

ENTRUST: Engineering Trustworthy Self-Managing Systems – Technical Report

1 INTRODUCTION

The increasing complexity of software systems combined with the need to develop more versatile, resilient, and reliable systems instigated the vision of self-managing systems, also known as autonomous computing [1, 2]. In this regard, self-managing systems are expected not only to operate with minimal administrator intervention throughout their lifetime, but also to adapt while providing service in response to environment changes, evolving requirements and unexpected failures. As a result, the software engineering research community devoted much effort in developing frameworks, methodologies and architectures that support the engineering of systems enhanced with self-* capabilities (e.g., self-adaptive, self-managing, self-healing, self-optimising); see [3, 4] for more information.

Despite the research progress achieved since the advent of autonomous computing, the engineering of trustworthy self-managing systems remains a major research challenge. This barrier constrains the applicability of self-managing systems in safety-critical and business-critical applications, as for example, in healthcare, e-commerce, defence and finance. Systems deployed in these application areas should work dependably and must be characterised by high-integrity runtime operation, as defined by NIST [5]: “High integrity software is software that must be trusted to work dependably in some critical function, and whose failure to do so may have catastrophic results, such as serious injury, loss of life or property, business failure or breach of security.”

The software engineering community classified the provision of evidence, i.e., assurances, that a system operates dependably throughout its lifetime among the most important research objectives for self-managing systems [6]. In fact, assurances was amid the research threads highlighted in the most recent roadmaps for self-adaptive systems [7, 8]. We define assurances as “*the provision of evidence that the system satisfies its stated functional and non-functional requirements during its operation in the presence of self-adaptation*” [8].

In this work, we extend the current practices on the provision of assurances for self-managing systems. To this end, we introduce the first tool-supported methodology for assuring the safety of the closed control loops of self-managing systems using established industry practices. Our framework for the ENgineering of TRUstworthy Self-managing sysTems (ENTRUST) integrates:

- an extended version of our approach to developing formally verified monitor-analysis-planning-execution (MAPE) autonomic control loops [9];
- our runtime quantitative verification technique for the analysis stage of these loops [10];

- an industry-adopted approach to arguing security [11] based on the widely used Goal Structuring Notation (GSN) for safety arguments [12].

In this report, we illustrate how ENTRUST is capable of providing assurances for the safety of MAPE-K control loops as well as for the compliance of a self-managing system with its Quality-of-Service requirements. Hence, our focus is on the stages comprising the MAPE-K control loop and we do not consider any information regarding GSN.

The report is organised as follows. Section 2 describes the self-adaptive unmanned marine vehicle embedded system used for illustrating and evaluating ENTRUST. Sections 3 and 4 introduce the approaches underpinning ENTRUST, while Section 5 presents the realisation of ENTRUST for the implementation of the UUV system described in Section 2.

2 Running Example

We will demonstrate the application of ENTRUST using a self-adaptive UUV embedded system, adapted from [13]. UUVs are increasingly used in a wide range of oceanographic and military tasks, including oceanic surveillance (e.g., to monitor pollution levels and ecosystems), undersea mapping, and mine detection. Limitations intrinsic to the environment in which these vehicles operate (e.g., impossibility to maintain UUV-operator communication during missions and high frequency of unexpected changes) require that UUV systems are self-adaptive. These systems are also safety critical (e.g., when used for mine detection and surveillance of ecosystems that should not be impacted) and/or business critical, since UUVs are often expensive equipment that should not be lost during missions.

The self-adaptive system in our study consists of a UUV deployed to carry out a data gathering mission. The UUV is equipped with $n \geq 1$ on-board sensors that can measure the same characteristic of the ocean environment (e.g., water current, salinity or temperature). When used, the sensors take measurements with different, variable rates r_1, r_2, \dots, r_n . The probability that each sensor produces measurements that are sufficiently accurate for the purpose of the mission depends on the UUV speed sp , given by p_1, p_2, \dots, p_n ¹. For each measurement taken, different amount of energy is consumed, given by e_1, e_2, \dots, e_n . Finally, the n sensors can be switched on and off individually (e.g., to save battery power when not required), but these operations consume an amount of energy given by $e_1^{\text{on}}, e_2^{\text{on}}, \dots, e_n^{\text{on}}$ and $e_1^{\text{off}}, e_2^{\text{off}}, \dots, e_n^{\text{off}}$, respectively.

