AutoReq: expressing and verifying embedded software requirements

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Abstract—Writing requirements for embedded software is pointless unless they reflect actual needs and the final software implements them. In usual approaches, the use of different notations for requirements (often natural language) and code (a programming language) makes both conditions elusive. To address the problem, we propose to write requirements in the programming language itself.

The expected advantages of this seamless approach, called AutoReq include: avoiding the potentially costly miss due to the use of different notations; facilitating software change and evolution, by making it easier to update code when requirements change and conversely; benefiting from the remarkable expressive power of modern object-oriented programming languages, while retaining a level of abstraction appropriate for requirements; leveraging, in both requirements and code, the ideas of Design by Contract, including (as the article shows) applying Hoare-style assertions to express temporal-logic-style properties and timing constraints; and taking advantage of the powerful verification tools that have been developed in recent years.

The last goal, verification, is a focus of this article. While the idea of verifying requirements is not widely applied, the use of a precise formalism and a modern program prover (in our case, AutoProof for Eiffel) makes it possible at a very early stage to identify errors and inconsistencies which would, if not caught in the requirements, contaminate the final code. Applying the approach to a well-documented industrial example (a landing gear system) allowed a mechanical proof of consistency and uncovered an error in a previously published discussion of the problem.

Index Terms—autoreq, seamless requirements, design by contract, autoproof, eiffel, landing gear system, specification drivers, multirequirements

I. OVERVIEW AND MAIN RESULTS

A key determinant of the quality of software systems is the quality of their requirements; nowhere is the need for good requirements higher than in embedded software, where an inconsistent or incomplete understanding of the requirements can lead to catastrophic results. This article presents the outline of a general method, called AutoReq for producing verified requirements of embedded software, and illustrates it on a widely used case study, an airplane landing gear system (LGS). The goal is to obtain requirements of high quality:

- Easy to write.
- Clear and explainable to domain experts.
- Amenable to change.
- Providing a close link to subsequent steps in software development, particularly implementation, particularly to support traceability.
- Amenable to mechanical verification and validation.

As the last point indicates, AutoReq includes not only techniques for expressing requirements but also for verifying their consistency. The LGS case study illustrated the effectiveness of the verification approach by uncovering a significant error in previous descriptions of this often-studied example (Section VI-E).

The method of expressing requirements does not introduce any new formalism but instead relies on a standard programming language providing mechanisms of Design by Contract (DbC)\(^1\) to state semantic constraints. While DbC relies on Hoare logic\(^2\), which at first sight does not cover temporal-logic-style and timing properties essential to the specification of embedded software, we show that it is in fact possible and even simple to express such properties in the DbC framework.

The method of verifying requirements does not introduce any new tools but instead relies on a powerful automatic program proving system, AutoProof\(^3\), associated with the programming language. This system can verify the temporal and timing properties expressed in the DbC framework. We have applied it to the verification of the landing gear system and the discovery of the error.

The advantages expected from the approach include:

- Expressiveness, since requirements benefit both from the expressive power of declarative assertions and from that of imperative instructions.
- Ease of learning, since there is in fact nothing new to learn for anyone familiar with the programming language.
- Continuity (in the sense of seamless development) with the rest of the development cycle, since design and implementation (not explored in this article) may rely on the same formalism, avoiding the impedance mismatches that arise from the use of different formalisms, and facilitating change.
- Precision and completeness, through formal specifications (contracts) covering the precise semantics of the system and its environment.
• Use of existing tools, as available in modern IDEs, to support the requirements process. A compiler for a typed language performs many checks that are as useful for requirements as for executable code.

More generally, the contributions of this work are:

• The outline of a general method for requirements engineering with application to embedded software.
• The demonstration (at least for problems of the kind covered so far) that it is possible to use a programming language as an effective mechanism for requirements specification.
• A precisely defined concept of verifying requirements (complementing the usual concept of verifying programs).
• A translation scheme from temporal-logic-style and timing properties to simpler Hoare-style properties (essentially, first-order predicates on states) as traditionally used in Design by Contract.
• A simple way to combine environment and machine properties (the two components of requirements in the well-known Jackson-Zave approach) in a requirements specification.
• A direct mapping of these requirements concepts into well-known verification concepts, “assume” and “assert”.
• The demonstration that it is possible, through the preceding techniques, to use an existing program prove to verify requirements.

Section II discusses consequences of poor embedded software requirements. Section III presents the Landing Gear case study. Section IV describes the requirements methodology: how to specify requirements, and how to verify them. Section V shows how to translate various patterns, common in requirements analysis, into the expected form for specification and verification; the source of the translation can be either temporal-logic-style or Abstract State Machine specifications. Section VI sketches the methods application to the case study, including an analysis of the uncovered error (with full results available in a GitHub repository [4]). Section VII discusses some related work. Section VIII discusses limitations and future work.

II. THE IMPORTANCE OF VERIFYING REQUIREMENTS

Embedded software – in aerospace, transportation, defense and other life-critical areas – raise some of the toughest demands on the reliability of software systems. Ensuring reliability begins with the quality of requirements for a system: the best implementation is useless if the requirements are inconsistent or do not reflect actual needs. It is well understood today that requirements are software and subject to the same scrutiny as other software elements such as code, designs and tests.

The literature contains many examples of software disasters arising from requirements problems. These problems are of two kinds:

• In the first kind, the problem arises from an incorrect relationship between the requirements and other software tasks, steps or products: the requirements may be incorrectly understood, incorrectly updated or incorrectly implemented.
• In the second kind, the problem lies with the requirements themselves, which are inherently wrong; for example, they may be inconsistent, incomplete, or not in line with the stakeholders actual needs.

