Offline Runtime Verification of Safety Requirements using CSP

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31st December 2021

Abstract

Dynamic formal verification is a key tool for providing ongoing confidence that a system is meeting its requirements while in use, especially when paired with static formal verification before the system is in use. This paper presents a workflow and Runtime Verification (RV) toolchain, Varanus, and their application to an industrial case study. Using the workflow we manually derive a Communicating Sequential Processes (CSP) model from natural-language safety requirements documents, which Varanus uses as the monitor oracle. This reuse of the model means that the monitor oracle does not have to be developed separately, risking inconsistencies between it and the model for static verification. The approach is demonstrated by the offline RV of a teleoperated manipulation system, called MASCOT, which enables remote operations inside the Joint European Torus (JET) fusion reactor. We describe our model of the MASCOT safety design documents (including how the modelling process revealed an underspecification in the design) and evaluate the Varanus toolchain’s utility. The workflow and tool provide validation of the safety documents, traceability of the safety properties from the documentation to the system, and a verified oracle for RV.

1 Introduction

Runtime Verification (RV) provides ongoing confidence that a system continues it meet its requirements after it has been developed and in use. These requirements are often expressed in natural-language safety documents, based on trusted (often non-formal) safety analysis techniques. Integrating formal methods with existing non-formal safety techniques is useful, often necessary [3], and provides another tool for the verification toolbox.

This paper presents an RV workflow and toolchain, where the oracle (the component that provides the verdict on whether or not the System Under Analysis (SUA) violates the specification) is a Communicating Sequential Processes (CSP) model of the behaviour described in the system’s design. In our workflow, we build this oracle (by hand) from existing natural-language safety documents, capturing both the behaviour and the safety requirements, then verify the model of the behaviour against the safety requirements using the CSP model checker, the Failures-Divergences Refinement checker (FDR) [5]. We then use this model as the monitoring oracle, again using FDR. Formally modelling and verifying the safety documents can expose errors, we discuss an instance of this in §6.

Our RV approach uses a CSP model directly, as the RV oracle; whereas related approaches use implementations or dialects of CSP (see §2). This means that the model has two uses in our workflow: first in model checking a system’s design, to identify faults; and second as the RV oracle, to verify that the system continues to obeys its safety requirements. Reusing the model supports traceability of the safety properties from the safety documentation to a system artefact, which has been formally verified so it also gives strong evidence that the correct safety properties are being monitored.

We illustrate our approach using offline RV of the MASCOT system (described in §4) which is a pair of master-slave robotic arms that enable engineers to operate remotely inside a fusion reactor.

*Work supported through the UKRI RAIN grant EP/R026084, and enabled by previous work carried out within the framework of the EUROfusion Consortium, which has received funding from the Euratom research and training programme 2014-2018 and 2019-2020, grant No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Thanks go to Luigi Pangione and Rob Skilton at CCFE; Matt Webster for helpful discussion; and Angelo Ferrando, Louise Dennis, and Marie Farrell for comments on early drafts. Most of this work was done when the author was employed by the University of Liverpool, UK.
For the upgrade to MASCOT version 6, which includes some autonomous movements, a new safety analysis and design were produced. These safety documents are the source material for our formal model and safety properties. The key concerns of the safety documents are the speed of the master arms (which could collide with the operator) and managing explicit changes between hands-on and autonomous modes of operation.

The rest of the paper is laid out as follows; §2 describes related work, and §3 describes our toolchain and workflow. In §4 we describe the MASCOT system, its CSP model, and how we validated and verified the model. §5 describes how we evaluate the toolchain. In §6 we discuss the development of this approach and toolchain. Finally, §7 summarises our approach and describes future work.

2 Related Work

Our approach uses a CSP model directly as the RV oracle. There are other approaches to RV that make use of CSP-style notations, as dialects or implementations of CSP. For example, the Jass system [1] provides an assertion language for Java programs (developed before Java introduced its assert statement). Jass includes an assertion for specifying the permissible traces of method invocations, using a dialect of CSP [8]. The dialect is adapted to make it easier to specify the requirements of Java programs, which means that a CSP model would need to be manually translated into the dialect. While this does not seem onerous, it is another manual step to add to the workflow. Further, Jass is specialised to Java programs, whereas the work we present in this paper is agnostic of the implementation language of the SUA.

Another indirect use of the CSP language is CSP_E [12], which is a shallow-embedded Domain Specific Language (DSL) in Scala, specifically for RV. Again, this would require another manual conversation to be added to the workflow. Further, CSP_E is missing elements of CSP that would make the conversion from standard CSP less straightforward than reusing the model.