The UUV is required to self-adapt to changes in the observed sensor measurement rates r_i , $1 \leq i \leq n$, and to sensor failures by dynamically adjusting:

- (a) the UUV speed sp

¹ This information can be extracted from the technical specification of sensors; for example, see <http://www.ashtead-technology.com/rental-equipment/teledyne-rdi-600khz-navigator/>

- (b) the sensor configuration x_1, x_2, \dots, x_n (where $x_i = 1$ if the i -th sensor is on and $x_i = 0$ otherwise)

so that the UUV complies with the following requirements at all times:

- R1:** The UUV should take at least 20 measurements of sufficient accuracy for every 10 metres of mission distance.
- R2:** The energy consumption of the sensors should not exceed 120 Joules per 10 surveyed metres.
- R3:** If requirements R1 and R2 are satisfied by multiple configurations, the UUV should use one of these configurations that minimises the cost function

$$cost = w_1 E + w_2 s^{-1}, \quad (1)$$

where E represents the energy consumed by the sensors to survey a 10m mission distance, and $w_1, w_2 > 0$ represent weights that reflect the relative importance of carrying out the mission with reduced battery usage and completing the mission faster.

3 ActivFORMS

ActivFORMS is a formal approach for self-adaptation that uses an integrated formal model of the adaptive components and knowledge models. The formal model is executed directly by a virtual machine to realize adaptation, hence called active model. ActivFORMS approach distinguishes itself from existing approaches in two ways. First, the formally verified model of the complete feedback loop is directly executed by the virtual machine, which guarantees the verified adaptation goals at runtime. As the active model is directly executed by ActivFORMS, the approach does not require coding. Second, ActivFORMS supports dynamic change of the active model. A new feedback loop model can be deployed at runtime to meet new or changing goals.

Figure 1 shows the primary modules of the ActivFORMS. The approach is in line with the three layered reference model for self-adaptive systems proposed by Kramer and Magee [14]. The managed system realizes the domain functionality for users. The active model consists of two parts: an integrated formal model that realises a feedback loop, i.e., the active model, and a virtual machine that can execute the active model. The active model monitors and adapts the managed system through probes and effectors, respectively.

ActivFORMS supports feedback loops modelled using networks of timed automata [15]. A timed automaton is a finite-state machine that models a behaviour, extended with clock variables. Automata can synchronize through channels. There are two types of channels, binary channels and broadcast channels. For a binary channel, a sender $x!$ can synchronize with a receiver $x?$ through a signal. If there are multiple receivers $x?$ then a single receiver will be chosen non-deterministically. The sender $x!$ will be blocked if there is no receiver. On the contrary, a broadcast channel sends a signal to all the receivers, and if there is no receiver, the sender will not be blocked. Behaviour specifications

can be complemented with expressions specified in a C-like language to define data structures (struct concept) and functions. Goals can be expressed in timed computation tree logic expressions (TCTL). TCTL expressions describe the state and path formulae that can be verified, such as reachability (a system should/can/cannot/... reach a particular state or set of states), liveness (something eventually will hold), etc. We use Uppaal [16], a model checking tool that supports modelling of behaviours and verification of properties.

The goal management layer handles adaptation issues that cannot be performed by the current active model. The goal management consists of four parts, i.e., goal model, goal monitor, goal adapter and goal manager. The goal model represents the adaptation goals. ActivFORMS uses a AND-OR tree-based goal model to specify goals. The goals can be expressed as boolean expressions, and the goals at the bottom level of each subtree have associated models to realise adaptations. The goal monitor checks periodically the status of the goals and if any goal is violated, it notifies the goal adapter. The goal adapter is the heart of goal management. When the goal adapter receives a signal from the goal monitor about a goal change, it consults the goal model and searches for a matching model that satisfies the changing situation. If the model associated with the changing goal differs from the currently deployed model, the goal adapter starts updating the current model with the new model at the virtual machine. If the model does not differ no further action is required. The goal manager offers support for three primary functions: inspecting the active model and its ongoing execution, monitoring and updating goals, and updating the goal model. In our current implementation, the ActivFORMS user interface connects with the goal managers of different system nodes. The user interface enables a software engineer, e.g., a system administrator, to operate the goal manager remotely.

