Extracting component-oriented behaviour for self-healing enabling

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Abstract—Rich and multifaceted domain specific specification languages like the Autonomic System Specification Language (ASSL) help to design reliable systems with self-healing capabilities. The GEAR game-based Model Checker has been used successfully to investigate in depth properties of the ESA ExoMars Rover. We show here how to enable GEAR’s game-based verification techniques for ASSL via systematic model extraction from a behavioral subset of the language, and illustrate it on a description of the Voyager II space mission. This way, we close the gap between the design-time and the run-time techniques provided in the SHADOWS platform for self-healing of concurrency, performance, and functional issues.1

I. INTRODUCTION

The SHADOWS project (Self-healing Approach to Designing Complex Software Systems) [19], [20], [21] aims at developing technologies that augment large software systems with a sort of immune response against various issues and contingencies that can occur at design-time or runtime. It targets general issues in the areas of performance, concurrency, and functional problems. Without self-healing protection, these would result in a costly, partial or complete breakdown of the system. By design, the SHADOWS techniques and methodology have wide applicability, reaching well beyond the scope of the case studies and application domains investigated in the project. In fact, the aim is to provide general techniques that augment a given or planned system independently from the system’s functionality.

Within SHADOWS, one of the central application domains brought in by the industrial partners and driving the development of the new techniques was avionics and space. They were contributed by our partners IAI - Israel Aerospace Industry, based in Haifa (IL) - and Artisys (based in Brno, CZ), a supplier to international constructors of airplanes and spacecrafts. Focussing on functional healing at design time, we developed a number of enabling techniques to functional self-healing. In particular, we introduced game based model checking of behavioral models in the GEAR tool [1], [15], [2] as a deep diagnosis tool for early realignment between behavioral models and requirements expressed as temporal properties.

We successfully applied this technique to investigate the recovery behavior of the ExoMars Rover2, as described in Kapellos [13], and we were able to modify and adapt the display and the illustration of the game and it playing in a way acceptable to engineers.

The weak point was however the lack of a link to an adequate, formal description of the Rover’s behavior. We derived our models and properties from the literature (textual descriptions and previous studies) [4], [13], while for a stringent demonstration of the techniques and for a validation of the underlying SHADOWS methodology it would have been advantageous to start from real models.

In this paper we show 1) how we are able to link the behavioral modelling style of our techniques with ASSL [23], a rich domain-specific language for the specification of autonomous systems, equipped with a formal semantics [23], and 2) how we can easily and systematically translate (parts of) the specification of the Voyager’s behavior into Service Logic Graphs (SLGs, introduced formally in Section III-A), thus enabling the application of the SHADOWS technologies to the large class of autonomous systems describable in ASSL. The advantage of SLGs over other models is that they are closer to the field engineer’s understanding, thus making advanced game-based diagnosis features accessible to non-experts in formal methods and models.

A. The ExoMars Rover Case Study

In the concrete mission example we examined in SHADOWS, the ESA ExoMars Rover is sent on a surface mission on Mars where it has to accomplish several tasks, including the acquisition of subsurface soil samples using a drill. As customary, the mission is organized in a hierarchical three-tier control model which accounts for partial autonomy of the Rover. Mission plans are designed and enforced by the ground control center, while finer-grained operational decisions, at the task level, are completely autonomous: the Rover has its own planning capabilities, which allows it to transform a task

2The ESA ExoMars Rover was studied in the FORMID Project (FOrmal Robotic Mission Inspection and Debugging), that aimed at creating a development environment for the verification and analysis of robotic missions [4].
assignment into a suitable executable sequence of actions in a context-dependent and error-aware way.

We showed in diverse publications about verification [1], [15], [2] how to take advantage of the interactive and exploratory benefits of game-based verification technologies. In the case of problems within highly reactive and concurrent systems – as in the context of autonomous aerospace missions – it is hard to automatically find recovery mechanisms to overcome these problems. Even for human system developers it is non-trivial to completely understand the nature of a problem if mismatches between the behavioral specification and the system implementation occur.