Examples of the first kind include [5]:

• November 2000 – National Cancer Institute, Panama City. In a series of accidents, therapy planning software created by Multidata Systems International, a U.S. firm, miscalculates the proper dosage of radiation for patients undergoing radiation therapy.
• June 4, 1996 – Ariane 5 Flight 501. Working code for the Ariane 4 rocket is reused in the Ariane 5, but the Ariane 5’s faster engines trigger a bug in an arithmetic routine inside the rocket’s flight computer. The error is in the code that converts a 64-bit floating-point number to a 16-bit signed integer. The faster engines cause the 64-bit numbers to be larger in the Ariane 5 than in the Ariane 4, triggering an overflow condition that results in the flight computer crashing.
• January 15, 1990 – AT&T Network Outage. A bug in a new release of the software that controls AT&T’s #4ESS long distance switches causes these mammoth computers to crash when they receive a specific message from one of their neighboring machines – a message that the neighbors send out when they recover from a crash.

Analysis of these examples suggests that the problem lies in part from the use of different methods and particularly of different notations for requirements and other tasks such as implementation. This observation is a basis for the seamless approach ([6], [7], [8], [9]) followed in this article, which uses a single notation throughout.

Examples of the second kind (from van Lamsweerde et al. [10]) are:

• Several cases (see [11]) in the London underground system where people were killed due to doors opening or closing in unexpected circumstances without alarm notification to the train driver.
• An aerospace project [12] where 49% of requirements errors were due to incorrect facts about the problem world.
• An inadequate assumption about the environment of the flight guidance system may have contributed to the tragic crash of an American Airlines Boeing 757 in Cali (Colombia) in December 1995 [13]. The information about the point in space where the pilot was expected to initiate the flap extension was assumed to arrive before the plane reached that point in space. The aircraft has already passed that point, which resulted in the guidance software ordering the plane to turn around towards a mountain.

These examples (and many others to be found in the literature) illustrate the importance of verifying requirements. While the concept of verification, largely accepted for code, its application to requirements is less common. We will see,
however, that it is possible to apply to requirements both the concept of verification and modern proof-oriented verification tools which were initially devised with code in mind.

III. THE LANDING GEAR SYSTEM

To assess a new approach, it is important to see it not only showcased in the authors own examples of choice but also benchmarked against the treatment of existing examples by the rest of the literature. This article focuses on the second task by applying the method to what may be the most widely discussed case study of embedded software in the literature.

The Landing Gear Systems (LGS) [14] has served as a basis for requirements methods and notations ([15], [16], [17], [18], [19], [20], [21]). The LGS physically consists of the landing set, a gear box that stores the gear in the retracted position, and a door attached to the box (Figure 1). A digital controller independently actuates the door and the gear. The controller initiates either gear extension or retraction depending on the current position of a handle in the cockpit. The task is to program the controller so that it sends correct signals to the doors and the gears actuators.

The following properties of the LGS system, reproduced from [14], all applied to the “command line” in “normal” mode (as opposed to “failure” mode), are the focus of the present discussion:

\[ R_{11} \text{bis} \]

When the command line is working (normal mode), if the landing gear command handle has been pushed DOWN and stays DOWN, then eventually the gears will be locked down and the doors will be seen closed.

\[ R_{12} \text{bis} \]

When the command line is working (normal mode), if the landing gear command handle has been pushed UP and stays UP, then eventually the gears will be locked retracted and the doors will be seen closed.

\[ R_{21} \]

When the command line is working (normal mode), if the landing gear command handle remains in the DOWN position, then retraction sequence is not observed.

\[ R_{22} \]

When the command line is working (normal mode), if the landing gear command handle remains in the UP position, then outgoing sequence is not observed.

We will work not directly from the original description of LGS in [14] but from one of the most interesting treatments of case study, by Arcaini et al. [16]. It uses the abstract state machine (ASM) approach and applies a process of successive refinements:

1) Starts with a “ground model” that only includes some of the requirements.
2) Model-check that model.
3) Repeatedly extend (refine) the model with more properties of the LGS system, proving the correctness of each refinement.

The AutoReq specification discussed in the next sections starts from the ASM ground model. Some of its features are a consequence of this choice:

- It does not consider properties that appear only (as a result of step 3 above) in ASM models other than the first (step 1), even though they are part of LGS.
- It only covers “normal mode”, ignoring the “failure mode” of LGS.
- Like the ASM model, it assumes that the only source of non-determinism is the pilots handle. In failure mode, there might be others.
- It takes over from the ASM model such instructions as gears := RETRACTED which posit that the system has a way to send the gear directly to the retracted position. This assumption is acceptable at the modeling level but not necessarily true in the actual LGS system.
- The ASM-to-Eiffel translation scheme (Section V-C) ensures preservation of the one-step semantics of ASM.

IV. REQUIREMENTS METHODOLOGY

AutoReq builds on the idea of seamless development [6], [7] and multirequirements [8], and continues the work on seamless requirements [9]. The new focus is particularly on requirements verification, and on reuse of previous requirements elements through a mechanism similar to the notion of routine call in programming. We examine in turn how to specify and reuse requirements and environmental assumptions (Section IV-A), what it means to verify them (Section IV-B), and how to add timing constraints (Section VI-B).