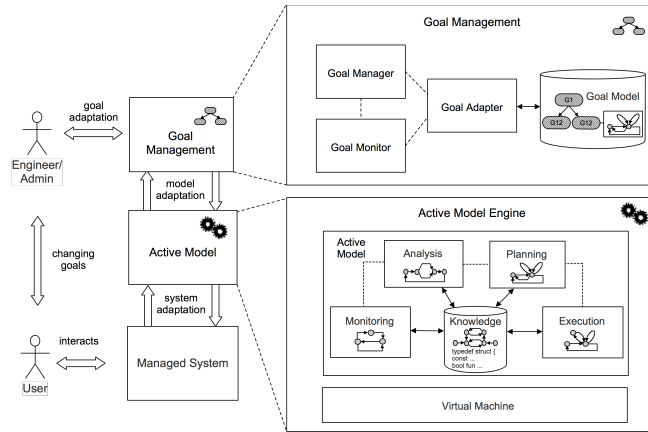


Fig. 1. ActivFORMS approach

4 Runtime Quantitative Verification

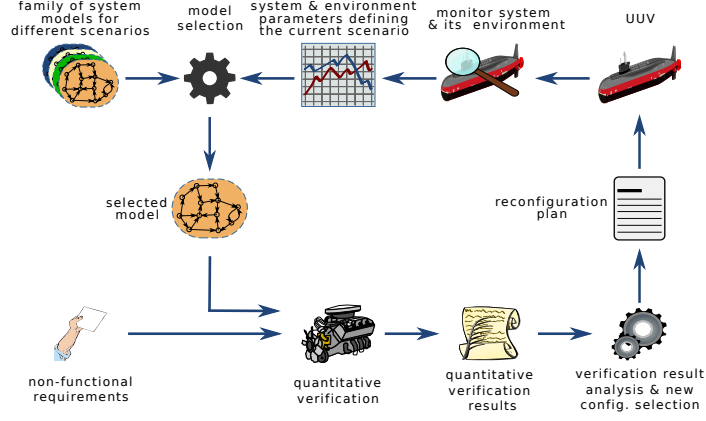


Fig. 2. RQV-based self-adaptive system

Runtime quantitative verification (RQV) [10] is an approach to implementing the closed control loop of self-adaptive systems in which the adaptation decisions are driven by the continual verification of stochastic models. RQV was introduced in [17, 18], refined further in [19–21] and applied successfully in multiple application domains including dynamic power management [17], reconfiguration of data-centre infrastructure [21], management of telehealth service-based system [19], and self-optimising unmanned underwater vehicles [13].

Figure 2 depicts the adaptation workflow of an RQV-based self-adaptive system. The approach involves monitoring the system (e.g., the UUV) and its environment continuously, to discover relevant changes and quantify them using fast on-line learning techniques. When these changes are significant and/or periodically, an RQV step is triggered, to identify which scenario the system operates in, and to select the associated model from a family of system models (i.e., a *parametric model*) that correspond to different such scenarios. The selected model is then analysed using quantitative verification, to identify and/or predict violations of QoS requirements such as response time, availability and cost. When QoS violations are identified or predicted, the verification results support the selection of a new set of values for the configurable system parameters, so that enforcing this new configuration is *guaranteed* to restore or maintain compliance with QoS requirements, respectively.

Example 1. Figure 3 depicts the CTMC model M_i of the i -th sensor of the UUV from our running example. The CTMC starts in state 0 and transitions in state 1 if the sensor is switched on ($x_i = 1$) or in state 6 otherwise ($x_i = 0$). With rate r_i , a measurement is performed, as indicated by the transition between states 1 and 2. The measurement is “sufficiently accurate” with probability p_i and

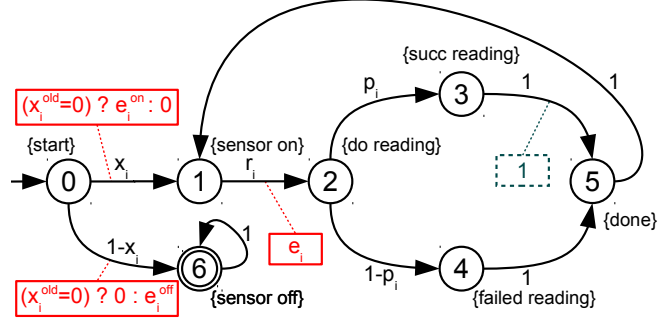


Fig. 3. CTMC model M_i of the i -th UUV sensor

the transition between states 2 and 3 is taken, whereas the transition between states 2 and 4 is enabled in case of an inaccurate measurement. An active sensor continues taking measurements while it is active, as modelled by the transition between states 5 and 1. The CTMC model is augmented with two cost/reward structures, whose non-zero elements are shown in Fig. 1 in rectangular boxes, and dashed rectangular boxes, respectively. The former, “*energy*” structure associates the energy used to switch the sensor on (i.e., e_i^{on}) and off (i.e., e_i^{off}) and to perform a measurement (i.e., e_i) with the CTMC transitions that model these events. Note that the ternary expression “*condition*?*a*:*b*” was used to indicate that the energy e_i^{on} is consumed only if the previous state of the sensor was “off”, i.e., if $x_i^{\text{old}} = 0$, whereas the energy e_i^{off} is used only if the opposite is true ($x_i^{\text{old}} = 1$). As concerns the latter, “*measurement*” cost/reward structure, it associates a reward of 1 with the transition that corresponds to an accurate measurement.