B. The NASA Voyager Mission Case Study

The NASA Voyager Mission started in 1977 and was designed for exploration of the outer planets of the Solar System. As the twin spacecraft Voyager I and Voyager II flew, they took pictures of planets and their satellites in 800x800 pixel resolution, then radiotransmitting them to Earth. Voyager II has two on-board television cameras - one for wide-angle images and one for narrow-angle images - that record images in black and white. Each camera is equipped with a set of colour filters, which help images to be reconstructed as fully-colored ones. Voyager II uses radar-like microwave frequencies to send the stream of pixels toward Earth. The signal suffers on this distance a 20 billion times attenuation [6].

In Vassev and Hinchey [24], the mission is specified as an autonomic system composed of the Voyager II spacecraft and four antennas on Earth, all specified as distinct autonomic elements. This paper bases on this specification and on those results on the behavior of the system.

In the rest of this paper, we briefly sketch ASSL (Sect. II) and then how to map the ASSL specification with our models (Sect. III), and illustrate it on the model for the NASA Voyager mission. We then discuss verification issues (Sect. IV) and how this model generation technique enables the use of SHADOWS self-healing techniques in a smooth fashion that combines design- and runtime (Sect. V). We then discuss some related work (Sect. VI), and finally conclude (Sect. VII).

II. ASSL

The Autonomic System Specification Language (ASSL) is a framework that provides a multi-tier structure for specifying and validating autonomic systems and targets the generation of an operational prototyping model for any valid ASSL specification [23]. ASSL provides a multi-tier specification model that tackles autonomic systems (ASs) as composed of autonomic elements (AEs) interacting over interaction protocols (ASIP and AEIP). We concentrate here on the behavioral aspects of the AS and AE description, since they are the part of ASSL that finds direct counterpart in the GEAR behavioral models.

- The AS tier - provides a general and global AS perspective. It defines the general system rules in terms of service-level objectives (SLO) and self-management policies, architecture topology, and global actions, events, and metrics applied in these rules. It is similar to the mission and task level of the ExoMars description.
- the AE tier - provides a unit-level perspective. It defines interacting sets of individual autonomic elements (AEs) with their own behavior. This tier is composed of AE rules (SLO and self-management policies), an AE interaction protocol (AEIP), AE actions, AE events, and AE metrics. It is similar to the Action level of the ExoMars description.

A. How the Voyager takes pictures

When a space picture must be taken and sent to Earth, the Voyager exhibits autonomous-specific behavior. The spacecraft must detect on the fly interesting objects and take their pictures. This reveals a sort of autonomic event-driven behavior that can be easily specified with ASSL at the three main tiers - AS (autonomic system) tier, ASIP (autonomic system specification protocol) tier, and AE (autonomic element) tier [23].

The Voyager II spacecraft and the antennas on Earth are specified at both AS and AE tiers as autonomic elements that follow their autonomic behavior encoded as a self-management policy called IMAGE_PROCESSING. ASSL specifies self-management policies with special ASSL constructs - fluents1 and mappings [23]. Whereas the former are special ASSL constructs used to denote specific system states, the latter simply map fluents to ASSL actions (actions to be performed when the system gets into a fluent).

B. AS Tier Specification.

The IMAGE_PROCESSING self-management policy is specified at the AS tier to process images from four antennas on Earth located in Australia, Japan, California, and Spain. In fact, we consider this specification as forming the autonomic image-processing behavior of the Voyager Mission base on Earth.

As shown in Figure 1, the policy is specified with four policy fluents - one per antenna. Fluents denote specific system states. They are initiated by events prompted when an image has been received and terminated by events prompted when the received image has been processed. Further, all the four fluents are mapped to an ASSL action: that is to be performed when the system enters in one of the fluents. Figure 2 shows the specification of the events that initiate and terminate the fluent presented by Figure 1. Note that the first event is prompted to occur in the system when a special message has been received. In addition, a processImage action (see [25] for this action’s specification) is specified to process images from all four antennas.

