should only be True if the extracted conditions are True.

This intuition is analogous to having extracted a complicated boolean condition into a new method that returns a boolean, then replacing the original condition with a call to the method. To capture this link in FRET, the ‘Rationale’ field of both the original and extracted requirements could be used to describe how refactoring has changed the requirements. FRET does not currently support ‘calling’ methods and §6 outlines ways of adding this support.

**Example:** Consider a requirement, R1, for a sensor subsystem component. R1 states that “if sensorA returns a value outside of its expected range, plus a margin, then it is invalid”, (satisfy !sensorA_valid). In fretish, R1 becomes:

```
if (sensorA > sensorA_Max + R) | (sensorA < sensorA_Min - R)
SensorSubSystem shall satisfy !sensorA_valid
```

Applying Extract Requirement to the condition sensorA > sensorA_Max + R) | (sensorA < sensorA_Min - R) moves these definitions to their own requirement which we call SENSOR_A_OUT_OF_BOUNDS:

```
if (sensorA > sensorA_Max + R) | (sensorA < sensorA_Min - R)
SensorA shall satisfy SENSOR_A_OutOfBounds
```

R1 is updated to read:

```
if SENSOR_A_OUT_OF_BOUNDS SensorSubSystem shall satisfy !sensorA_valid
```

This refactoring means that any changes to the extracted conditions only require updates to SENSOR_A_OUT_OF_BOUNDS. It also simplifies R1 and makes it easier to read, with the extracted requirement describing what triggers the response (satisfy !sensorA_valid). Other repetitions of the condition can be similarly replaced by the extracted requirement. In each case a check is performed to ensure that the behaviour is preserved.

### 3.2 Rename Requirement

**RENAME Requirement** changes a requirement’s name and then updates any references to it to match its new name. FRET enables the user to rename a requirement, but any references to it in the ‘Parent Requirement ID’ field of child requirements are not updated. This means that child requirements are left with a broken reference, reducing traceability. Updating the renaming function to act like rename would solve this problem. It would also be useful when updating a requirement name that is referenced in many requirements.

In addition to the steps proposed by Ramos et al. [18], this refactoring should also check that renaming has not caused any inconsistencies when applied over multiple requirements. Similar rename refactoring has been provided for other formal methods, e.g. Event-B3.

### 3.3 Move Definition

**MOVE Definition** takes part of a requirement and moves it to another, adapting Move Activity [18]. It focusses a requirement on a single responsibility. Because this refactoring will change the behaviour of both the source and destination requirements, it should check that the parts that were moved are no longer in the source requirement, but are in the destination requirement.

FRET’s parent-child link creates a requirements hierarchy, so MOVE DEFINITION could be specialised into a Pull-Up Definition refactoring that explicitly moves common definitions from a

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3[https://wiki.event-b.org/index.php/Refactoring_Framework](https://wiki.event-b.org/index.php/Refactoring_Framework)
child requirement up to its parent to represent the notion that the definitions is common to all of that requirement’s children. This is similar to the Pull-Up Method code refactoring in [10].

The parent-child link between FRETISH requirements is based on their IDs, but it does not imply any semantic link between the requirements. However, moving a definition up the hierarchy makes it more obvious that it is common to all of the requirement’s children. This is similar to a method being placed in the superclass of an Object-Oriented program’s class hierarchy. Using Pull-Up Definition makes it more likely that this notion will be implemented.

Pull-Up Definition should check that the destination requirement implies the source requirement, because the destination (parent) now covers the definitions in the source (child). When applying this refactoring, care must be taken not to reduce traceability of the origin or the pulled-up definition(s).

Example: Consider the previous example of R1 (§3.1). Elicitation discussions then reveal a new condition, “switchA is triggered” \(\text{switchA} = \text{true}\), which is added to R1’s children. Using Pull-Up Definition to move this condition from the children to R1 simplifies the requirements set, and makes it clear that the condition is common to all of R1’s children. However, traceability is potentially reduced unless the condition’s origin and destination are documented.