A. Specifying requirements

The principles are the following:

- Unity of software construction and verification: seamless requirements stimulate construction and, at the same time, are suitable for checking correctness of the deliverables.
- Unity of functional requirements and code: the requirements document becomes one of the classes in the source code repository, readable by both customers and developers.
- Independence from a development model choice: there is no need to adjust the requirements notation in the event of switching the development model on the go.
- Traceability for free: existing features of the underlying IDE assist in requirements traceability management.
- (Multirequirements [8]) Use of complementary notations geared towards different stakeholders: graphical (e.g.
UML), textual (English) and formal (in this case Eiffel), the last one serving as a reference.

While the approach is general, it includes specific mechanisms for embedded software:

- Specification of environmental assumptions.
- Specification of timing assumptions and requirements.
- Reuse of assumptions and requirements for construction of other ones.

The basic notation is Eiffel. All the examples have been written in Eiffel under the EiffelStudio development environment [22], compiled, and processed by the AutoProof verification environment. The interest of compilation is not in the generated code, since at this stage the Eiffel texts represent requirements only, but to perform the many consistency checks of a modern compiler, such as type checking. Note that the requirements can take full advantage of object-oriented mechanisms such as classes, inheritance and genericity.

There is sometimes an instinctive resistance to using a programming language for requirements, out of a fear to lose the fundamental difference between the goals of the two steps: programming languages are normally used for implementation, while requirements should be descriptive. The AutoReq approach, however, uses the programming language not for implementation but for specification, restricting itself to requirements patterns discussed next. The imperative nature of these patterns does not detract from this goal; empirical evidence indeed suggests [23] that operational reasoning works well for programmers and other stakeholders. An added benefit is the availability of program verification tools, which the approach of this article channels towards the goal of verifying requirements.

For this verification goal, there seems to be a mismatch between the standard properties that program verification tools and the needs of embedded software. Program verification generally relies on Hoare-style properties as embodied in Eiffels Design by Contract properties of either one program state or, in the case of postconditions, two program states (initial and final, for a routine). The specification of embedded software generally relies, as in the ASM model used here for reference, on temporal-style properties, involving properties of an arbitrary number of (future) states of the system.

One of the contributions of this work is to resolve the mismatch, taking advantage of the use of a full programming language, used here not to describe an imperative program — we are at the requirements level, not implementation — but to emulate temporal-style properties, expressed through schemes described in Section V.

B. Verifying requirements

As noted in the introduction, many software errors are requirements errors. To avoid inconsistencies, AutoReq specifications include formal properties which can be submitted to proof tools for verification.

The properties are of two kinds, based on the distinction introduced by Jackson and Zave [24], followed by van Lam-sweerde:

- Environment (or “domain”) properties characterize the context in which the system must work. The development team has no influence on them.
- Machine (sometimes called “system”) properties characterize what the system must do. It is the job of the development team to work on them.

AutoReq specifications reflect this distinction using two constructs, common in modern verification work, at least since ESC-Java [25]:

- **assume E end** specifies an environment property E.
- **assert E end** specifies a machine property E.

For the proof process, **assume** adds E to the set of properties that the prover may rely on, or **assumptions**; **assert** adds M to the set of properties that the prover must prove, or **proof obligations**. (It is interesting to see how neatly the Jackson-Zave distinction, classic in the requirements literature, maps into the assume/assert distinction, classic in the verification literature.)

Verifying requirements in AutoReq simply means proving that all **assert** properties hold, being permitted to take **assume** properties for granted.

Notational convention: the above notations are for presentation. The actual Eiffel texts, as verified through the process reported in the next sections, use the following standard Eiffel equivalents:

- For **assert X end**, the notation in the actual Eiffel texts is **check X end**. (check is a standard part of Eiffels Design by Contract mechanism.)
- For **assume X end**, the actual notation is **check assume: X end**. (The “assume” tag is also supported by Eiffel and is a standard part of the notation for programs prepared for verification with the AutoProof prover [3].)

The notation **old X**, in a routine body, denotes the value of an expression X on entry to the routine. Until recently available in postconditions only, it is now permitted anywhere in the routine text. Since our verification runs predated the compiler versions supporting this generalization, they simulated it by using a local variable, i.e. **old_x**, initialized on routine entry.

The framework defined in this section generalizes the notion of verification from the realm of programs, where it is usually applied, to the realm of requirements. The verification process described above describes what a program prover such as AutoProof (internally, its Boogie engine), does: relying on the hypothesis that certain assertions (including not just **assume** but also routine preconditions and class and loop invariants) hold at the corresponding program points, prove that certain other assertions (including not just **assert** but also postconditions and again invariants) hold at their own program points. The only difference is in the elements that appear between these assertions, which can be any instructions such as assignments in programs, and are more restricted in requirements. In addition, the specifications include timing properties, using the translation into classic assertions described in the previous section.

Formal methods and notations are essential for one of the goals of this work (precision/completeness, see Section I), but
non-technical shareholders sometimes find them cryptic at first sight, hampering other goals, readability and ease of use. The “multirequirements” approach addresses this problem by using complementary views, kept consistent, in various notations: formal (such as Eiffel or a specification language), graphical (such as UML) and textual (such as English). In line with this general idea, AutoReq specifications rely on systematic commenting conventions (somewhat in the style of Knuths “literate programming” [26]). A typical example from the specification in the next section is

```plaintext
-- Assume the system run_in_normal_mode
```

The second line is formal; the comment in the first line helps put it in context. These seemingly informal comments actually follow precise rules. For non-expert users, and for the present discussion, it is enough to treat them as natural-language explanations.