At the autonomic system interaction protocol (ASIP) tier, the image messages (one per antenna), a communication channel that is used to communicate these messages, and communication functions to send and receive these messages over that communication channel to the Earth are specified [25].

1ASSL adopts some AI-planning terminology: a fluent is comparable to a state variable in our transition system view.
FLUENT inProcessingImage_AntSpain {
    INITIATED_BY { EVENTS.imageAntSpainReceived }
    TERMINATED_BY { EVENTS.imageAntSpainProcessed }
}

MAPPING {
    CONDITIONS { inProcessingImage_AntSpain }
    DO_ACTIONS { ACTIONS.processImage("Antenna_Spain") } }

Fig. 1. An IMAGE_PROCESSING Fluent

EVENT imageAntSpainReceived {
    ACTIVATION { RECEIVED {
        ASIP.MESSAGES.msgImageAntSpain } }
}

EVENT imageAntSpainProcessed {
    }

Fig. 2. AS-tier Events

C. ASIP Tier Specification.

They concern the autonomic system interaction protocol (ASIP) [23], which is used by the four antennas when communicating with the Voyager Mission base on Earth. Here, at this tier we specified four image messages (one per antenna), a communication channel that is used to communicate these messages, and communication functions to send and receive these messages over that communication channel [25].

D. AE Tier Specification.

At this tier, we have five autonomic elements: the Voyager II spacecraft and the four antennas on Earth. For each, an own part of the IMAGE_PROCESSING self-management policy is specified.

a) AE Voyager.: The spacecraft’s IMAGE_PROCESSING self-management policy (see Figure 3) uses two fluents. The inTakingPicture fluent is initiated by a timeToTakePicture event and terminated by a pictureTaken event. This event also initiates the inProcessingPicturePixels fluent, which is terminated by the pictureProcessed event. The fluents are mapped to the actions takePicture and processPicture respectively. Metrics are used e.g. to count all the detected interesting objects which the Voyager AE takes pictures of.

b) AE Antenna.: Also the four antennas receiving signals from the Voyager II spacecraft are specified as autonomic elements. Their IMAGE_PROCESSING self-management policy uses pairs of fluents inStartingImageSession - inCollectingImagePixels, one for each colour filter. These sets of fluents determine the states of the antenna AEs when an image-receiving session is starting and when an antenna AE is collecting the image pixels.

Since the Voyager AE processes the images by applying different filters and sends each filtered image separately, we have distinct fluents for each colour and antenna. This allows an antenna AE to process a collection of multiple filtered images simultaneously.\(^4\) It is the Voyager AE that notifies an antenna that an image-sending session begins and ends. Figure 3 shows two of the IMAGE_PROCESSING fluents. They are further mapped to AE actions that collect the image pixels per filtered image (see [25]).

In Figure 3 we see how two of the events initiate the AE Antenna fluents. The greenImageSessionIsAboutToStart event is prompted (triggered) when the Voyager’s msgGreenSessionBeginSpn message has been sent and the imageSessionStartedBlue event is prompted when the Voyager’s

\(^4\)Note that according to the ASSL formal semantics, a fluent cannot be re-initiated while it is initiated, thus preventing the same fluent be initiated simultaneously twice or more times [23].
starting green image session

equips

{ act over a set of atomic propositions

iappping

act

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of the system as being the

s, s

the AS tier: Service-Level Objectives, Self-Management

gear

the AE tier: Service-Level Objectives, Self-Management

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→

→

is a set of transitions where

equips

i

is the set of possible branching conditions, to be
determined upon execution of the preceding SIB,

trans = (s, a, s) is a set of transitions where s, s ⊆ S

and a ∈ Act, and

a labelling interpretation function I : S → 2AP equips

SIB occurrences with atomic propositions.