Dynamic verification approaches have been applied to other robotic examples where speed and potential collision with humans is of concern. For example an approach that calculates the reachable sets, where a collision is possible between a mobile robot and humans in its environment [6]. The calculation is based on kinematic models of the robot and humans, and checks that the robot cannot enter an area that a pedestrian could reach at the same time. This approach has also been applied to robot arms that share a workspace with a human [10]. Both of these are online techniques, but do not also offer static validation.

By contrast, ModelPlex [7] combines offline (static) verification of a model of a cyber-physical system with online validation of the system’s runtime behaviour against the model. If the system deviates from is verified model, then ModelPlex triggers safe fallback behaviour. This approach uses hybrid models, written in differential dynamic logic (dL), and automatically synthesises the runtime monitors. Another example of this combination of static verification and dynamic RV checks an autonomous robot against its model of its deployment environment [4]. The approach highlights where interactions with the real world invalidate the design-time assumptions about the robot’s environment. Both of these approaches are similar in intent to our work, but our case study is human-controlled and does not use a model of its environment.

3 Toolchain and Workflow

This section describes our RV toolchain and its intended workflow. Our toolchain, VARANUS\footnote{VARANUS, named for the biological genus of Monitor Lizards, is available at https://github.com/autonomy-and-verification/varanus/tree/FMICS-Data.} uses FDR’s API to check the behaviour of the SUA against a CSP model of its safety system. This paper presents an example of offline RV, where VARANUS read events from a file; but it can also listen for events over a socket or WebSocket, for online RV. VARANUS constructs a trace from the events, asks FDR if it is a valid trace of the model, and returns the verdict (pass or fail). VARANUS produces a log of the check and the response time, used in §5.

Figure 1 illustrates the VARANUS toolchain and workflow. In step 1 we formalise the system’s safety properties and functions, extracted from safety documents (see §3.1). Step 2 verifies the model against the safety properties, validating the model (see §3.2). Then, in step 3, VARANUS listens for
events emitted by the SUA (see §3.3). Finally, step 4 checks the events against the model (using FDR) to determine if the system is performing the safety functions (see §3.4).

3.1 Step 1: Formalising

This step involves modelling the behaviour and the safety requirements in the system’s safety documents, both the behaviour and the requirements become CSP processes. This step was performed manually, so required careful reading of the natural-language descriptions to formalise them. This can be time-consuming and requires formal modelling expertise. Discussion in the literature makes it clear that building specifications is still the biggest bottleneck in formal methods [11]. It is vital that the model built in this step is correct because it is the RV oracle in the VARANUS toolchain.

Using CSP enables us to model both the behaviour and requirements described in the safety documents using events. For example, the MASCOT safety subsystem monitors the speed of the master arms and initiates a protective stop if a speed limit is exceeded, which we model with the speed and protective_stop events. We describe CSP and our modelling approach in §4.2. There are examples of requirements in the safety design and their CSP translation in §4.3. In the author’s experience, software engineering or safety specifications are often written in a way that enables smooth translation into CSP, as discussed in §6.

The system’s safety requirements, safety properties, are formalised as CSP processes. The next step (§3.2) describes how we verify that the model preserves these safety properties. This direct link between the safety documents and our model supports traceability of the requirements into a formal artefact (our model) of the system’s development.

3.2 Step 2: Verifying

This step takes the CSP model and safety properties from §3.1 and verifies that the model preserves the properties. Since both the properties and model are written in CSP, this step uses the CSP model checker, FDR.

We use FDR to debug the model, by a combination of built-in assertions (deadlock, determinism, and divergence), and its Probe tool (which allows a user to step through a process’s available events). Then, the model can be verified against the safety properties. Both of these processes are iterative, and verification may highlight more areas to debug.

Verifying that the model preserves the safety properties has the side-benefit of validating the safety document itself. Formalising the natural-language specification of the safety system’s behaviour can highlight inconsistencies in the document. Even simple verification checks, such as checking for...
deadlock-freedom, can provide counterexamples showing an error in the safety document. An instance of this occurred during this work, which we discuss in §4.3.

3.3 Step 3: Listening

In this step, Varanus listens to and translates events of the SUA into events of the CSP model. As previously mentioned, Varanus can read a file of recorded events, for offline RV; or connect to a running system, for online RV. Each SUA will require a specific mapping between its events and those in the model; and an implementation of the system interface, which connects to the SUA or file.

