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Modelling Feedback Control Loops for Self-Adaptive Systems

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Abstract: *Feedback Control Loops* (FCLs) are the heart of any self-adaptive system. Existing engineering approaches for building self-adaptive systems mask FCL by providing abstraction layers that hide the application complexity. In this paper, we investigate a model-driven approach for the engineering of FCLs whose architecture is based on the *Service Component Architecture* (SCA) model. Our proposal consists in exploiting the data streaming model, to specify the characteristics of the control policies, and to generate FCLs of self-adaptive systems deployed in large-scale environment. We argue that the use of a data-oriented model for designing self-adaptive systems significantly increases FCL visibility.

Keywords: Modelling, Feedback Control Loop, Self-Adaptation

1 Introduction

This last decade, there has been an increasing demand for self-managing systems, achieving desired quality requirements with a reasonable cost. Self-adaptive systems (or autonomic systems) are self-managing system that use *Feedback Control Loops* (FCLs) to *monitor*, *analyse*, *plan*, and *act* according to changes occurring in their environment. Existing engineering techniques for building self-adaptive systems hide software complexity behind abstraction layers. However, these layers do not provide support for handling control elements (sensors, actuators, etc.) of the system explicitly. This situation results in fastidious, opaque (there is no explicit view of different politics implemented by the FCL), and not scalable FCLs [BSC$^+$09]. In this paper, we introduce a model-driven approach for generating distributed FCLs. In particular, this approach exploits the data streaming model [BBD$^+$02] to specify the flow and the deployment of the components implementing FCLs. The originality of the proposed approach lies in the use of annotations within models, which are seamlessly processed as specific runtime artefacts. We illustrate the key elements of our approach on a case study, focusing on real-time tracking of a large fleet of trucks. The rest of this paper is organized as follows. After introducing some backgrounds on FCL, we next present an example of a large-scale self-adaptive system, dedicated to the real-time tracking of a fleet of trucks (cf. section 2). Then, we introduce our design approach and the associated distributed infrastructure (cf. section 3). After that, we compare our approach with some state-of-the-art related works (cf. section 4). Finally, we conclude and discuss the perspectives of this work (cf. section 5).

2 Background & Scenario

This section presents some background on autonomic FCL and a motivation scenario, that we use later to illustrate our modelisation approach for FCLs in a self-adaptive systems.

2.1 MAPE-K Loop

The reference standard from the IBM *Autonomic Computing Initiative*, codifies an external, FCL approach in its *Monitor-Analyze-Plan-Execute* (MAPE) Model [IBM06].

The *Monitor* part provides the mechanisms that collect, aggregate, filter and report information (such as metrics and topologies) collected from managed resources. The *Analyze* part contains the mechanisms that correlate and model complex *adaptation situations*. The *Plan* function encloses the mechanisms that construct the actions needed to achieve goals and objectives. The planning mechanism uses *adaptation policies* information to guide its work. The *Execute* function groups the mechanisms that control the execution of an *adaptation plan* with considerations for dynamic updates. In the MAPE-K loop model as shown in Figure 1, *Knowledge* (symptoms, policies) is the relevant data shared amongst the *Monitor*, *Analyze*, *Plan* and *Execute* activities of the *Autonomic Manager*. The run-time knowledge must be complete—*i.e.*, including the whole aspects influencing adaptation decisions—, modifiable—*i.e*, following the application changes—, and at a high-level of abstraction—*i.e*, comprising only relevant information.

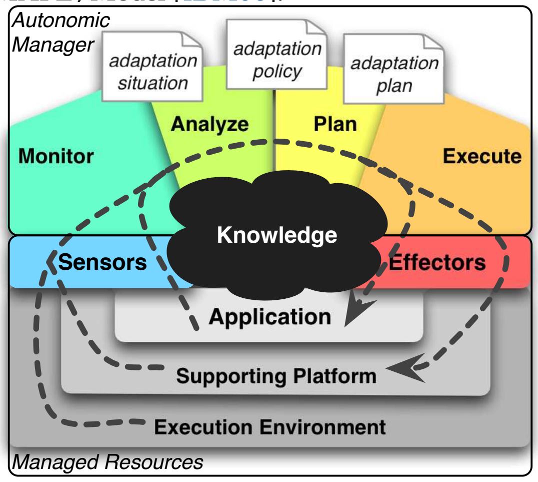

Figure 1: Overview of the autonomic MAPE model

2.2 Motivating Scenario

We consider a self-adaptive application for the management of the truck fleet (80,000 to 1,000,000 trucks) of a company specialized in the transportation of fragile products. The trucks do not have the same characteristics: some are equipped with good a air conditioning system, while others provide a robust slip system. In the same way, transported goods do not have the same requirements: some are very sensitive to temperature variations, while others need high security systems. The overall objective of the application is to make sure the trucks reach their destination on time. The application must be able to detect stop times, temperature variation inside containers, security violation and truck position. The application is also connected to remote services, like the weather service or the city traffic service. The self-adaptive application must also notify the destination platform about truck arrivals. All the aforementioned information is sent to the central control center, which processes and decides which adaptation process can be triggered. From the analysis of the data exchanged between the nodes (hosts) of the application, several adaptations can result, such as the frequency of the positioning requests or the number of resources (server node) allocated to process data.