The structural match, KTS and SLGs are both graph structures
with labeled branches and nodes that are enriched with atomic
propositional properties, suffices to adopt the established
model checking technologies for the SLGs.5

In mapping the elements of the ASSL specification to a
graphical representation in the behavioral model we focus on
those constructs that describe behavioral and self-* aspects:
these are the central elements which will be most frequently
used to specify autonomic systems. We currently cover


the AE tier: Service-Level Objectives, Self-Management Policies, Actions and Events, and additionally behavioral models and outcomes.

Architectural, communication, and quantitative aspects will be
dealt in future work.

B. Mapping ASSL Elements

From the point of view of model generation, AS and AE
specifications are structurally similar wrt. events, self mana-
gement policies, and actions, but differ in the scoping: while
the AS specification has a global scope, the AE specification
is only valid for the local element. Due to the similarities,
we focus in the description on the autonomic element (AE)
tier. The AS tier is captured similarly, by means of hierarchy
(where single nodes of the AS-level KTS are expandable to
AE-level models).

We refer to Figure 6, showing a specification fragment
for the Voyager (right) and the corresponding section of the
behavioral model (left). In the textual specification (right), we
have two events, one fluent with a mapping, and one action.
Dashed arrows illustrate a trace of an event within the specs.
Arrows indicate the correspondence between elements of the

In fact both system representation styles can easily be translated into each
other by adequately mapping edges to nodes and vice versa.

msg blue session begin spn message has been received by the antenna.

III. MAPPING ASSL TO GEAR MODELS

ASSL specifications describe all the different aspects of an
antonomic system in one comprehensive document. This is
practical, but by nature in realistic cases it becomes very complex,
the complexity to a good extent due to the many cross
references between the specification elements. A trace through
the specified autonomic system may request jumping between
different aspects (e.g. from messages \rightarrow events \rightarrow fl uents \rightarrow mappings \rightarrow actions) and “pages”. Another submission to this
workshop proposes mapping ASSL specifications to LTS, in
order to verify LTL properties [26] and with focus on concerns
of state space explosion. Here, we address a different mapping,
that privileges intuition of the graphical models, expression of
constraints in any mu-calculus derivative, and a deep support
to diagnosis by means of reverse model checking and games.
Our models are Service Logic Graphs (SLG).

A. Behavioral models: Service Logic Graphs

To complement the original textual view, and in perspective
to visualize and reify certain aspects of the SOS semantics of
ASSL, we map selected behavioral elements of the specification
to GEAR’s behavioral models. These can be visualized as
Service Logic Graphs (SLG) in the jABC framework [18], [22]
(of which GEAR is the model checking plugin) and analyzed,
guiding the user through the processes and workflows of the
specified autonomic system. These same models are directly
amenable to model checking.

SLGs themselves are composed of reusable building blocks
that are called Service Independent Building Blocks (SIBs) [10], [11], and may represent both a single atomic
service or a whole subgraph (i.e. another SLG). Thus SLGs
are hierarchical, which grants a high reusability not only
of the building blocks, but also of the models themselves,
within larger systems. SLGs formally stem from the concept
of Kripke Transition Systems [16].

Kripke Transition System: A Kripke Transition System
K is defined as a tuple (S, Act, \rightarrow, I) over a set of atomic
propositions AP, disjoint from Act, where

S are the states of the model,

Act is a set of actions,

\rightarrow\subseteq S\times Act\times S are the possible transitions in the model,

and

- a labelling interpretation function I : S \rightarrow 2AP equips

states with atomic propositions.

A KTS is best-suited for verification tasks that focus on
transitions of the system as being the edges. On the contrary,
one can think of an SLG as being the engineer’s view on the
system that focuses on the actions of the system as being the

nodes.