Step 2 (§3.2) provides confidence that the model accurately represents the safety system (and therefore the SUA’s behaviour), so that it can be used for RV.

Varanus stores a trace of the events generated by the SUA, translated for the CSP model. The trace begins with the model’s initial event, and for each new event Varanus converts the SUA event into a CSP event, using the user-supplied mapping, and appends it to the trace. In the offline case, Varanus converts the whole trace before checking (described in §3.4). In the online case the trace is checked after each event is appended, which is a limitation of the current approach, because the FDR API was not designed for RV, and is why we focus on offline RV in this paper.

3.4 Step 4: Checking

Varanus uses FDR’s built-in [has trace] assertion to check if the SUA’s trace (from §3.3) is a valid trace of the model; that is, that the system is behaving according to the model. Each check is built from the template:

\[
\text{assert MODEL : [has trace] : (sua_trace)}
\]

where MODEL is the CSP process that defines the safety model, and sua_trace is a trace of events from the SUA. FDR checks that the MODEL can perform the sua_trace without diverging or refusing its events. This means that if MODEL offers a choice of events, each option will be explored.

FDR returns that the assertion check has either passed or failed, and provides a counterexample for a failing result. In our case study (§4), Varanus passes information is returned to the user. In online RV examples, this information could be used by the SUA for replanning or recovery.

4 Case Study: The MASCOT System

This section describes an application of the Varanus toolchain (§3). Our case study is MASCOT, a pair of master–slave robotic arms used at the Culham Centre for Fusion Energy (CCFE) in the UK to service the Joint European Torus (JET) nuclear fusion reactor. JET is operated by the UK Atomic Energy Authority (UKAEA) under contract from the European Commission, and exploited by the EUROfusion consortium of European Fusion Laboratories. The slave arms mirror the movements of the master arms, which are manually controlled by a human operator, enabling human operators to work remotely inside JET.

Over 350 tools have been adapted to fit on the end of the MASCOT manipulators. Tools can be changed during operations, picked from a ‘tool box’ that is also moved inside the reactor. MASCOT can be used to install, clean, and repair components inside the reactor. One major project used MASCOT for 18 months, two shifts a day, for replacement of tiles inside the reactor.

A programme is underway to update the system to ‘MASCOT 6’, which includes adding an autonomous mode to perform some basic repetitive operations without human intervention. This update has prompted a new safety design upon which we base our formal model. The key safety concerns relate to keeping the human operator safe during operation and maintenance.

The rest of this section is structured as follows. In §4.1 we describe the pertinent parts of the MASCOT 6 Safety Design document. § 4.2 describes how the safety design was modelled. Finally, §4.3 describes how the model was validated and verified.

\(^2\text{https://www.euro-fusion.org}\)

\(^3\)The safety design is confidential, so we are unable to make it publicly available. The relevant part of the document is available to reviewers in Appendix ??
4.1 MASCOT 6 Safety Design

The MASCOT 6 safety design identifies that autonomous movement in the slave-arms would be mirrored in the master-arms, causing a hazard to the operator. Mitigating this risk is the key concern of the safety subsystem described in the safety design, which introduces two modes of operation: hands-on and autonomous, with a different speed limit for the MASCOT arms in each mode.

The safety design defines seven safety ‘concepts’, which are the components of the safety control system. The safety properties are mixed in with the descriptions of the concepts, often as sentences that abstractly state that the system should or should not do something.

We directly model the following six components:

1. Emergency/Protective Stop, which controls both manually (Emergency) and automatically (Protective) stopping the system;
2. Safe State Key Switch, which initiates an emergency stop, triggered from the work area of either the master- or slave-arms;
3. Master Commissioning Mode Key Switch, which enables the operator to put the master arms into a Commissioning State, for repairs etc.;
4. Slave Commissioning Mode Key Switch, which enables the operator to put the slave arms into a Commissioning State (different to that of concept 3);
5. Master Safe Speed Monitor, which monitors the speed of the master arms, and raises a Protective Stop if the speed limit is broken; and,
6. Master Hands-on Mode Monitor, which toggles the safety system between the Hands-on and Autonomous modes, in response to the foot pedal switch.

The final component (which is not modelled explicitly) is an output that indicates the control system is still active, which is indirectly shown by other components in the model.

The Safe Speed Monitor (SSM) and the Hands-On Mode Monitor (HOMM) are the core components of the safety subsystem, cooperating to enforce the speed limit relevant to the current mode. The speed limit when the system is in autonomous mode is half that of the speed limit when in hands-on mode.