3 Feedback Control Loops Engineering

This section introduces the design and runtime architecture of FCL for the scenario presented in Section 2 using our approach.

3.1 Feedback Control Loop Metamodel

One way to provide visibility for FCL in an application, is to find a way of specifying required control features. To meet this goal, we present here a meta-model to express control properties in the application. The presented metamodel allows to express control elements concepts like *sensors*, *processors*, *or actors* which correspond to architectural elements aiming to *sense*, *process*, or *act* on the system respectively. The metamodel characterizes also the process flow between the elements of the system, by offering concepts to express non-functional properties such as stabilization or security. All these concepts can be used at design time by the application architect in order to specify control elements of the system, using annotation artefacts. The following section shows an example of how this metamodel can be used, by presenting a variant of the data processing model for the scenario presented above.

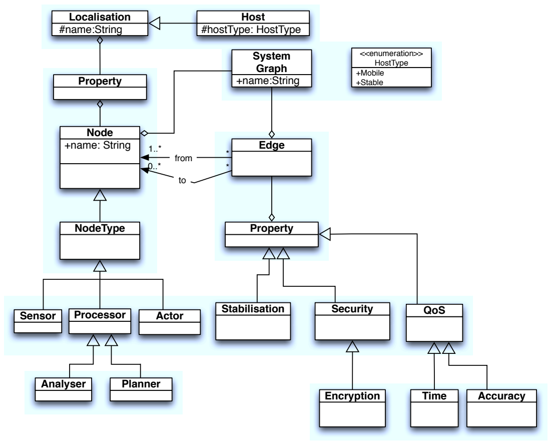

Figure 2: Feedback Control Loop Metamodel

3.2 Data-oriented Modelling of Feedback Control Loops

Our model is inspired by the context policy specification of the COSMOS context processing framework [RCS08]. Concretely, the data processing model that we defined is a connected graph where the nodes reflect processed data, and the edges identify data dependencies. Nodes on the left side of Figure 3 are raw data sensors, while the right-side nodes describe decision actuators. Nodes located in the middle are called processor (analyzer, planner) nodes. The data therefore flows through the nodes, where it is incrementally transformed into information of an higher level of abstraction.

Figure 3 shows the specification of the real-time truck tracking infrastructure, that we introduced in Section 2. The shaded nodes of the graph identify data sensors and effectors of the infrastructure, whose location is statically assigned. For example, the *Truck Position* node is shaded to specify that the associated sensor is necessarily deployed in the truck. White nodes represent data processors, whose host is not explicitly identified and can therefore be deployed in any part of the infrastructure.

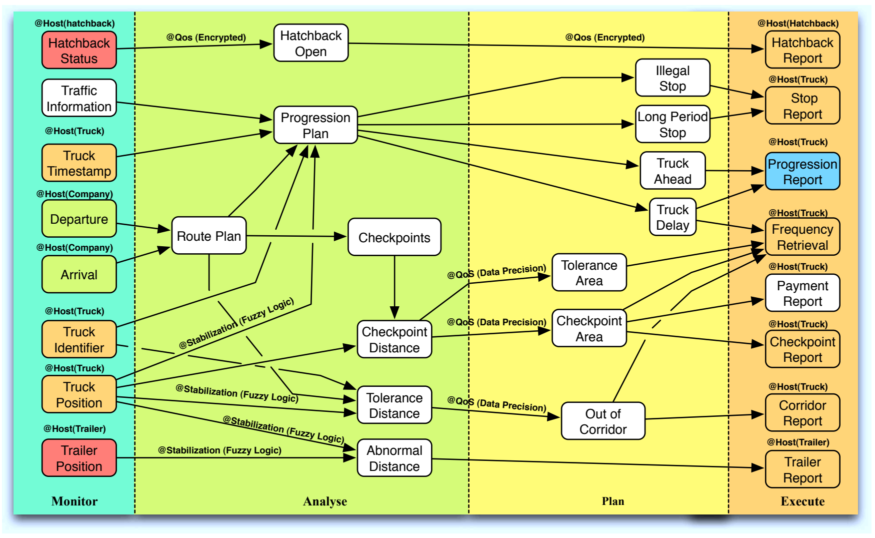

Figure 3: Data Processing Model of the Feedback Control Loop.

Then, the deployment infrastructure shown in Figure 4, specifies how the infrastructure is deployed as a network of physical or virtual devices, which can eventually host the data processors. The connections between the devices describe the available communication links.