Service Logic Graph: A Service Logic Graph (SLG)
is defined as a tuple (S, Act, \rightarrow, I) over a set of atomic
propositions AP, disjoint from Act, where

- S represents the occurrences of the Service Independent

building blocks (SIBs), which are the actions or functions
in the graph

- Act is the set of possible branching conditions, to be
determined upon execution of the preceding SIB,

- Trans = (s, a, s) is a set of transitions where s, s \in S

and a \in Act, and

- a labelling interpretation function I : S \rightarrow 2AP equips

SIB occurrences with atomic propositions.
EVENT greenImageSessionIsAboutToStart {
  ACTIVATION { SENT { AES.Voyager.AEIP.MESSAGES.msgGreenSessionBeginAus } }
}
EVENT imageSessionStartedBlue {
  ACTIVATION { RECEIVED { AES.Voyager.AEIP.MESSAGES.msgBlueSessionBeginAus } }
}

ASSL-specification and of the behavioral. The InTakingPicture cloud defines the current state of the system (an atomic proposition).

AE Event. Event is the central language element in ASSL. It specifies fluents, actions, and policies globally in the AS tier and locally in the AE tier. Events could be activated by messages, other events, actions or metrics. In our behavioral model, events are mapped to homonymous Branches. In Figure 6, the behavioral model starts with the event timeToTakePicture, activated for interesting objects or after a time period of 60 s. It initiates the self management policy (fluent) inTakingPicture.

AE Self Management Policy. It defines the behavior of the autonomic system by connecting specific system states with the intended (re)action. A policy consists of two elements:

- A fluent, similar to a state. It is initiated (ie., that state is reached) when the system satisfies specific conditions. It will be terminated (left) if specific events occur. Fluent activation and termination is driven by events.
- A mapping of certain conditions to actions. The conditions test fluents: in a certain state, certain actions (in the AS or AE tier) are performed. Actions activate specified actions.

They are central to the model extraction: the information contained in a self management policy is used and useful both for model construction and for verification.

Together, fluent and mappings define the control flow, i.e. create branches with the name of the initiating event. They define all possible incoming branches of an action. The specific condition that activates the fluent is stored in the context of the system’s model. The context represents the current global state of the system, like a global Blackboard or shared memory-mechanism. For model checking purposes, the fluent is additionally associated as atomic proposition to the corresponding node(s) of the behavioral model. This enables global model checking. The fluent can be used as preconditions of actions. They hold on all states in the region between initiation and termination.

The fluent in our example is activated by the timeToTakePicture.
ture-event and the overall status of the autonomous system is changed to intakingPicture. This change activates an action: takePicture which is specified in the Mapping section of the self management object.

The self management policy which connects the event to actions is additionally used to annotate the nodes in the behavioral model with atomic propositions (AP). The name of the AP is equal to the name of the fluent. They can later be used for model checking.

**AE Action.** Actions are routines performed by AE or AS (global and local). In our behavioral model, they are the second essential element: the nodes of our behavioral model, named as the action. The different elements of an action are used to describe the nodes and for verification purposes. Action parameters become parameters of a node, the does part represents the body of a node. It can be a single action (then the node is an atomic node), but for complex does it is an entire behavioral model. We then model them as a SLG hierarchy, as in Figure 6: the node takePicture has a corresponding sub-model, presented on the left. The guards, returns and outcomes are used for verification. We offer two possibilities for verification:

- The Localchecker uses the Guard to verify if an Action could be executed within the current system state (defined by the fluents and stored in a global context).
- We can use a model checker to verify relations of nodes and actions expressed as temporal logic constraints. GEAR uses internally the modal mu-calculus [14] enriched with forward and backward modalities, so it is best equipped e.g to express dataflow properties, or other behavioral constraints like e.g. CTL formulas.

The specified action in Figure 6 contains a guard which must conform to the AP annotated at the node.

How to define the outgoing branches of a node depends on the information found in the action’s specification: Actions can use events; triggers are communication functions to communicate with the autonomic system and its elements. We thus have several possibilities to detect outgoing branches.