The HOMM monitors the foot pedal and tells the SSM what mode the subsystem is in. The SSM checks the speed and issues a protective stop if that mode’s speed limit is broken. The other components of the safety system interact with these core components, adding extra complexity to the system. A user can trigger an emergency stop at any time, using the Safe State Key Switch. If the system is in the Master Commissioning Mode, then a protective stop is not issued if the speed limit is broken. If the Slave Commissioning Mode Key Switch is used, then the system performs an emergency stop (as with the Safe State Key Switch) and then allows power to some parts of the slave-arms.

Interactions between these six components make manual analysis of the whole system very difficult. Formalising the components makes the natural-language descriptions into an unambiguous specification, which enables automatic checking. In §4.2, we describe our CSP model of the MASCOT safety system.

4.2 Modelling Approach

This section describes our CSP model of the MASCOT 6 safety subsystem, which is the result of step 1 (§3.1) of our workflow. The model is composed of communicating processes that correspond to the safety system’s components (see §4.1). The model comprises ~ 810 lines over eight files (including comments, but excluding two files of non-model validation code). FDR shows that the model contains 321 states and 804 transitions (during a determinism check).

Four of the six safety system components are each modelled by a process; the Emergency/Protective Stop and the Safe State Key Switch are represented by a single process, because their behaviour is very closely linked and combining them produced a simpler model. Other modelling abstractions include, abstracting the safe state key switches in the master and slave work areas into one component. Similarly, the speed of three different joints on each of the slave arms should be monitored. Our model abstracts this to one single speed measurement, though since the speed limit for each joint is the same, this process could be replicated.

Here, we briefly describe the CSP notation relevant to the examples in this section. CSP specifications are built from (optionally parametrised) processes. A process describes a sequence of events; for example $a \rightarrow b \rightarrow \text{Skip}$ is the process where the events $a$ and $b$ happen sequentially, followed
Figure 2: An extract from the HOMM, showing the process controlling the HOMM in autonomous mode.

by Skip which is the terminating process. An event is an instantaneous communication on a channel. Channels enable message-passing between processes, they are synchronous, non-lossy, and may have multiple end-points; but a process may perform an event (communicate an event on a channel) internally without a cooperating process.

Channels may declare typed parameters: channel c : int declares a channel c with one integer parameter. Parameters communicated on c may be inputs (c?in), outputs (c!out), or a given value (c.value); here in, out, and value are all of type int. Inputs can be restricted (c?p : set) to only parameters (p) in a given set (here, a set of type int).

P □ Q offers the option of either P or Q, once one process is picked the other becomes unavailable. Additionally, processes can be composed in sequence or parallel. CSP provides two parallel operators; in P || chan || Q, P and Q run in parallel, and agree to communicate on channels in the set chan; in P || [pChan | qChan] || Q, P and Q run in parallel, and agree to communicate on the channels common to the pChan and qChan sets.

The safety system is represented by the MASCOT_SAFETY_SYSTEM process, which comprises a parallel composition of the processes for each of the components. Each process starts by synchronising on the system_init event, which ensures that all of the components start executing at the same time.

The model contains two helper processes, which do not represent safety system components. The MASCOT_SYSTEM_STATE process tracks the system’s state: Safe, Autonomous, Hands-On, and the Master and Slave Commissioning modes. We assume that these states are mutually exclusive, though this was not clear from the safety design. The ATOM_CHAINS process enforces certain atomic chains of events that are required by the safety properties – for example, when the foot pedal is pressed, the next event is a change of mode.

The HOMM process starts in autonomous mode, we assume that the foot pedal is not being pressed when the system is initialised. Figure 2 shows the definition of the HOMM in autonomous mode. The foot_pedal_pressed event toggles the process between hands on mode and autonomous mode. In Fig. 2, foot_pedal_pressed.True takes the HOMM process into hands on mode (HMM_HANDS_ON_MODE).

Two events, enter_safe_state and enter_slave_commissioning_state, trigger a change to the safe state, which is controlled by the HMM_SAFE_STATE process. This can happen in either mode. In Fig. 2 the HMM_SAFE_STATE process is called with the AM parameter, which tells it to return to the autonomous mode when leaving the safe state. A different parameter is used when in hands on mode, to return to hands on process.

Finally, in either mode, the speed event pauses the HOMM so that the mode cannot be changed before the SAFE_SPEED_MONITOR (SSM) has checked the speed. This is handled by the HMM_PAUSE process, which only offers the protective_stop or speed_ok events. In Fig. 2, HMM_PAUSE is called with the AM parameter to tell it to return to the autonomous mode when resuming.