3.4 Inline Requirement

Inline Requirement is the opposite of the Extract Requirement refactoring (§3.1); it takes one requirement and merges it into another. It is useful where a requirement is only referenced in a few places, and is simple enough that its definitions are as clear as its name. Care must be taken when merging a FRETISH requirement’s fields. This is relatively simple for the condition and response fields; but if the scope, component, or timing fields do not match, then Inline Requirement might not be applicable. (We discuss this further in §6.) Inline Requirement should check for equivalence between the original two requirements and the refactored requirement, similarly to Extract Requirement (§3.1).

4 Refactoring FRETISH: Application

In this section we describe the application of the Extract Requirement refactoring (§3.1) to a set of FRETISH requirements. Here, we focus on the whole requirement set; first identifying the parts of the requirements to refactor, then systematically extracting repeated definitions, before cleaning up the requirements set, and comparing the requirements to check that their behaviour has not changed. Because FRET does not automatically perform the comparison that we perform, and because we are refactoring the whole requirement set, we defer the comparison until after all of the refactorings are complete.

Our FRETISH requirements are derived from the natural-language requirements for a high-bypass civilian aircraft turbofan engine software controller, provided by our industrial partner on the VALU3S [1] project, described in our prior work [15]. The controller’s high-level objectives are: to manage engine thrust, regulate 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 in the presence of: sensor faults, perturbation of system parameters, and other low-probability hazards. The controller must also detect engine surge/stall, and change mode to avoid these hazardous situations.

Our FRETISH requirements set is derived from the 14 English-language requirements and 20 abstract test cases provided by our industrial partner, see [7]. We reuse the natural-language requirements’ naming convention in the FRETISH set. As mentioned in §2.1, FRET allows requirements to be hierarchically linked: a requirement can have many parent requirements, and a parent requirement can have many child requirements. Thus, the naming convention in our requirements:

\(<\text{use case id}>._R_.<\text{parent requirement id}>._<\text{child requirement id}>\)

For example, this is Use Case 5 in the VALU3S project, so Requirement 1 is named UC5_R_1; we use a sans serif font style to denote requirement names.

The natural-language requirements (examples in Table 1) repeat concepts like “sensor faults” or “control objectives”, which we call fragments; we use a slanted font style to denote fragment names. We mapped the natural-language requirements, one-to-one, in to the 14 FRETISH parent requirements; in
### Table 1: Natural-language requirements UC5_R_1 and UC5_R_3 for our case study.

| 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_3| Under sensor faults, while tracking pilot commands, operating limit objectives shall be satisfied (e.g., respecting upper limit in shaft speed) |

### Table 2: The seven repeated fragments in the natural-language requirements.

| Fragment ID | Description                           |
|-------------|---------------------------------------|
| F1          | Sensor Faults                         |
| F2          | Tracking Pilot Commands               |
| F3          | Control Objectives                    |
| F4          | Regulation Of Nominal Operation       |
| F5          | Operating Limit Objectives            |
| F6          | Mechanical Fatigue                    |
| F7          | Low Probability Hazardous Events      |

which the fragments are represented by boolean variables. For example, the natural-language version of UC5_R_1 shown in Table 1 is encoded in **FRETISH** as:

```fretish
if sensorFaults & trackingPilotCommands Controller shall satisfy controlObjectives
```

A **FRETISH** condition can start with one of several different keywords, including *if* and *when*, which each have the same semantics. Here the **condition** captures the fragments as booleans, e.g. “Under sensor faults” becomes `sensorFaults`.

The child requirements add detail from the test cases and elicitation discussions with our industrial partner. Each fragment’s definition is duplicated in one or more child requirements. For example, UC5_R_1 relies on its child requirements to define `sensorFaults`, `trackingPilotCommands`, and `controlObjectives`.

This duplication of fragments leads to a lot of repetition. For example, **Sensor Faults** appears in 4 parent requirements, with its definition duplicated in a further 8 children. This repetition is the **Duplicated Activities** problem [18] (similar to the smell of **Duplicated Code** [10]) meaning that a change to one fragment requires changes to all of the child requirements that use it. The rest of this section describes how we identify the fragments in our requirements set, and reduce the repetition with the **EXTRACT REQUIREMENT** refactoring (§3.1).