- a trigger statement in the specification of an action will create an event which introduces the next fluent and/or action, and is comparable to an outgoing branch.
- event statements in the Does part are added as possible outgoing branches.
- if communication functions are used, we follow the chain from the function to the communication channel to the events which will be activated by a specific message in the channel. It is not unusual that more than one event will be created from one message.

The takePicture action of Figure 6 is closed by a new event pictureTaken. This is specified in the triggers section and represents the outgoing branch of this node. The new event will again initiate a fluent, and it terminates the inTakingPicture fluent. Therefore, the next action has another AP.

**AE Outcomes, AE Behavioral Models, and AE Recovery Protocol.** These elements are not yet treated in depth. They will become relevant when applying the SHADOWS methodology. In short, AE Outcomes are post-conditions of actions or behavioral models - they are useful for verification purposes.

An **AE Behavioral Model** is comparable, from the model generation point of view, to a further mapping in the self management policy. It consists of conditions, a do element where an action is activated, and outcomes. We can model the behavioral model similarly to an action (atomic or hierarchical). Condition and outcomes become the pre- and post-condition and the action is the implemented behavior.

An **AE Recovery Protocol** should guarantee fault-tolerant operation of the autonomous system (e.g. create snapshots, log messages, consistency checking). A recovery protocol specification is rather complex, and it is specified in a separate submodel.

IV. VERIFYING THE VOYAGER’S BEHAVIORAL MODEL

Figure 7 contains the behavioral model of the Voyager II spacecraft. Note that the error handling graph at the right was not part of the original ASSL specification.

A simple verification issue that immediately emerges is whether the system takes care of an error-handling process whenever picture pixels are transmitted. This can be easily expressed in CTL [7] as

\[
\text{AG(inProcessingPicturePixels} \Rightarrow \text{EF(errorHandling)})
\]

This formula can be interpreted as follows:

Wherever the system evolves to (the AG-part), whenever picture pixels are about to be processed (the atomic proposition inProcessingPicturePixels) it follows that the system has an option to evolve into an error-handling process (the EF(errorHandling)-part).

Since the original model of Figure 7 does not support any kind of self-healing capabilities, this property does not hold.

Therefore, in a first attempt to reconcile model and property, we added an error-handling routine directly in the model. We slightly changed the design manually, by refining the sendImgPixelMsg action, originally atomic, to an entire routine. Now, if problems during the transmission process occur, the system tries to resend those picture pixels that were not transmitted correctly. If the problem still exists afterwards, the system is halted and needs manual interaction from ground control.

A game-based approach as presented in Bakera et al. [15] would do much more than just allowing the identification of the missing recovery mechanism in the original specification. Enabling this investigation for self-healing and self-healing enactment is our aim. A domain-dependent guidance also enables to pinpoint that part of the model which is best-suited for integration of recovery mechanisms. Due to space limitation, we cannot discuss this process in detail in this contribution.
A. Enabling Model Based Self-healing

Within SHADOWS, we adopt a model-based approach, where models of desired software behavior direct the self-healing process. This allows for life cycle support of self-healing applicable to industrial systems. We contribute to SHADOWS a number of enabling technologies for model-driven self-healing residing in the functional part of the architecture. Our technologies deal with self-healing issues at design-time for ensuring functional correctness, i.e. correctness with respect to the system’s behavior over time. For this, we apply among others a game-based model-checking approach as a powerful technique for the verification, diagnosis and adaptation according to desirable temporal properties that the system’s behavior must exhibit.

In particular, we show how to model the several abstraction levels of the system’s behavior in a uniform and formal but intuitive way. This happens in term of processes in the jABC framework [22], a mature, model-driven, service-oriented process definition platform. Subsequently, we leverage the formality of these models to prove properties by model checking. In particular we exploit the interactive character of game-based model checking to show how to discover an error, then localize, diagnose, and correct it. Design-time healing technologies that naturally emerge when dealing with self-adaptive systems, as in the context of the SHADOWS project, demand for a deeper insight of design-time faults to effectively identify and overcome them.