The SSM process also starts in autonomous mode and toggles between that and hands-on mode, but its trigger to change mode is an enter_hands_on_mode or enter_autonomous_mode event from the HOMM. This allows both processes to change mode together, while HOMM handles the foot_pedal_pressed event alone. This modular design is repeated throughout, where one process handles an external event and communicates with other processes via an internal channel.

Figure 3 shows the definition of the SSM in autonomous mode. The enter_hands_on_mode event is driven by the HOMM, and triggers the SSM to change to hands on mode. The events enter_safe_state or enter_slave_commissioning_state trigger a change to the safe state; similarly to the HOMM this
SSM_AUTONOMOUS_MODE =
  enter_hands_on_mode → SSM_HANDS_ON_MODE
  speed? : AutonomousSafeSpeeds → speed_ok → SSM_AUTONOMOUS_MODE
  speed? : AutonomousUnsafeSpeeds → protective_stop →
    enter_safe_state → SSM_SAFE_STATE(AM)
  enter_safe_state → SSM_SAFE_STATE(AM)
  enter_slave_commissioning_state → SSM_SAFE_STATE(AM)

Figure 3: An extract from the SSM, showing the process controlling the SSM in autonomous mode.

calls a process with the AM parameter so that the SSM returns to autonomous mode when leaving
the safe state.

The SSM’s role is to check the parameter of the speed event. In Fig 3, if the speed parameter is in
the set of safe speeds for the autonomous mode, speed? : AutonomousSafeSpeeds, then the response
is speed_ok; if it is in the set of unsafe speeds, speed? : AutonomousUnsafeSpeeds, then the response
is protective_stop and moving to the safe state. This drives the HOMM, as described earlier.

Other parts of our model make use of more complex CSP operators. The full model is available
online. The next section describes how we validate the model against the safety design and verify
that it preserves the safety properties

4.3 Model Validation and Verification

This section describes applying step 2 of our workflow (§3.2) to: validate the model against the
MASCOT 6 Safety Design (§4.1), and verify that it preserves the safety properties. This step ensures
that the model correctly represents the safety design, so that it can be used as the RV oracle.

First, we validate the model to show that it represents the safety design. We use FDR to automati-
cally check for deadlock, divergence, and determinism, which can identify undesirable behaviour; we
also use FDR’s Probe tool to step through a process, choosing the order of events. Both are invaluable
tools for specification debugging. This is an iterative process where: the model is checked, compared to
the safety design, and edited (where needed). This step provides confidence that the model accurately
captures the safety concepts.

Specification debugging revealed a problem in the safety design where the HOMM could change
mode before the SSM had reacted to an unsafe speed. For example, if the system was in au-
tonomous mode and the SSM (Fig.3) receives a speed event with an unsafe speed, it should per-
form protective_stop and tell the HOMM to enter_safe_state, but the HOMM (Fig.2) had the chance
to perform foot_pedal_pressed.True, before receiving enter_safe_state. This deadlocked the two pro-
cesses, with HOMM waiting for enter_hands_on_mode to be available in SSM, and SSM waiting for
enter_safe_state to become available in HOMM.

This problem allowed the speed limit to be changed, after a potentially unsafe speed had been
recorded but before the system could enter the safe state. Discussions with the MASCOT team at
CCFE confirmed that this was incorrect behaviour. Once it was confirmed that the SSM should take
precedence over the HOMM, we added a process to ensure this behaviour. Identifying bugs like this
shows the utility of careful specification debugging.

Next, we show that the model implements the safety system’s requirements by verifying model
against the requirements, as captured by the safety properties. In CSP, a safety property is specified
as a process. The CSP model checker, FDR, checks that the safety specification is refined by the
system specification; that is, that the system implements the safety property. Again, this is an iterative
process, where if checking a property failed, the cause of the failure was investigated and the model
was updated to fix this bug. In turn, this required edits that led back to the validation step.

We use the HOMM process as an illustrative example of the model verification. We identified three
safety properties in the safety design for the HOMM. The simplest of these is: “The monitored foot

4The model is available at https://doi.org/10.5281/zenodo.3932004
pedal is the only way for Hands-on Mode to be entered", which is captured by the safety specification:

\[ \text{HMM1} = \text{foot\_pedal\_pressed.} \text{True} \rightarrow \text{enter\_hands\_on\_mode} \rightarrow \text{HMM1} \]

The HMM1 process allows the foot pedal to be pressed (\text{foot\_pedal\_pressed.} \text{True}) and then enters hands on mode (\text{enter\_hands\_on\_mode}). We use FDR to check that the \text{MASCOT\_SAFETY\_SYSTEM} process implements HMM1.