### 4.1 Step 1: Identify Fragments

This step identifies the repeated fragments that are ‘baked into’ the requirements, so that we can apply **EXTRACT REQUIREMENT** to them. We were able to perform this analysis manually, because our requirements set is relatively small. For larger requirements sets, automatic tools may be needed. For example using Machine Learning to identify dependencies within requirements sets [5]. We focus on two requirements, providing a useful illustration of our approach.

Table 1 shows the natural-language version of UC5_R_1 and UC5_R_3, provided by our industrial partner. Both requirements are active “Under sensor faults” and “while tracking pilot commands”. Whereas UC5_R_1 satisfies “control objectives”, while UC5_R_3 satisfies “operating limit objectives”.

To analyse the whole requirements set, we first identify the fragments that are repeated in the natural-language requirements, which we list in Table 2. We collect the requirements and the fragments into two sets:

\[
\text{Reqs} = \{\text{UC5}_R_{1, \ldots, 14}\} \text{ and } \text{Frags} = \{F1, F2, \ldots, F6, F7\},
\]

which are linked by dependency: understanding a requirement is dependant on first understanding the fragments that it contains, a change to the fragment is duplicated across all of the requirements that depend on it.
We capture the dependencies as a set of tuples:
\[ \text{Dependencies} = \{ (UC5\_R\_1,F1), (UC5\_R\_1,F2), (UC5\_R\_1,F3), \ldots \} \]
each tuple maps a requirement to one fragment upon which it depends. There are 38 dependencies in the natural-language requirements, which are mapped into the FRETISH parent requirements; a full dependency graph is shown in [8].

For brevity, we focus on the dependencies of UC5\_R\_1 and UC5\_R\_3, shown in the dependency graph in Fig. 2. This figure exposes the mapping between the parent requirements and the fragments on which they depend. These dependencies are hidden within the requirements, which makes maintaining the duplicated definitions of the fragments troublesome.

Our elicitation discussions identified two more fragments within the child requirements, which define when a requirement is Active and Not Active by comparing the set and measured values of the system’s variables. Each child requirement depends on both of these fragments, therefore we also extract them in Step 2 (§4.2).

In this original requirements set, dependencies always lead to duplication. In total, there are 94 dependencies, across the 42 requirements. This includes the 38 dependencies from the natural-language requirements, and the 56 dependencies from the Active and Not Active fragments. We use this dependency information as the starting point for extracting the fragments.

### 4.2 Step 2: Apply Extract Requirement

In this step we use the Extract Requirement (§3.1) refactoring to decouple the requirements from the duplicated fragments. We use Extract Requirement on the seven natural-language fragments (Table 2) and both the Active and Not Active fragments (§4.1) (which can be seen in the when() and until() clauses of each child requirement). In total, this step produces nine new requirements, each is the destination for an extracted definition.

We focus on UC5\_R\_1 (Table 1), which contains three fragments that are drawn from the natural-language version of the requirement: sensorFaults, trackingPilotCommands, and controlObjectives. UC5\_R\_1 has three child requirements. For example, UC5\_R\_1.1 contains the detailed definitions of the three fragments from UC5\_R\_1 and both of the Active and Not Active fragments:

\[
\text{when } (\text{diff}(r(i),y(i)) > \text{E}) \text{ if } \left( (\text{sensorValue}(S) > \text{nominalValue} + \text{R}) \right. \left. \| (\text{sensorValue}(S) < \text{nominalValue} - \text{R}) \| (\text{sensorValue}(S) = \text{null}) \right) \& \left( \text{pilotInput} \Rightarrow \text{setThrust} = V2 \right) \& (\text{observedThrust} = V1) \\
\text{Controller shall until } (\text{diff}(r(i),y(i)) < \text{e}) \text{ satisfy } (\text{settlingTime} \geq 0) \& (\text{settlingTime} \leq \text{settlingTimeMax}) \& (\text{observedThrust} = V2)
\]

The Active fragment is defined in the when() clause of the condition. The first three comparisons in the if clause define sensorFaults, and the last three conditions define trackingPilotCommands. The Not Active fragment is defined in the until() clause. Finally, the first two conditions in the response partially define the controlObjectives fragment.