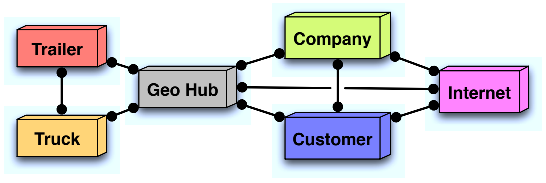

Figure 4: Physical Infrastructure Deployment Model.

3.3 Deployment and Execution of Feedback Control Loops

This section describes the runtime part of our approach, which exploits the data-oriented specification of the FCL, to generate a component-based infrastructure that implements it. In particular, during the feedback loop generation process, we convert the previously introduced models into software components, by combining the data processing and the deployment infrastructure models. We can assign the unshaded data processors to the devices of the infrastructure. For each unallocated data processor, the algorithm computes the list of devices which are 0 or 1-hop away from the data dependencies. Then, the most relevant device selected for hosting the data processor is the one that minimizes the memory consumption and the communication cost. Figure 5 depicts a candidate architecture obtained when applying this algorithm.

The resulting architecture is mapped to the *Service Component Architecture* (SCA) [SCA] standard by applying the following rules: *i)* the nodes of the connected graph are mapped into *primitive components*, *ii)* local data dependencies are converted into *component wires*, while remote data dependencies are exposed through *bindings*, and finally *iii)* nodes that are located on the same device are grouped within *composite components*.

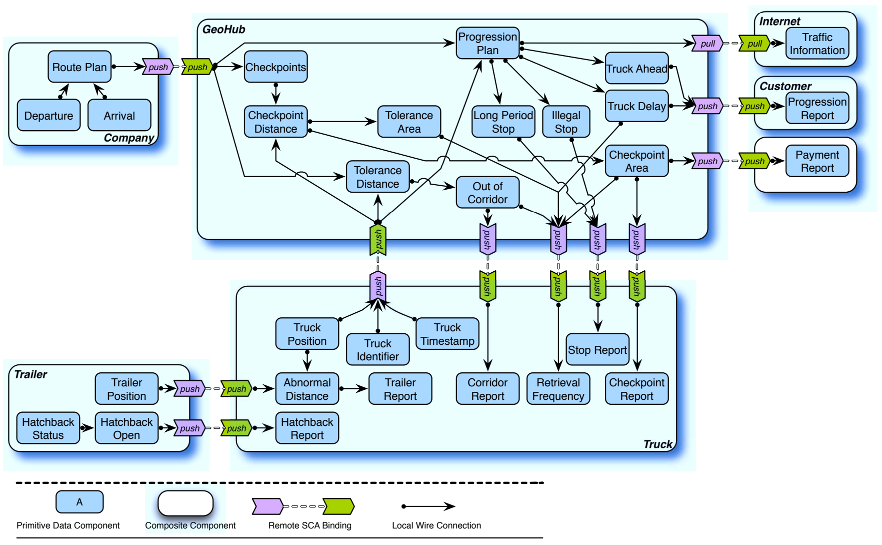

Figure 5: Component-based Architecture of the Feedback Control Loop.

4 Related Work

The RAINBOW [GCH+04], ENTROPY [HLM+09], and CAPPUCINO [RRS+09] frameworks provide components that fulfill the *MAPE Loop* (cf. section 2.1) phases to support self-adaptation. Nonetheless, these frameworks propose a static or closed infrastructure for managing the adaptation policies. Besides that, in terms of autonomic software system, literature abounds of many resources, such as *KX* (Kinesthetics eXtreme) [KPGV03], *Astrolabe* [BRV03], or *Unity* [CSWW04]. However, as in the case of autonomic frameworks, the lack of transparency in the design and the management of the FCL systems is one of the major limitations to the scalability of such systems. To solve the problem of the opacity and the non-scalability of existing FCL, some recent research works suggest that, "*the feedback loops that control self adaptation must become first-class entities*." [BSC+09]. The approach we propose in this paper stands in that perspective. The idea is to generalize the autonomic MAPE model and to extend the CAPPUCINO framework to address very-large-scale environments. In particular, we propose to reify the MAPE model as a very-large-scale data processing infrastructure, which converts data collected in the environment into real-time reactions. The data processing distribution is driven by the specification of data dependencies [RCS08] in order to maximize the performances of the system and balance the processing load among the nodes available in the environment.

5 Conclusion

We have outlined in this paper an approach for the engineering of FCLs drawing on the data flow model. We argue that, the data flow model comes with additional information that can be crucial for FCL engineering earlier at design time, to understand ongoing control mechanisms, and later at runtime for an efficient adaptation of the system. We used the *truck tracking* scenario, to explain how to specify a data-oriented model of a FCL, and how to generate the underlying execution platform with the SCA standard. As futur works, we are planning to evaluate the overhead introduced by our approach in a realistic deployment.

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