The next identified requirement is a little more complicated: \text{“Autonomous mode is entered if the control system indicates it is no longer in Hands-on Mode”}. This is modelled by the safety specification:

\[ \text{HMM2} = \]

\[ \text{foot\_pedal\_pressed.} \text{False} \rightarrow \text{enter\_autonomous\_mode} \rightarrow \text{HMM2} \]

\[ \bigwedge \text{enter\_autonomous\_mode} \rightarrow \text{HMM2} \]

HMM2 allows a non-deterministic choice (\bigwedge) between detecting that the foot pedal has not been pressed, then entering autonomous mode; or entering autonomous mode, which allows the system to perform this event when triggered by something else that doesn’t affect this safety specification. We use \bigwedge to allow HMM2 to refuse one of the choices, ensuring that the model can enter autonomous mode for other reasons then the foot pedal not being pressed. Again, we use FDR to check that the model of the system implements HMM2.

We check that the model implements similar safety specifications for the processes that capture the other safety concepts, which provides confidence that the model implements the requirements in the safety design. The validation step gives crucial confidence that the safety design is modelled correctly, and gives the benefit of checking the safety document ‘for free’.

5 Toolchain Evaluation

This section describes the evaluation\(^5\) of the \text{VARANUS} toolchain (\S3) using offline RV of the case study presented in \S4. This corresponds to steps 3 (\S3.3 and 4 (\S3.4) of our workflow. All of the results are from running Python 2.7.18 and FDR 4.2.7 on a PC using Ubuntu 20.04.02, with an Intel Core i5-3470 3.20 GHz \times 4 CPU, and 8 GB of RAM.

This work focuses on offline RV. As previously mentioned, \text{VARANUS} is also capable of \text{online RV} but when trailed, the response time was too high for effective use online. We discuss this limitation in \S6 and intend to investigate mitigations as future work.

We trial \text{VARANUS’s} response times on constructed traces: first, stress-testing \text{VARANUS}, with increasingly long, semi-random traces; then, checking a set of scenarios that might occur during a hypothetical mission. The scenarios were based on MASCOT log files and personal correspondence with the MASCOT team at CCFE. This approach was taken because MASCOT 6 is still under development, so it was not possible to test RV directly, or to compare the execution times of MASCOT with and without monitoring.

We built a Python test harness that checks both the stress-testing and scenario traces directly in FDR’s API and using \text{VARANUS} for offline RV. The FDR API is called by the test harness and only the checking time is logged. For offline RV, the time taken to read the whole trace from a file and get the result from checking it in FDR is logged. These trials give us an idea of the scalability of the model checking in FDR, and the response times for \text{VARANUS} checking traces from a log file.

The stress-test traces begin with \text{system\_init} and add from 10 upto 100,000 \text{foot\_switch\_pressed} and \text{speed} events. We used a Python script to generate the traces so as to make sure that the \text{foot\_switch\_pressed} channel’s parameter toggled between \text{true} and \text{false}, and the \text{speed} channel’s parameter was always below the autonomous (lower) speed limit. This was to ensure that the entire trace would be checked, instead of a counterexample being generated midway through.

Table 1 shows the mean result in seconds of running 10 \text{has trace} checks using FDR’s API and \text{VARANUS}, on different trace lengths. It also shows the difference between these times. The checking times in both cases rises with the length of the trace. The results for traces of 1001 events or fewer, are 0.31s or less, each with an overhead of less than 0.15s.

\(^5\)The log files and results are available at https://doi.org/10.5281/zenodo.3932004
| Trace Length | FDR (s) | VARANUS Offline (s) | Difference (s) |
|--------------|---------|---------------------|----------------|
| 11           | 0.02    | 0.11                | 0.09           |
| 101          | 0.03    | 0.13                | 0.10           |
| 1001         | 0.17    | 0.31                | 0.14           |
| 10,001       | 1.53    | 2.02                | 0.49           |
| 100,001      | 17.97   | 20.60               | 2.63           |