The natural-language version of UC5\_R\_1 lists three control objectives: “settling time, overshoot, and steady state error”, each of which we defined in one child requirement. For example, UC5\_R\_1.1 partially defines controlObjectives (Settling Time), the other two control objectives are captured by UC5\_R\_1.2 and UC5\_R\_1.3, respectively. This approach simplified each child requirement, but increased the difficulty of updating the repeated fragments.

Both UC5\_R\_1 and UC5\_R\_3 depend on Sensor Faults and Tracking Pilot Commands (Fig.2) meaning that the fragments’ definitions are duplicated four times over the children of UC5\_R\_1 and UC5\_R\_3 (UC5\_R\_3 only has one child). The children also duplicate the definition of Active and Not Active eight times.
In the rest of this section, we describe how we use the **Extract Requirement** refactoring on the five fragments that UC5_R_1 and UC5_R_1.1 depend on: Sensor Faults, Control Objectives, Tracking Pilot Commands, Active, and Not Active. We remind the reader that we defer checking that a requirement’s behaviour has not changed after refactoring, until Step 4.4.

**Sensor Faults**
Applying **Extract Requirement** to Sensor Faults was relatively easy, because its complete definition is simply repeated across several requirements. The detailed specification was extracted to a new requirement `SENSOR_FAULTS`:

```plaintext
when (sensorValue(S) > nominalValue+R) | (sensorValue(S) < nominalValue-R) | (sensorValue(S)=null)
Controller shall satisfy SensorFaults
```

After creating the new requirement, the original repeated definitions were replaced with a reference to this new requirement. For example requirements UC5_R_1 and UC5_R_1.1 become:

```plaintext
UC5_R_1 = if (SENSOR_FAULTS & (trackingPilotCommands)) Controller shall satisfy (controlObjectives)
UC5_R_1.1 = when (diff(r(i),y(i)) > E) if(SENSOR_FAULTS & (pilotInput=> setThrust=V2) & (observedThrust=V1)) Controller shall until (diff(r(i),y(i))<e) satisfy (settlingTime>=0) & (settlingTime<=settlingTimeMax) & observedThrust=V2
```

**Control Objectives**
Applying **Extract Requirement** to Control Objectives was a little more difficult than for Sensor Faults, because its definition was spread over several children, but was still achievable. As previously mentioned, each of UC5_R_1’s child requirements (UC5_R_1.1, UC5_R_1.2, and UC5_R_1.3) contains part of the definition of controlObjectives.

Each of the part-definitions of controlObjectives was extracted and combined into a single requirement `CONTROL_OBJECTIVES`. The part-definitions in the child requirements were replaced with a reference to the new requirement. For example UC5_R_1 and UC5_R_1.1 became:

```plaintext
UC5_R_1 = if (SENSOR_FAULTS & TRACKING_PILOT_COMMANDS) Controller shall satisfy CONTROL_OBJECTIVES
UC5_R_1.1 = when (diff(r(i),y(i)) > E) if(SENSOR_FAULTS & (pilotInput=>setThrust=V2) & (observedThrust=V1)) Controller shall until (diff(r(i),y(i))<e) satisfy CONTROL_OBJECTIVES & observedThrust=V2
```

**Tracking Pilot Commands**
The final natural-language fragment, Tracking Pilot Commands, was slightly more difficult to extract because its definition occurs in a requirement’s condition field (`pilotInput => setThrust=V2`) and its response field (`satisfy observedThrust=V2`).