V. STRUCTURING AN EMBEDDED SOFTWARE SPECIFICATION

The mechanisms of the preceding section enable us to write the requirements for an embedded software and verify them. Such specifications will follow standard patterns:

- Overall program structure (Section V-A).
- Translation rules from temporal-style properties as commonly found in requirements documents (Section V-B).
- Translation rules for properties in the Abstract State Machine style (Section V-C).

These schemes and translation patterns are fundamental to the methodology because they govern the use of the programming language. While the methodology relies on a programming language for expressing requirements, it does not use the language in the same way as actual programs do: the goal is requirements, not implementation. These requirements stick to predefined schemes that precisely match the needs of embedded software requirements.

For the present work, the translation patterns have been applied manually. A possible goal for future work (Section VIII) is to formalize the input language, respectively timed temporal logic and ASM, and turn the translation patterns into formal rules and automatic translation tools. See also [27] and [28].

A. Overall program structure

An embedded program is typically (unlike sequential programs in other application areas) repeating and non-terminating. AutoReq reflects this property by assuming a program of the form `from until False loop main end` so that the task of the requirements is to specify “main”.

B. Translating temporal and timing properties

In developing “main”, the methodology uses translation rules for four typical requirements patterns, divided into two orthogonal binary criteria:

- Time-independent versus timing-related.
- In line with the Jackson-Zave distinction (Section IV-B), describing an assumption about the environment or prescribing a property expected of the system (machine).

Some of the patterns can be expressed in temporal logic, in either of the non-timed variants LTL and CTL or in timed propositional temporal logic (TPTL, [29]).

The time-independent patterns are:

- **P1** Environment assumption: Assume the system runs in mode \( \text{c} \) under conditions \( \text{cs} \).
- **P2** System obligation: The system should immediately meet property \( \text{p} \) under conditions \( \text{cs} \). The LTL formulation is \( \square (\text{cs} \implies \Diamond \text{p}) \).

The timing-related patterns are:

- **P3** Environment assumption: Assume the system spends \( t \) time units to meet property \( \text{p} \) in the worst case under conditions \( \text{cs} \). The TPTL formulation is \( \Box t.((\neg \text{p} \land \text{cs}) \implies \Diamond y. (\Diamond (y = (x + t))) \).
- **P4** System obligation: The system should spend no more than \( t \) time units to meet property \( \text{p} \) under persistent conditions \( \text{cs} \). In TPTL the property reads \( \Box (\text{cs} \implies \Diamond y. (\Diamond (y \land y \leq x + t))) \).

These four cases suffice for the examples that have been addressed with AutoReq so far, and for this paper. Translation schemes are possible for more general LTL/CTL/TPTL schemes if the need arises in the future.

The Eiffel translations will, as one would expect, use `assume` for the environment assumptions P1 and P3, and `assert` for the system obligations P2 and P4.

The translation for P1:

```plaintext
-- Assume the system run_under_condition_c
do
  assume c end
main_under_conditions_cs
end

where main_under_conditions_cs is either of the form P1 or P3.
```

P2 translates into

```plaintext
-- Require the system to immediately_meet_property_p
do
main_under_conditions_cs
assert p end
end
```

The technique for handling the timing-related patterns relies on an integer, non-decreasing variable `duration`. For P3, the translation is:

```plaintext
-- Assume it takes t time units to take the system from_not_p_to_p:
do
  main_under_conditions_cs
  if (not old p and p) then
duration := duration + t
  end
end
```

The technique for handling timing system obligations of the form P4 differs from the others in that it uses loops as the core expression mechanism:
C. Translating ASM properties

Abstract State Machines \cite{30} are a commonly used specification formalism for embedded software, and the treatment of the LGS system in \cite{16} served as a starting point for this article's own treatment of the example. The translation scheme from ASM to Eiffel (applied manually) is the following.

An ASM specification is a collection of rules taking one of three forms \cite{31}: assignment, do-in-parallel and conditional.

An ASM assignment reads:

\[ f(t_1, \ldots, t_j) := t_0 \]  

The semantics is: update the current content of location \( \lambda = (f(a_1, \ldots, a_j)) \), where \( a_i \) are values referenced by \( t_i \), with the value referenced by \( t_0 \).

In Eiffel locations are represented with class attributes, so an ASM's location update corresponds in Eiffel to an attribute assignment.

ASMs parallel operator applies several rules simultaneously in one step. For this work we only need to handle parallel assignments such as:

\[ a, b := \max(a - b, b), \min(a - b, b) \]  

whose translation in Eiffel uses auxiliary variables:

\begin{verbatim}
local
  a_intermediate, b_intermediate: INTEGER

do
  a_intermediate := max(a-b, b)
  b_intermediate := min(a-b, b)
  a := a_intermediate
  b := b_intermediate
end
\end{verbatim}

The translation of an ASM conditional \textbf{if} \( t \) \textbf{then} \( R_1 \) \textbf{else} \( R_2 \) is an Eiffel conditional instruction.

VI. THE LANDING GEAR SYSTEM IN AUTOReq

Equipped with the AutoReq mechanisms as described, we can now see the core elements of the AutoReq specification of the LGS example. The whole example appears in a public GitHub repository \cite{4}.