Table 1: Results, in seconds, for checking traces of length 11, 101, 1001, 10,001, and 100,001 in FDR’s API and VARANUS, and the difference between these times

| No. | Concept(s) | Description |
|-----|-------------|-------------|
| 1   | 1, 5, and 6 | Operator stays in hands on mode, speed stays below limit. |
| 2   | 1, 5, and 6 | Operator stays in hands on mode, speed exceeds limit and tries to continue (causes a failure). |
| 2a  | 2           | Instead of the failure in Scenario 2, the system handles the broken speed limit, then resets, restarts, and finishes the mission. |
| 2b  | 2           | Instead of the failure in Scenario 2, the system handles the broken speed limit, the safe state key is removed (to allow servicing). Then the key is returned, the system is reset, restarted, and operation continues. |
| 3   | 1, 5, and 6 | Operator switches to autonomous mode after collecting tools, speed stays below limit. |
| 4   | 1, 5, and 6 | Operator switches to autonomous mode after collecting tools, speed exceeds limit and tries to continue (causes a failure). |
| 4a  | 2           | Instead of the failure in Scenario 4, the system handles the broken speed limit, then resets, restarts, and finishes the mission. |
| 4b  | 2           | Instead of the failure in Scenario 4, the system handles the broken speed limit, the safe state key is removed (to allow servicing). Then the key is returned, the system is reset, restarted, and operation continues. |
| 5   | 2           | The Safe State Key is used to trigger an emergency stop. Then the system is reset, restarted, and the mission is completed. |
| 6   | 3           | System enters Master Commissioning Mode. After some unmonitored movements (not triggering protective stop), Safe State Key is used to enter Safe State, and system is reset. |
| 7   | 4           | System enters the Slave Commissioning Mode, where no speed events are registered. Then Slave Commissioning Mode is disabled, again using the Slave Commissioning Mode key. |

Table 2: Table of scenarios used to evaluate the VARANUS toolchain, showing the Scenario Number, the identifier of Safety Concepts that it tests, and its description.

The scenario traces represent 13 different ‘attempts’ at a hypothetical mission using MASCOT to replace insulating tiles on the inside of the reactor. Notes in MASCOT logs suggest that this consists of repeated actions on a group of tiles, such as: removing, installing, and tightening the bolts, etc. The data in the logs shows mainly low velocities, with some spikes that tend to appear much later on, possibly as the task becomes more difficult, this is mirrored in the scenarios.

Table 2 summarises the scenario traces, which exercise different features of the safety system under a variety of circumstances. They test different combinations of events, mixing changes between autonomous and hands on modes, different speeds, and other safety system components. Between them, the scenarios cover all of the safety concepts modelled from the safety design.

Table 3 shows the mean result in seconds of running 10 [has trace] checks in FDR’s API, and using VARANUS for offline RV, for each scenario trace. It also shows the length of the trace and the difference between these times. Scenarios 2 and 4 are built to fail, so while they are each 193 events long they fail after 84 events and 66 events, respectively.

VARANUS adds an overhead of ~ 0.10s, and the maximum checking time is 0.16s, though this is no surprise since the traces are all less than 1001 events long. Again, the overhead varies slightly with trace length, but since the lengths of the scenario traces only has are range of 193 events, the range
Table 3: Results, in seconds, of checking the scenarios in Table 2, in FDR’s API and Varanus, and the difference. Each result is a mean over 10 checks. Scenarios 2 and 4 are built to fail, the length of the passing trace is noted in brackets.

| Scenario Name | Trace Length | FDR (s) | Varanus Offline (s) | Difference (s) |
|---------------|--------------|---------|---------------------|----------------|
| Scenario 1    | 193          | 0.05    | 0.15                | 0.10           |
| Scenario 2    | 193 (84)     | 0.04    | 0.13                | 0.10           |
| Scenario 2a   | 155          | 0.04    | 0.14                | 0.09           |
| Scenario 2b   | 158          | 0.04    | 0.14                | 0.10           |
| Scenario 3    | 193          | 0.05    | 0.15                | 0.10           |
| Scenario 4    | 193 (66)     | 0.03    | 0.13                | 0.10           |
| Scenario 4a   | 200          | 0.05    | 0.15                | 0.10           |
| Scenario 4b   | 203          | 0.05    | 0.16                | 0.11           |
| Scenario 5    | 201          | 0.05    | 0.16                | 0.11           |
| Scenario 6    | 45           | 0.03    | 0.13                | 0.10           |
| Scenario 7    | 10           | 0.02    | 0.12                | 0.10           |

of the differences is only 0.02s. Possibly these trace lengths aren’t indicative of those that would be produced by MASCOT, mitigation strategies for this are discussed in §6.

The response times for both FDR and Varanus rise with the length of the trace because both of them must process each event in the trace to conclude a verdict. There is little discernable difference in the response time for a trace that uses one safety concept (such as scenarios 5 or 6) and those use many safety concepts (such as scenarios 1, 2, 3, and 4). A more detailed study of FDR is required to answer questions about the response times for more complex traces or assertions, this is left for future work.