We decided to extract the parts of this fragment that are in the condition to their own requirement `TRACKING_PILOT_COMMANDS`. However, we made a design decision to leave `observedThrust=V2` in place, which simplifies the intuition of how extracted fragments work in FRET. For example UC5_R_1 and UC5_R_1.1 became:

```plaintext
UC5_R_1 = if(SENSOR_FAULTS & TRACKING_PILOT_COMMANDS) Controller shall satisfy CONTROL_OBJECTIVES
UC5_R_1.1 = when (diff(r(i),y(i)) > E) if(SENSOR_FAULTS & TRACKING_PILOT_COMMANDS Controller shall until (diff(r(i),y(i))<e) satisfy CONTROL_OBJECTIVES & observedThrust=V2
```

In the refactored version of UC5_R_1.1, the references to SENSOR_FAULTS and TRACKING_PILOT_COMMANDS guard the update `observedThrust=V2`: both references are interpreted as booleans that are intuitively `true` if their condition is `true`. Had we extracted `observedThrust=V2` into the response of TRACKING_PILOT_COMMANDS, then `observedThrust=V2` could happen even if SENSOR_FAULTS is `false` because TRACKING_PILOT_COMMANDS could trigger the update independently.

**Active and Not Active**
As previously mentioned, Active and Not Active are contained within the `when()` and `until()` clauses of each child requirement. Because they define the triggering and stopping condition (respectively)
for a requirement, these two fragments must be extracted separately to preserve their book-ending structure.

The `when()` clause defines the triggering condition for the interval in which the requirement should be **Active** `(when (diff(r(i),y(i))>E))` and is extracted into **Active**; the `until()` clause defines the stopping condition for the interval `(until (diff(r(i),y(i))<=0))` and is extracted into **Not Active**. Each of these was then substituted into the relevant location in the child requirements; therefore, **UC5_R_1** remains the same, and **UC5_R_1.1** becomes:

```
when ACTIVE if (SENSOR_FAULTS & TRACKING_PILOT_COMMANDS Controller shall until NOT_ACTIVE satisfy
CONTROL_OBJECTIVES & observedThrust=V2
```

4.3 Step 3: Remove Redundant Requirements

In this step we remove the redundant identical child requirements that were produced in Step 4.2. As an example of the identical requirements, **UC5_R_1.1**, **UC5_R_1.2** and **UC5_R_1.3** all now read:

```
when ACTIVE if (SENSOR_FAULTS & TRACKING_PILOT_COMMANDS Controller shall until NOT_ACTIVE satisfy
CONTROL_OBJECTIVES & observedThrust=V2
```

Hence, we only need one child requirement to specify the detail of **UC5_R_1**.

In these cases, we simply remove all but one of the identical child requirements. This results in a cleaner set of requirements, which maintains traceability back to the natural-language version, and uses FRET’s parent-child link to maintain internal traceability between the abstract (parent) and detailed (child) versions of the FRETISH requirements. Now, in the refactored set of requirements, a change to one of the fragments only needs an update in one place.

4.4 Step 4: Check the Requirements

Our final step is to check that the refactoring steps have not changed the behaviour of the requirements. This step is almost impossible with natural-language requirements, even those written in semi-structured languages, because of ambiguity in the requirements’ meaning. However, we can formally compare the two versions of FRETISH requirements, because FRET automatically translates them into temporal logic.

We use the Spot library\(^4\) to compare the temporal logic generated by FRET for each refactored requirement with its original version. First, we abstracted away from the detailed terms in the FRETISH requirements, replacing them with boolean variables. This was to ensure that the temporal logic produced by FRET was compatible with Spot. Then, we used FRET to recompile the newly abstracted FRETISH statements, to get the corresponding temporal logic formulae. Finally, we used Spot to compare the two temporal logic formulae.

Out of the 30 requirements, 24 are equivalent, meaning that the refactoring has made no change to their behaviour. Of the remaining 6 requirements that are not equivalent, each of the factored requirements implies the original. These 6 requirements are all children: **UC5_R_1.1**, **UC5_R_2.1**, **UC5_R_5.1**, **UC5_R_6.1**, **UC5_R_9.1**, **UC5_R_10.1**. After refactoring, each of these requirements contains the full definition of **Control Objectives**; whereas, before refactoring, they only contained a part-definition, hence implication holds.