A. Normal mode of execution

We follow the ASM ground model in considering only "normal mode". The formal expression of this property is:

\begin{verbatim}
-- Assume the system in normal mode
run_in_normal_mode
  -- the handle status range:
  assume handle_status = up_position or
    handle_status = down_position end
  -- the door status range:
  assume door_status = closed_position or
    door_status = opening_state or
    door_status = open_position or
    door_status = closing_state end
  -- the gear status range:
  assume gear_status = extended_position or
    gear_status = extending_state or
    gear_status = retracted_position or
    gear_status = retracting_state end
  -- the door may extend or retract
    only with the door open:
  assume (gear_status = extending_state or
    gear_status = retracting_state) implies
    door_status = open_position end
  -- closed door assumes
    retracted or extended gear
  assume door_status = closed_position implies
    (gear_status = extended_position or
    gear_status = retracted_position) end
main
end
\end{verbatim}

The routine is a multiple application of the \text{run_under_condition_c} pattern. It wraps around \text{main} to make additional assumptions before calling it. The definition of normal mode comes from the ASM specification.

B. Timing properties

The present section introduces timing assumptions corresponding to the P3 pattern of \text{Section V-B}. The original description of the LGS case study \cite{13} does not state these assumptions: it imposes general response requirements on the system, without limiting the response in time. We refine the requirements by adding to them time limits and formulating environmental timing assumptions upon which the implementation may rely.

It may take up to 8 time units for the door component to close:

\begin{verbatim}
-- Assume it takes 8 time units to take the door
from_open_to_closed -- position:
  from_closed_to_open
  run_in_normal_mode
    do
      run_in_normal_mode
        if (old door_status ≠ closed_position and
            door_status = closed_position) then
          duration := duration + 8
        end
    end
end
\end{verbatim}

It may take up to 12 time units for the door to open:

\begin{verbatim}
-- Assume it takes 12 time units to take the door
from_closed_to_open -- position:
  do
    run_in_normal_mode
      if (old door_status ≠ open_position and
        door_status = open_position) then
        duration := duration + 12
      end
  end
end
\end{verbatim}
The first instruction is a call to the assumption expressed by the previous routine.

It may take up to 10 time units for the gear to retract:

```plaintext
-- Assume it takes 10 time units to take the gear from_extended_to_retracted -- position:
do
  from_closed_to_open
  if (old gear_status ≠ retracted_position and gear_status = retracted_position) then
    duration := duration + 10
  end
end
```

Note again a call to a previous assumption. It may take up to 5 time units for the gear to extend:

```plaintext
-- Assume it takes 5 time units to take the gear from_retracted_to_extended -- position:
do
  from_extended_to_retracted
  if (old gear_status ≠ extended_position and gear_status = extended_position) then
    duration := duration + 5
  end
end
```

from_retracted_to_extended will include all the previously stated assume instructions together with main.

C. Baseline requirements

Section III introduced a set of core LGS requirements, \( R_{11} \) to \( R_{22} \), which we now express in AutoReq. \( R_{11} \) and \( R_{21} \) talk about the system running with the handle pushed down:

```plaintext
-- Assume the system run_with_handle_down
do
  assume handle_status = down_position
  from_retracted_to_extended
end
```

run_with_handle_down routine is an application of the run_under_condition_c pattern. This assumption calls the last previously defined one, from_retracted_to_extended, to consider all the assumptions made so far.

Now that the execution mode with the handle pushed down is formally defined, it is possible to express the requirements talking in terms of this mode. Property \( R_{21} \) requires the controller to immediately prevent retraction whenever the handle is pushed down:

```plaintext
-- Require the system to never_retract_with_handle_down
do
  run_with_handle_down
  assert gear_status ≠ retracting_state end -- known as \( R_{21} \)
end
```

Requirement \( R_{11} \) obliges the system to eventually extend the gear and close the door if the handle stays down. Like the rest of the ASM specification it does not include timing constraints, but this makes it unsuitable for the specification of an embedded software: we need to specify an upper bound on time the system may spend on gear extension. That upper bound is the sum of the maximal times for door closing, door opening and gear extension. From the assumptions made, this value is 25:

```plaintext
-- Require that extension_duration -- never takes more than -- 25 time units:
do
  run_with_handle_down
  until gear_status = extended_position and
door_status = closed_position or
  (duration − old duration) > 25
  loop
    run_with_handle_down
    assert gear_status = extended_position end
    assert door_status = closed_position end
    assert (duration − old duration) ≤ 25 end
end -- known as \( R_{12} \) bis
```

Requirements \( R_{12} \) bis and \( R_{22} \) talk about the system running with the handle pushed up:

```plaintext
-- Assume the system run_with_handle_up
do
  assume handle_status = up_position
  from_retracted_to_extended
end
```

The rest of the requirements can rely on the specification of the execution mode with the handle pushed up as we have now obtained it.

Property \( R_{22} \) requires the controller to prevent immediate extension whenever the handle is pushed up:

```plaintext
-- Require the system to never_extend_with_handle_up
do
  run_with_handle_up
  assert gear_status ≠ extending_state end -- known as \( R_{22} \)
end
```

Requirement \( R_{12} \) bis obliges the system to eventually retract the gear and close the door if the handle stays up. Like \( R_{11} \) it does not include timing constraints. The upper bound for \( R_{12} \) bis is the sum of the maximal times for door closing, door opening and gear extension. From the assumptions made, this value is 30:

```plaintext
-- Require that retraction_duration -- never takes more than -- 30 time units:
do
  run_with_handle_up
  until gear_status = retracted_position and
door_status = closed_position or
  (duration − old duration) > 30
  loop
    run_with_handle_up
    assert gear_status = retracted_position end
    assert door_status = closed_position end
    assert (duration − old duration) ≤ 30 end
end -- known as \( R_{12} \) bis
```