5 Implementation

To illustrate how ENTRUST is capable of assuring runtime compliance of a self-adaptive system with its non-functional Quality-of-Service (QoS) requirements, we developed a simulator for the unmanned underwater vehicle (UUV) embedded system (Section 2), using the open-source framework MOOS-IvP². Note that in ENTRUST self-adaptive systems there is separation of concerns between the managed system (i.e., the UUV and how it works) and the managing system (i.e., the autonomic component that enables a system to adapt). This consideration is in line with the autonomic computing vision [1]. In this realisation of ENTRUST, the focus is on the managing element; we omit any details about how the actual UUV operates. In the following paragraphs, we explain how we use ENTRUST to provide offline and online assurances for the UUV self-adaptive system.

² <http://oceanai.mit.edu/moos-ivp>

5.1 Online assurances

The managing system adopts the MAPE-K (Monitor–Analyse–Plan–Execute–Knowledge) autonomic control loop proposed by Kephart and Chess [1]. Also, the managing system uses probes and effectors to receive input from and send instructions to the managed system, respectively. In the following paragraphs we describe briefly the automata we developed for realising ENTRUST in the UUV embedded system.

Monitor. Monitor automaton receives sensors rates from probes. After that, the monitor automaton checks whether the received sensor rates are equal to the previously measured sensor rates. If both rates are equal, there is no need for adaptation; hence ENTRUST terminates and does not continue with the remaining MAPE-K control loop steps. If the sensor rates are different, then analysis is required and the monitor automaton invokes the analyse automaton sending a *start_analysis!* signal as shown in Figure 4.

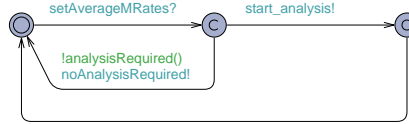


Fig. 4. Monitor automaton of our UUV embedded system

Analyser. Analyse automaton takes the current measured rates of sensors and tries to find the best configuration which satisfies requirements R1, R2 and R3. Figure 5 depicts the analyse automaton. The automaton starts the analysis as soon as it receives the signal *start_analysis?* from the monitor automaton. It then sends the signal *calcProbability* along with the sensor rates and invokes RQV to carry out quantitative analysis. For this operation we use an embedded instance of the probabilistic model checker PRISM [22]. This analysis evaluates

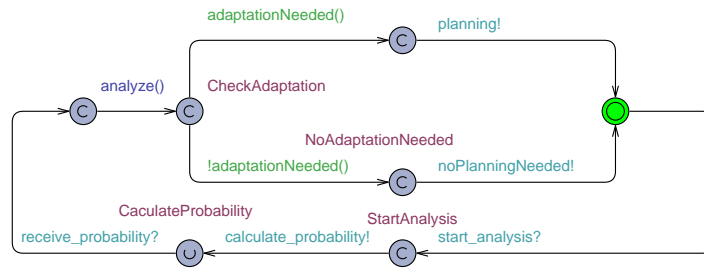


Fig. 5. Analyse automaton of our UUV embedded system

all the possible system configurations for the current environment state (i.e., rates of sensors). The analyse automaton receives the quantitative verification results through the *recvProbability?* channel. Next, it examines the received set of configurations and determines the configuration that satisfies requirements R1 and R2, and optimises requirement R3. Once the best configuration is found, the automaton compares the new configuration to the current best configuration. If the configurations are the same, there is no need to proceed to planning. If adaptation is required, the analyse automaton invokes the planner sending the signal *planning!*.