For example, the `response` in the original version of **UC5_R_1.1** defines the part of the **Control Objectives** fragment relating to settling time: `(settlingTime >= 0) & (settlingTime <= settlingTimeMax)`. Whereas, in the refactored version, the `response` defines all three parts of the fragment:

```
(settlingTime >= 0) & (settlingTime <= settlingTimeMax) & (overshoot >= 0) & (overshoot <= overshootMax) & (steadyStateError >= 0) & (steadyStateError <= steadyStateErrorMax)
```

The refactored version of the requirement implies the original, because the refactored version’s `response` covers the original’s. The behaviour of many requirements has merged into one, but overall the required behaviour is the same.

5 Analysis

In this section we compare our original set of requirements to our refactored set of requirements. The original requirements set contains dependencies that always lead to duplication of information. To

\(^4\)Spot library: [https://spot.lrde.epita.fr/](https://spot.lrde.epita.fr/)
Table 3: The number of fragment dependencies for each parent requirement, and the number of child requirements before and after refactoring. Note: this does not include Active and Not Active, because they only occur in the child requirements.

| Parent ID | № of Dependencies | № of Child Requirements |
|-----------|--------------------|-------------------------|
|           |                    | Before Refactoring | After Refactoring |
| UC5_R_1  | 3                  | 3                      | 1                    |
| UC5_R_2  | 3                  | 3                      | 1                    |
| UC5_R_3  | 3                  | 1                      | 1                    |
| UC5_R_4  | 3                  | 1                      | 1                    |
| UC5_R_5  | 3                  | 3                      | 1                    |
| UC5_R_6  | 3                  | 3                      | 1                    |
| UC5_R_7  | 3                  | 1                      | 1                    |
| UC5_R_8  | 3                  | 1                      | 1                    |
| UC5_R_9  | 3                  | 3                      | 1                    |
| UC5_R_10 | 3                  | 3                      | 1                    |
| UC5_R_11 | 3                  | 1                      | 1                    |
| UC5_R_12 | 3                  | 1                      | 1                    |
| UC5_R_13 | 1                  | 2                      | 2                    |
| UC5_R_14 | 1                  | 2                      | 2                    |

Total Child Requirements | 28 | 16

Table 4: The number of times each fragment’s definition occurs in a child requirement. Note that this table includes Active and Not Active.

| ID  | Fragment Name                          | № of (Re)Definitions |
|-----|----------------------------------------|-----------------------|
|     |                                        | Before Refactoring | After Refactoring |
| F1  | Sensor Faults                          | 8                     | 1                   |
| F2  | Tracking Pilot Commands                | 13                    | 1                   |
| F3  | Control Objectives                     | 18                    | 1                   |
| F4  | Regulation Of Nominal Operation        | 14                    | 1                   |
| F5  | Operating Limit Objectives             | 6                     | 1                   |
| F6  | Mechanical Fatigue                     | 8                     | 1                   |
| F7  | Low Probability Hazardous Events       | 8                     | 1                   |
| F8  | Active                                 | 28                    | 1                   |
| F9  | Not Active                             | 28                    | 1                   |

Total (Re)Definitions | 132 | 9

quantify the impact of our refactoring approach, we analyse the original and the refactored requirements sets, and compare: the total number of requirements, and the number of repetitions of a fragment’s definition.

Table 3 shows, for each parent requirement, upon how many fragments it depends, and how many child requirements it has both before and after refactoring. Note, the parent requirements do not depend on Active and Not Active. The number of dependencies remains constant: understanding a requirement still depends on understanding the definition of its fragments. However, the number of child requirements has been reduced, lowering the total number of requirements.

In total, we removed 12 child requirements, reducing the total from 28 down to only 16. The addition of 9 requirements, to define the fragments (§4.2), mean that the total number of requirements dropped from 42 to 39. The requirements set contains 14 parent requirements (rephrased to refer to the fragments), 16 child requirements, and the 9 fragments.

After refactoring, only one child is needed to define the detail of most of the parent requirements, because the fragments have been extracted and merged. The exception to this is UC5_R_13 and 14, which specify the system’s switching behaviour between two different modes; hence they have two child requirements.