D. Complementary requirements

Requirements \( R_{11} \) bis and \( R_{12} \) bis talk about reaching the desired state under some conditions, but do not talk about preservation of that state. For example, even if the gear
becomes extended and the door closed with the handle pushed down, it is important that this situation does not change for no reason. The following application of the pattern captures this property:

```
-- Require the system to
keep_gear_extended_door_closed_with_handle_up
  do
    run_with_handle_up_gear_extended_door_closed
    assert gear_status = extended_position
    assert door_status = closed_position
  end
```

under the assumption that the doors are already closed, the gear is extended, and the handle is down:

```
-- Assume the system
run_with_handle_down_gear_retracted_door_closed
  do
    assume gear_status = retracted_position
    assume door_status = closed_position
    run_with_handle_down
  end
```

The following seamless requirement captures the corresponding property for the handle pushed up:

```
-- Require the system to
keep_gear_retracted_door_closed_with_handle_up
  do
    run_with_handle_up_gear_retracted_door_closed
    assert gear_status = retracted_position
    assert door_status = closed_position
  end
```

under the assumption:

```
-- Assume the system
run_with_handle_up_gear_retracted_door_closed
  do
    assume gear_status = retracted_position
    assume door_status = closed_position
    run_with_handle_up
  end
```

As one can see, AutoReq becomes a rich expressive mechanism in the presence of a powerful program prover such as AutoProof. The AutoReq method is suitable for expressing various kinds of statements: timing assumptions and requirements, execution mode assumptions, invariant properties assumptions and requirements. These statements are not only expressible, but also reusable and formally provable.

E. An error in the ground model

Applying the AutoReq method and tools to the published ASM specification of the LGS system by Arcaini et al. uncovered an error. The application consisted of the following major steps, in this order:

1) Take the ASM specification. The language in which the ASM specification is expressed contains syntactic sugar in addition to the standard ASM operators. The first step consisted of analyzing these additional constructs to understand how they should translate to Eiffel.

2) Translate it into Eiffel. This step consisted of mechanical translation of the specification and the requirements to Eiffel.

3) Try to verify it with AutoProof. Default settings of AutoProof will not work with the AutoReq method. This step consisted of investigating AutoProof’s command-line options to find the ones that might help. The GitHub repository with the translation includes a “readme” file that explains how to launch AutoProof.

4) Identify the error. When AutoProof reports a verification failure, it does not point at a place in the program. It is the developer’s responsibility to find the actual mistake. The last step consisted of this search.

The error is that the specification does not meet the requirement, which states that pushing the handle down should lead to the gear extended and the door closed.

Normally, when the crew pushes the LGS handle down, the controller should initiate the gear extension process. Regardless of the initial system’s state, this process should end up correctly – so that in the end the gear is extended and the LGS latch is closed. A state exist from which the erroneous ASM specification will not bring the system to the correct configuration. This state corresponds to a situation in which the gear has just been retracted and the door is closing. The gear extension sequence in the erroneous specification does not handle this state, thus leading to a deadlock. Imagine a situation in which the crew tries to retract the gear during take-off, and some physical obstacle prevents the latch from closing completely. In this case a possible solution might be to extend the gear back, and then try to retract it again. A real software controller implemented around the erroneous specification would make extension with the latch partially closed impossible. Analysis of possible consequences for such a situation goes beyond the article’s scope.

The published Eiffel translation of the specification does not have the error. To catch it with the AutoReq method one needs first to introduce the error back by commenting out two lines in the routine of the Eiffel translation:

```
open_door
  do
    inspect door_status
    when closed_position then
      door_status := opening_state
    when opening_state then
      door_status := opening_state
  end
```

and then submit requirement to verification with AutoProof; the verification will fail.

AutoProof detects an error in the following major steps:

Inline the unqualified calls inside of the routine to the level of attribute updates and statements.

Unroll the loop inside of . How much to unroll is a configurable setting; the default configuration suffices for the LGS example.

Check the statements based on the outcome from the Inline step.

We have contacted an author of the article that contains the erroneous ASM specification, and he confirmed the presence of the error, though the repository the authors were using contained a correct specification.
VII. RELATED WORK

A. Existing formalisms

Reasoning about programs, imperative and concurrent, has been the focus of computer science researchers for decades \[42\], and it traces back as early as Turing’s work \[33\]. Different techniques have been developed over time, and it soon became clear that, while post facto verification can be successful for small programs, an effective verification strategy should support and be part of the software development itself, and be fully embedded in the process.

The AutoReq method follows this idea and relies on DbC-style verification; however, one should understand that DbC is not well suited for embedded software as it is. The possibility of non-deterministically changing sensors introduces the gap between DbC and embedded software. Traditional DbC relies on invariant-based reasoning, in particular on the principle of invariant stability \[34\]: it should be impossible for an operation to make an object inconsistent without modifying the object. This principle does not work with embedded software because of the possible non-determinism in the environment. In other words, any attempt to constrain a non-deterministic variable trough a contract will inevitably lead to a failure of the contract.

Embedded software communicates asynchronously with the environment. This introduces another gap with DbC, which is designed from the beginning to deal with synchronous software. For non-life-critical systems \[24\] one may sacrifice the asynchronicity under additional assumptions \[35\], but the landing gear system clearly does not fall into this category.

Approaches to requirements that take the non-determinism into account rely chiefly on the notion of a monitor introduced by Zave \[36\]. A monitor is an executable requirement that runs in a dedicated process and observes the software from outside logging possible anomalies. A monitor continuously polls the state of the non-deterministic variables and checks if the software evolves accordingly. This approach respects the non-determinism, but is dynamic and thus cannot be viewed as the ultimate way to establish correctness of embedded software.