The use of models rather than code is already a significant step towards the understandability of the actual behavior’s descriptions to non programmers, like the engineers, in charge of designing a space module. This enables e.g. early discovery of misbehaviors, hazards, and ambiguities via design-time analysis. We strive to improve the diagnostic features making them as detailed as necessary yet as intuitive as possible.

For this purpose we use GEAR [15], a model checker capable of the full modal $\mu$-calculus temporal logic with a rich user interface that allows for pinpointing problems in system design. This is achieved by interactively exploring the problem space in a game-based way. The game-based nature of GEAR’s verification algorithm supports the system designer at design-time to interactively explore the problem space upon property mismatches.

In case of the Voyager mission case study such properties can be used to check for complete picture transmission to the four antennas in case of transmission interrupts. Further the verification process is able to assure the application of all four color filters before picture transmission. In addition it is essential for the picture transmission to send closing notification signals of transmission endings to the antennas. This as well can be assured by the aforementioned Model Checking techniques.

If problems occur in the verification task one immediate result of the game-based algorithm of the Model Checker is an interactive counter-example. This counter-example both pinpoints the problem of the property mismatch and provides a strategy encoded into the counter-example to adapt and self-heal the system. GEAR [15] elaborates on the application of this technique on an ESA mission example.
V. CONNECTING THE SHADOWS DESIGN-TIME AND RUN-TIME TECHNIQUES

In SHADOWS we have developed a rich set of self-healing techniques that span concurrency, performance, and functional issues. Table I summarizes the main technologies and related tools that were developed and used in SHADOWS to cope with issues that appear in designing autonomous systems like those from aerospace contexts. These technologies are suitable to handle several kinds of issues on different kinds of abstraction levels. A detailed description of the organization of the SHADOWS self-healing platform and of the underlying methodology is provided in [12].

As shown in Table I, these techniques, however, strike at runtime. They are currently driven or triggered by annotations in the applications, which are for the moment produced mostly manually and inserted in the application’s source code. In order to develop the full benefits of the SHADOWS platform, it would be necessary to link the runtime power of the healers to annotations placed automatically in the design time artifacts, typically models.

In fact, the behavioural model extraction we just described is in our opinion the right bridge between

- the high-level specification provided in a domain specific language like ASSL,
- behavioural models that capture the functionality and that spot the possible critical locations in the behaviour, and
- the annotations that are necessary in order to include the issue monitoring mechanism.

As shown in Figure 8(left), the SHADOWS architecture is organized in this fashion. It foresees the use of models to link the design-time and the run-time aspects of the healing platform, and it provides (annotation-driven) issue monitoring as the mechanism that implements this link. As shown on the right on a fragment of the Voyager model derived from the ASSL specifications, the SLGs are adequate models for this abstraction because they present a suitable granularity: they are coarse enough to be still abstract, and fine enough to support spotting where to place which kind of annotation. We see that concurrency monitoring is well placed at fork/join locations, where multiple threading happens, functional monitoring (e.g. for runtime extension and adaptation) is suitably introduced where complex functions are foreseen, and performance monitoring is useful at locations that may be subject to timeouts, as here the conclusion of receiving an image.

Once the annotations are properly inserted, the model-to-code generation provided by Genesys can transfer/link the annotations to the SHADOWS runtime. How these runtime techniques are organized and how they jointly work in practice is summarized in [12].

In Table II we show the mapping of the specialized tools used in SHADOWS with the ASSL tiers. The AS and AE tiers