Planner. The plan automaton is responsible for establishing an adaptation policy. It starts running when the signal *planning?* is received. First, it creates the plan steps for the new configuration of sensors, i.e., whether a sensor should be turned on or off. To this end, the plan automaton checks the current sensor configuration with the new configuration and determines whether there is a need to make a change to one or more sensors. If the current sensor configuration is same as in the new configuration, there is no need to create a plan step. Otherwise, if the sensor configurations do not match, then the plan automaton creates the plan step, according to the new configuration. When all sensors are checked, the plan automaton checks if the current UUV speed is different to the new UUV speed and if this true, it creates a new plan step to change the speed of the UUV. Finally, the plan automaton invokes the execute automaton by sending the *execute!* signal. Figure 6 shows the plan automaton of the UUV.

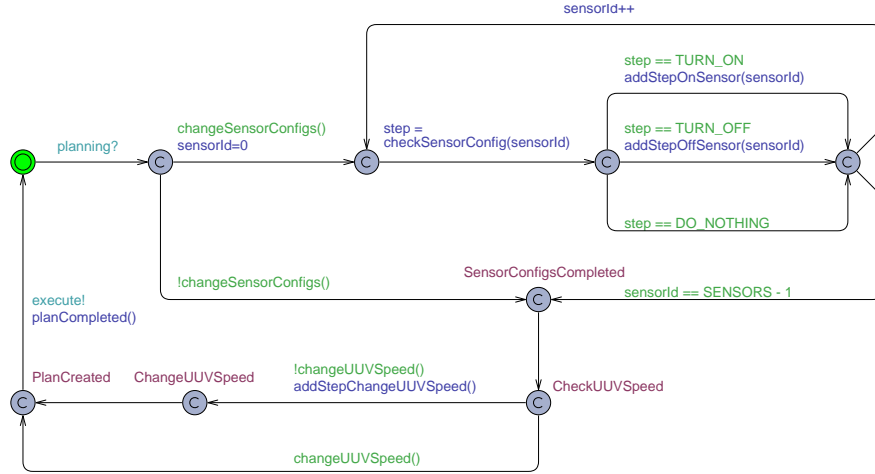


Fig. 6. Plan automaton of our UUV embedded system

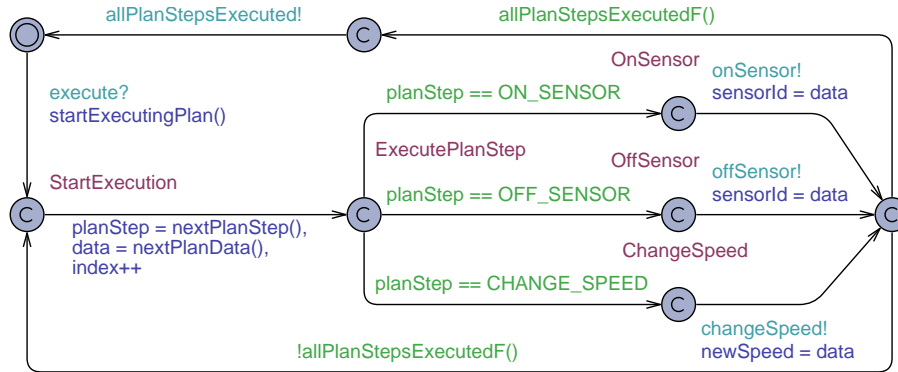


Fig. 7. Execute automaton

Executor The execute automaton starts after receiving the signal *execute?* from the plan automaton. It then goes through all the plan steps, one-by-one, and executes them. The operation completes when the signal *allPlanStepsExecuted!* is sent. The plan automaton is presented in the Figure 7.

5.2 Offline Assurances

We used ENTRUST to produce offline assurance evidence for the UUV embedded self-managing system. We verified both the MAPE-K autonomic control loop and the QoS system requirements (Section 2) using the knowledge part which comprises the probabilistic and automata models. For the verification of the MAPE-K control loop we checked various properties of the MAPE-K loop, e.g., if it is deadlock free and if its elements communicate and synchronise through signals. We also confirmed that each stage of this control loop operates as expected, e.g., if the analyser determines that no adaptation is required then it has to be the case that the current configuration is the same as the new configuration, if the planner creates an adaptation policy then the executor will realise this policy. For the verification of the QoS requirements, we used the nominal sensor rates (as defined in their specifications) and carried out the analysis stage to confirm that there is at least one policy satisfying the QoS requirements of the self-adaptive UUV system. In particular, we provided evidence for the compliance of the UUV system with requirements R1 and R2 (Section 2) verifying the following properties:

$$\begin{aligned} &A[\text{current_Configuration.R1_Result} > 20 \\ &A[\text{current_Configuration.R2_Result} < 120 \end{aligned}$$

6 Methodology

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