The general aspiration towards sound static verification resulted in numerous modeling approaches that rely on a declarative logic. The declarative view simplifies static reasoning, but the software will eventually have to physically operate. C. A. R. Hoare introduced an imperative logic to statically reason about software way back in 1969, but this invention has still been treated only as a verification mechanism, not a requirements specification notation. The recent notion of seamless requirements proposes a use of generalized Hoare triples called specification drivers \[40\] as a requirements notation for deterministic software.

The AutoReq method steps forward by applying the idea of seamless requirements to the non-deterministic setting. It empowers the operational view of Pamela Zave on requirements with AutoProof – a Hoare-style prover of Eiffel programs with contracts that relies on the Boogie technology \[41\]. In AutoReq a requirement is a routine enriched with assume statements capturing environmental assumptions, and assert statements that capture the obligations for AutoProof corresponding to the assumptions. The resulting method respects the non-determinism as monitors do, but does not assume the requirements to physically run. The AutoReq method will benefit the development process even when there is no static verifier like AutoProof: an operational requirement will become a subject to testing. The testing will consist in this case of running the requirement in the simulated environment described in its assume statements.

B. Timing properties

Modeling of real-time computation and related requirements has been a well-investigated matter for long \[42\]. Representation of real-time requirements, expressed in general or specific form, is a challenging task that has been attacked through several formalisms both in sequential and concurrent settings, and in a broad set of application domains. The difficulty (or impossibility) to fully represents general real-time requirements other than in natural language, or making use of excessively complicated formalisms (unsuitable for software developers), has been recognized.

In \[43\] the domain of real-time reconfiguration of system is discussed, emphasizing the necessity of adequate formalisms. The problem of modeling real time in the context of services orchestration in Business Process, and in presence of abnormal behavior has been examined in \[44\] and \[45\] by means, respectively, of process algebra and temporal logic. Modeling of protocols also requires real-time aspects to be represented \[46\]. Event-B has also been used as a vector for real-time extension \[47\] to handle embedded software requirements.

In all these studies, the necessity emerged of focusing on specific typology of requirements using ad-hoc formalisms and techniques, and making use of abstractions. The notion of “real-time” is often abstracted as number of steps, a metric commonly used.

The AutoReq method works with the explicit notion of time distance between events by stating operational assumptions on the environment; it also supports the abstraction of time as number of steps through finite loops with integer counters (the retraction requirement).

VIII. CONCLUSIONS AND FUTURE WORK

The approach presented above is a comprehensive method for requirements analysis based on ideas from modern object-oriented software engineering and the application of a seamless software process that relies on the notation of a programming language as a modeling tool throughout the software process. The work also introduces the notion of verifying requirements and shows how to use a program prover to perform the verification.

The work is subject to the following possible limitations, also suggesting areas of improvement:

- While the idea of seamless requirements has been widely applied, its AutoReq development as described here needs more validation on diverse examples.
- The patterns given are not necessarily complete; here too experience with more examples is necessary to find out whether more patterns are needed.
The idea of using a programming language for requirements runs counter to accepted ideas; while there are strong arguments supporting it, given in this article, it may be hard to accept for some people.

The approach as given relies on Eiffel, because of its support for a seamless process, its powerful abstraction mechanism, and its Design by Contract mechanism. More work is required to determine how applicable it would be to a software process using other implementation languages.

As discussed in Section V, parts of the process may benefit from automation. The tool support is currently under development.

With these reservations, we believe that the article and the case study demonstrate the benefits and contributions listed in the introduction, and point to a promising approach to producing and verifying effective requirements for embedded software.