6 Discussion

An important benefit of our workflow is that it promotes specification reuse, which partly mitigates this bottleneck in using formal methods [11]. The CSP model is built for static verification, and then reused for RV. Because Varanus uses the model as the RV oracle, if we are confident of the model’s validity, we can be confident of the monitor’s validity.

The modelling and validation steps of our workflow may reveal problems in the original documentation, ‘for free’. Formalisation forces ambiguous natural-language descriptions to be clarified, and model checking examines the system’s design. As previously mentioned, the model validation step (§4.3) highlights an omission in the MASCOT 6 safety design that caused a spurious deadlock in the model. Our approach provides an example of the utility of formal methods even if only applied to some stages of a system’s development lifecycle.

This paper focuses on using Varanus for offline RV, which is useful for detecting when the system violates its safety requirements. Formalising requirements and then using that formal model directly as an RV oracle has the added benefit of easing the burden of traceability of the requirements into a system artefact. This should make updates and debugging simpler and make it easier to demonstrate to a regulatory authority that the system meets its requirements.

CSP generally allowed for easy translation of the behaviour described in the safety design. The MASCOT 6 safety system is composed of separate, but interacting, safety functions; this leads naturally into modelling the safety functions as parallel processes. The safety design often describes behaviour in a way that was easy to formalise in CSP, for example “Initiate a Protective Stop if the speed threshold is exceeded” easily translates into:

\[
\text{speed}?:\text{AutonomousUnSafeSpeeds} \rightarrow \text{protective} \_\text{stop}
\]

from Fig.3 where the speed event occurring with a parameter that is in the set AutonomousUnSafeSpeeds (there is a similar set of unsafe speeds for the hands-on mode) triggers the protective\_stop event. Earlier incarnations of this work attempted to convert our model into existing implementations of CSP; two in Python (Python-CSP [9] and PyCSP [2]) and the other in Scala (CSP\_E [12]). However, all three implementations differed slightly from ‘standard’ CSP, which made systematic conversion difficult.

As mentioned in §5, Varanus was trailed on online RV but the response time is too high for effective online use. The mean (over 10 runs) online response time for Scenario 1 was 6.8s, compared
to the 0.15s for offline RV (Table 2). This large overhead is because FDR’s API is not designed for online RV and requires the whole trace to be rechecked after each new SUA event. We intend to improve Varanus’s online response times in future work.

Varanus’s response times for all but the the largest stress-testing trace (100,001 events), are less than 0.50s. The largest scenario trace is 203 events long, but the MASCOT logs contain many thousands of records. It is unclear how fast MASCOT 6 will produce events, but it is likely that the trace will eventually become too long. We can see two paths for optimisation, both left for future work. (1) Traces could be filtered, to only contain events for one safety concept; sampled, to yield shorter representative traces; or reset after the SUA’s behaviour cycles back to the initial state. (2) Investigate optimisations in FDR’s API, or replace it.

7 Conclusion

This paper presents the application of a workflow and novel RV tool (Varanus) to an industrial case study. We model the safety requirements found in a natural-language safety document in CSP, and use Varanus for offline RV of the system against the CSP model. The events from the case study system are converted into a CSP trace and sent to FDR to test if the model accepts the trace.

Our approach enables a system to be modelled and monitored using the same language, without modifications between these two activities. Reusing the model like this is helpful, since modelling is often the bottleneck in using formal methods [11]. It also provides validation of the safety documents ‘for free’. CSP is designed for specifying processes, so it is suited to capturing imperative descriptions of behaviour. In the author’s experience, modelling requirements for or by software or mechanical engineers in CSP is relatively easy.

We demonstrate Varanus and the workflow, on the MASCOT teleoperation system. We model the safety system and safety properties from an English-language safety design document. We stress-test Varanus to find the response times for traces of different lengths. This shows that traces under 1000 events are checkable in less than 1s. MASCOT currently does not implement the safety system so we evaluate Varanus on scenarios constructed from MASCOT logs and personal communication with members of the MASCOT team at Remote Applications in Challenging Environments (RACE).

For future work, we intend to investigate improvements to Varanus’s online response times. As previously mentioned, the FDR API is not designed for online RV, and our current approach adds an unacceptable time overhead. We also intend to apply the workflow to safety cases and examine what benefits can be gained from their structure. If possible, we want to automate the extraction of safety properties from a safety case – or at least highlight the likely nodes in safety case that contain the safety properties to ease the modelling workload.

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