Before refactoring, each fragment was redefined in each child requirement that used it. After
refactoring, each fragment is defined in a single requirement. Table 4 shows the number definitions of each fragment (including Active and Not Active). We reduced the number of duplicated definitions of fragments by 123: from 132 before refactoring to only 9 afterwards.

6 Discussion

In this section we discuss how to incorporate refactoring into FRET, and how our FRETISH requirements compare to others in the literature.

User View of Extending FRET: In §4 we described how we manually refactored and checked our requirements, but automatic support in FRET is preferable because it would be quicker and less error-prone. FRET should enable the user to select the parts of a requirement (possibly in different fields) that are the target for refactoring; then present the user with the applicable refactorings, and allow them to select the (existing or new) destination requirement for the refactoring. The formal comparison of the original and refactored requirements should happen automatically, and the results should be shown to the user.

It is also important to maintain the relatively easy readability of FRETISH. In §4, the referenced requirement names were always in block capitals, to make them obvious. This, or similar, should be supported in FRET; additionally, a requirement should have a ‘Depends’ ID link, to document its dependencies. Also, FRETISH notation should make it clear to the user that var=1 in the condition is a boolean comparison, but var=1 in the response is an update.

Technical View of Extending FRET: The ‘Depends’ ID link, mentioned above, would also help the technical implementation of our proposals. As previously mentioned, FRET interprets the references to other requirements as boolean variables. But with a ‘Depends’ ID link, FRET would know which requirements were being referenced. This link would facilitate translating requirements with dependencies to temporal logic, and to both CoCoSim [3] and CoPilot [6].

A simple route to updating FRET’s translations to cope with requirements that have dependencies is to simply merge the requirement and its dependencies. This approach also supports the implementation of Inline Requirement (§3.4). As previously mentioned, merging the condition and response fields is relatively simple; but for the scope or component fields, or if there is a conflict between the timing fields, the user may have to choose which to keep. However, this would reintroduce the repetition of definitions in the translation output. A more sophisticated approach would carry the refactoring relationship to the generated conditions, but we leave developing this as future work.

Requirements in the Wild: Our requirements set was developed in collaboration with our industrial partner [7]. To the best of our knowledge, this is the first set of FRETISH requirements that have been constructed alongside an industrial partner for a system that is still under development [8]. Related work generally present FRETISH requirements for pre-existing example applications or conceptual systems [2,13,17], apart from a set of FRETISH requirements for a robotic system [9] which was constructed alongside developers of an academic prototype.

Our natural-language requirements seem to have much more repetition than in related work, though [13] does contain some. The natural-language version of our requirements contained repetitions; and, because we opted for a one-to-one mapping to maintain traceability, so too did our FRETISH requirements. This is the reality of encountering requirements for systems in-the-wild and was observed in recent work [5].

7 Conclusion

This paper adapts four code refactorings for requirements written in FRETISH, the input language of FRET. We take inspiration from prior work on refactoring natural-language requirements [18], which we extend by exploiting the temporal logical translations of FRETISH requirements to check that refactoring steps do not alter the meaning of requirements.

In previous work, we derived FRETISH requirements for an aerospace engine controller, from natural-language requirements and test cases supplied by our industrial partner [7,15]. We used our adapted
Extract Requirement refactoring to extract duplicated definitions of concepts that were repeated in the natural-language requirements, which we call fragments, into their own requirement. This breaks the link between a requirement’s dependencies and the duplication of definitions.

Despite creating 9 new requirements, the total dropped by 3. Crucially, the number of duplicated definitions dropped by 132; each of the duplicated definitions is now only stated once. Further, the requirements themselves are now easier for a user to read, reducing the cognitive overhead in understanding them. Formally comparing the temporal logic versions of original and refactored requirements required some manual effort, but we are confident that future work on incorporating refactoring into FRET can mechanise these checks. Examining our approach’s scalability and applicability is ongoing work within our project.

FRET supports an integrated approach to verification, by translating fretish requirements into temporal logic, and the input languages of other verification tools (CoCoSim and CoPilot). Additional future work is to examine the impact of our proposed refactoring steps on these translations.

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