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REFERENCES

[1] B. Meyer, “Applying ‘design by contract,’” Computer, vol. 25, no. 10, pp. 40–51, 1992.
[2] C. A. R. Hoare, “An axiomatic basis for computer programming,” Communications of the ACM, vol. 12, no. 10, pp. 576–580, 1969.
[3] J. Tschannen, C. A. Furia, M. Nordio, and N. Polikarpova, “AutoProof: Auto-active functional verification of object-oriented programs,” in International Conference on Tools and Algorithms for the Construction and Analysis of Systems, pp. 566–580, Springer, 2015.
[4] A. Naumchev, “Landing Gear System ground model specification and requirements in Eiffel.” https://github.com/anaumchev/lgs_ground_model, 2017.
[5] M. Lake, “Epic failures: 11 infamous software bugs — InfoWorld,” 2010.
[6] B. Meyer, Object-oriented Software Construction (2Nd Ed.), Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 1997.
[7] K. Waldén and J. M. Nerson, Seamless object-oriented software architecture. Prentice-Hall, 1995.
[8] B. Meyer, “Multirequirements,” in Modelling and Quality in Requirements Engineering (Martin Glinz; Festschrift) (N. Seyff and A. Koziolk, eds.), MV Wissenschaft, 2013.
[9] A. Naumchev and B. Meyer, “Seamless requirements,” Computer Languages, Systems & Structures, vol. 49, pp. 119–132, sep 2017.
[10] A. Van Lamsweerde, Requirements engineering: From system goals to UML models to software, vol. 10. Chichester, UK: John Wiley & Sons, 2009.
[11] P. G. Neumann, Computer-related risks. Addison-Wesley Professional, 1994.
[12] I. A. Hooks and K. A. Farry, “Customer-Centred Requirements,” in AMACOM, 2000.
[13] F. Modugno, N. G. Leveson, J. D. Reese, K. Partridge, and S. D. Sandys, “Integrated safety analysis of requirements specifications,” in Requirements Engineering, 1997., Proceedings of the Third IEEE International Symposium on, pp. 148–159, jan 1997.
[14] F. Boniol and V. Wiels, The Landing Gear System Case Study, pp. 1–18. Cham: Springer International Publishing, 2014.
[15] W. Su and J.-R. Abrial, Aircraft Landing Gear System: Approaches with Event-B to the Modeling of an Industrial System, pp. 19–35. Cham: Springer International Publishing, 2014.
[16] P. Arcaini, A. Gargantini, and E. Riccobene, Modeling and Analyzing Using ASMs: The Landing Gear System Case Study, pp. 36–51. Cham: Springer International Publishing, 2014.
[17] P. Dhaussy and C. Teodorov, “Context-Aware Verification of a Landing Gear System,” in Communications in Computer and Information Science, vol. 433, pp. 52–65, 2014.
[18] D. Hansen, L. Ladenberger, H. Wiegard, J. Bendisposto, and M. Leuschel, Validation of the ABZ Landing Gear System Using ProB, pp. 66–79. Cham: Springer International Publishing, 2014.
[19] A. Mammar and R. Laleau, “Modeling a landing gear system in Event-B,” International Journal on Software Tools for Technology Transfer, vol. 19, pp. 167–186, apr 2017.
[20] B. Berthomieu, S. Dal Zilio, and Ł. Fronc, Model-Checking Real-Time Properties of an Aircraft Landing Gear System Using Fiacre, pp. 110–125. Cham: Springer International Publishing, 2014.
[21] R. Banach, The Landing Gear Case Study in Hybrid Event-B, vol. 433, 2014.
[22] “Eiffel Community.” https://www.eiffel.org/.
[23] D. Fahland, D. Lübke, J. Mendling, H. Reijers, B. Weber, M. Weidlich, and S. Zugal, Declarative versus Imperative Process Modeling Languages: The Issue of Understandability, pp. 353–366. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.
[24] M. Jackson and P. Zave, “Deriving specifications from requirements: an example,” in Proceedings of the 17th international conference on Software engineering, pp. 15–24, ACM, 1995.
[25] D. R. Cok and J. R. Kiniry, ESC/Java2: Uniting ESC/Java and JML, pp. 108–128. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005.
[26] D. E. Knuth, “Literate programming,” The Computer Journal, vol. 27, no. 2, pp. 97–111, 1984.
[27] A. Bormotova, “Translation of natural language into abstract Hoare triples.” https://github.com/flosca/hybrid, may 2017.
[28] V. Skukov, “Translation of abstract Hoare triples into natural language.” https://github.com/flosca/hybrid, may 2017.
2017.

[29] R. Alur and T. A. Henzinger, “A really temporal logic,” Journal of the ACM, vol. 41, no. 1, pp. 181–203, 1994.

[30] Y. Gurevich, Evolving algebras. No. A-51, 1994.

[31] Y. Gurevich, “Sequential abstract-state machines capture sequential algorithms,” ACM Transactions on Computational Logic, vol. 1, no. 1, pp. 77–111, 2000.

[32] C. B. Jones, “The early search for tractable ways of reasoning about programs,” IEEE Annals of the History of Computing, vol. 25, no. 2, pp. 26–49, 2003.

[33] C. B. Jones, Turing’s 1949 Paper in Context, pp. 32–41. Cham: Springer International Publishing, 2017.

[34] N. Poliakpova, J. Tschannen, C. A. Fria, and B. Meyer, “Flexible invariants through semantic collaboration,” in FM 2014: Formal Methods, pp. 514–530. Springer, 2014.

[35] A. Naumchev, B. Meyer, and V. Rivera, “Unifying requirements and code: An example,” in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 9609, pp. 233–244, 2016.

[36] P. Zave, “An Operational Approach to Requirements Specification for Embedded Systems,” IEEE Transactions on Software Engineering, vol. SE-8, no. 3, pp. 250–269, 1982.

[37] D. Jackson, Software Abstractions: Logic, Language, and Analysis. The MIT Press, 2006.

[38] J.-R. Abrial, S. Schuman, and B. Meyer, “A Specification Language,” On the Construction of Programs, 1980.

[39] D. Jackson, “Alloy Applications.” http://alloy.mit.edu/alloy/citations/case-studies.html, 2017.

[40] A. Naumchev and B. Meyer, “Complete Contracts through Specification Drivers,” in Proceedings - 10th International Symposium on Theoretical Aspects of Software Engineering, TASE 2016, 2016.

[41] K. R. M. Leino, “This is boogie 2,” Manuscript KRML, vol. 178, p. 131, 2008.

[42] H. Yamada, “Real-time computation and recursive functions not real-time computable,” Electronic Computers, IRE Transactions on, vol. 2, pp. 544–546, dec 1962.

[43] M. Mazzara and A. Bhattacharyya, “On Modelling and Analysis of Dynamic Reconfiguration of Dependable Real-Time Systems,” Dependability (DEPEND), 2010 Third International Conference on, 2010.

[44] M. Mazzara, “Timing issues in Web Services composition,” in Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 3670 LNCS, pp. 287–302, 2005.

[45] L. Ferrucci, M. M. Bersani, and M. Mazzara, “An LTL semantics of business workflows with recovery,” in 2014 9th International Conference on Software Paradigm Trends (ICSOFT-PT), pp. 29–40, aug 2014.

[46] M. Berger and K. Honda, “The two-phase commitment protocol in an extended pi-calculus,” in Electronic Notes in Theoretical Computer Science, vol. 39, pp. 21–46, 2003.

[47] A. Iliasov, A. Romanovsky, L. Laibinis, E. Troubit-