<table>
<thead>
<tr>
<th>Tool</th>
<th>ASSL (Sub-) Tier</th>
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<tbody>
<tr>
<td>GEAR</td>
<td>AS/AE Service Level Objectives, AE Behavioral Models (high-level)</td>
</tr>
<tr>
<td>Java Pathfinder</td>
<td>AS/AE Service Level Objectives, AE Behavioral Models (code-level)</td>
</tr>
<tr>
<td>BCT</td>
<td>AE Behavioral Models (runtime in test and field), AE Metrics, AE Actions, AE:Events</td>
</tr>
<tr>
<td>ConTest</td>
<td>AE Friends, AE Behavioral Models (runtime in test)</td>
</tr>
<tr>
<td>Panacea</td>
<td>AE Self Management, AE Metrics, AE Outcomes</td>
</tr>
<tr>
<td>TPTP</td>
<td>AS/AE Metrics, AE Outcomes</td>
</tr>
</tbody>
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**TABLE II**
TOOLS FOR AUTONOMOUS SELF-HEALING AND THEIR RELATED ASSL TIERS.

are linked in many ways and under several specific aspects to the SHADOWS platform.

VI. RELATED WORK

Nowadays, there is a growing consensus that model checking is most effective as an intelligent and early error-finding technique rather than a technique for guaranteeing correctness. This is partly due to the fact that specifications that can be checked automatically through model checking are necessarily partial in that they specify only certain aspects of the system behavior. Therefore, successful model checking runs, while reassuring, cannot guarantee full correctness. Rather, model checkers are increasingly conceived as elaborate debugging tools that complement traditional testing techniques.

Various model checkers are used to verify aerospace systems. Java Pathfinder [8] developed at NASA Ames is a prominent representative for verifying smaller systems. It assists developers at the Java code level, and therefore addresses a later phase than to our approach. We aim at assertions on interactions between components or of the system as a whole, with a focus on demanding properties.

For model checkers to be useful as debugging tools it is important that failing model checking attempts are accompanied by appropriate error diagnosis information that explains why the model check has failed. Model checkers may in fact also fail spuriously, i.e., although the property does not hold for the investigated abstraction it may still be valid for the real system. In order for model checking to be useful, it should therefore be easy for the user to rule out spurious failures and to locate the errors in the system based on the provided error diagnosis information. Therefore, it is important that error diagnosis information is easily accessible by the user.

Currently, ASSL provides a consistency checking mechanism to validate specifications of autonomic systems against correctness properties. Although proven to be efficient with handling consistency errors, this mechanism cannot handle logical errors. Another submission to this workshop [26] proposes a different model checking approach for ASSL, based on Labelled Transition systems and LTL properties.

For linear-time logics, error diagnosis information is conceptually of a simple type: It is given by a (possibly cyclic) execution path of the system that violates the given property. Thus, in case model-checking fails, linear-time model checkers like SPIN [9] compute an output in form of an error trace that represents a violating run, and is therefore valuable for the subsequent diagnosis and repair. The situation is more complex for properties that embody recovery issues. These claim for more demanding properties expressible in branching-time logics like CTL or the modal μ-calculus. Such logics do not just specify properties of single program executions but properties of the entire execution tree, comprising the local of decision points. Hence, meaningful error diagnosis information for branching-time logic model checking cannot be represented by linear executions in general. This is where games help.

ESA’s FORMID Project (FOrmal Robotic Mission Inspection and Debugging) aimed at creating a development environment for the verification and analysis of robotic missions [4]. Unfortunately the system is solely concerned with predefined property patterns for safety, liveness, and conflict-freedom of the system. Therefore it is unable to handle more demanding properties as they typically arise during system modelling of complex systems that deal with self-healing and recovery issues.

VII. SUMMARY AND CONCLUSION

In this paper we have shown how to translate parts of an ASSL specification for autonomic systems into a behavioral model. This task implied to map the ASSL specific self-management policy, action, and event parts that made up the investigated abstraction it may still be valid for the real system. In order for model checking to be useful, it should therefore be easy for the user to rule out spurious failures and to locate the errors in the system based on the provided error diagnosis information. Therefore, it is important that error diagnosis information is easily accessible by the user.

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in [23] and possibly take it as a starting point for an SOS-driven generation of the SLGs. This way, the palette of model analyses developed in the jABC and the self-healing specific techniques developed in SHADOWS would become immediately applicable to all ASSL descriptions.

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REFERENCES