ALGORITHMS AND TECHNIQUES FOR MANAGING EXTENSIBILITY IN CYBER-PHYSICAL SYSTEMS

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To my beloved late grandparents,
Jitendra Lal Maskey, Hiranneshwor Man Pradhan, and Badan Pradhan

and

To my beloved grandmother, Sushila Maskey

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CHAPTER I

INTRODUCTION

I.1 History, Evolution and Emerging Trends in Distributed Computing

Over the past decades, distributed computing paradigm has evolved from smaller and mostly homogeneous clusters to the current notion of ubiquitous computing, which consists of dynamic and heterogeneous resources in large scale; an outline of this evolution is presented in Figure 1. Although the history of distributed computing can be traced back to the late 1960s and the early 1970s when ARPANET and ARPANET e-mail were invented, it was only during the 1990s when early distributed systems came into prominence with the introduction of client/server architecture. However, these early distributed systems were small scale homogeneous clusters.

Starting the mid 2000s, distributed computing paradigm shifted towards utility computing. This transition was instigated by the introduction of grid computing [37], which is a form of utility computing that provides scalability to achieve different kinds of high performance computing. The main goal of grid computing was to enable coordinated resource sharing between multi-institutional organizations resulting in distributed ownership of heterogenous resources. Towards the late 2000s, cloud computing [10] was introduced as a different form of utility computing. Cloud computing is used to provide software, platform, and infrastructure services to consumers without them having to worry about infrastructure or maintenance cost. As such, unlike grid computing, scaling in cloud computing is geared towards achieving high scalability computing that facilitates dynamic service elasticity.

Ubiquitous computing [59] represents the present and future of distributed computing paradigm. It refers to a paradigm where computing resources are made available everywhere and anywhere. Although the term *ubiquitous computing* was coined by Mark Weiser in 1991 [109], realization of these systems happened recently due to wider adaption and

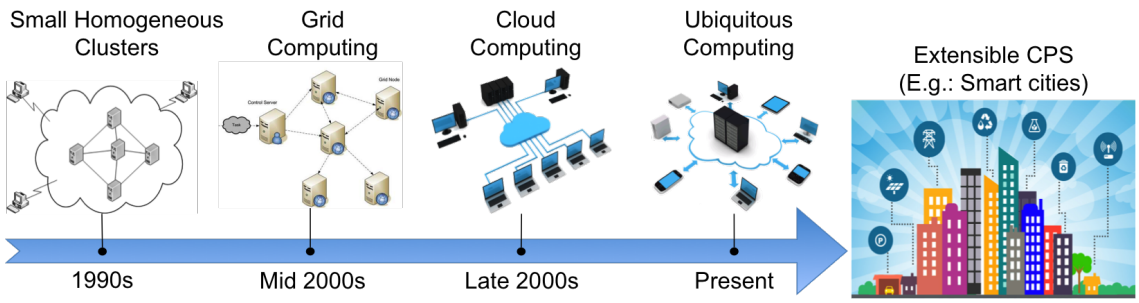


Figure 1: Evolution of Distributed Computing Paradigm.

availability of wireless networking technologies and edge computing devices such as single board computers, smart phones and tablets. Applications of ubiquitous computing has evolved from mobile computing [36], which focuses on mobile devices connecting users to networks (including the Internet) via wireless networking technologies, to the Internet of Things (IoT) [13], which consists of "things" (devices) connected via the Internet.

Recent advancement of edge computing devices has resulted in sophisticated and resourceful devices that are equipped with variety of sensors and actuators (for example, Intel Edison module mounted on Arduino board[1] compatible with various sensors available as part of the Grove Starter Kit[2]). These devices can be used to connect physical world with the cyber world [17, 25]. As such, the future of ubiquitous computing is cyber-physical in nature, and therefore, Cyber-Physical Systems (CPS) will play a crucial role in the future of ubiquitous computing. CPS are engineered systems that integrate cyber and physical components, where cyber components include computation and communication resources and physical components represent physical systems [56, 91]. CPS can be considered a special type of ubiquitous system that combines control theory, communications, and real-time computing with embedded applications that interact with the physical world [68]. As shown in Figure 2, CPS can be considered feedback control loops in which the controllers are cyber components that, based on desired behavior, use actuators to make changes to the physical systems and sensors to monitor/observe those systems.

[1] https://www.arduino.cc/en/ArduinoCertified/IntelEdison
[2] http://wiki.seeedstudio.com/wiki/Grove_-_Starter_Kit_v3

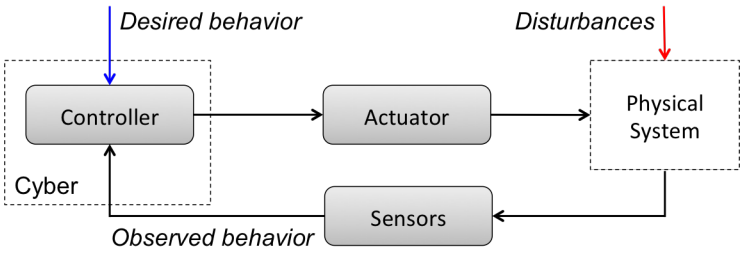


Figure 2: CPS Feedback Control Loop.

As shown in Figure 1, smart cities [31, 104] are a great exemplar of the future of ubiquitous computing. A smart city will comprise heterogeneous resources for domains varying from transportation, emergency response, power grid, etc. Furthermore, resources for each domain can vary from resource-constrained edge devices (such as Road Side Units (RSU), smoke detecting sensors, wireless cameras) that are cyber-physical devices equipped with sensors and/or actuators to resourceful private and public cloud instances. However, in order to realize this future of ubiquitous computing comprising CPS, we need to investigate and understand limitations of traditional CPS that were not meant for large-scale dynamic environment comprising resources with distributed ownership and requirement to support continuous evolution. Hence, the goal is to transition from traditional CPS to the next-generation CPS [48] that supports extensibility by allowing us to view CPS as a collection of heterogeneous subsystems with distributed ownership and capability to dynamically and continuously evolve throughout their lifetime, as well as, support continuous operation.

I.2 Extensible CPS

Now that we have established the relevance and need of extensibility in CPS, we need to clearly describe (1) what extensible systems are, (2) how have they evolved, (3) what it means for a CPS to be extensible and how extensible CPS differ from traditional CPS, and (4) what are the challenges for realizing extensible CPS, that is, how can we transition from traditional CPS to this notion of next-generation, extensible CPS.

I.2.1 Extensible Systems

Extensibility of a system is its ability to support dynamic and continuous evolution by allowing addition of new entities or modification of existing entities. Removal of existing entities, whether or not it is part of a modification process, can also be considered an aspect of extensible system. In general, a system can evolve across three different planes of extensibility – (1) hardware resources comprising the system, (2) functionalities/services provided by different applications hosted on the system, or (3) languages, frameworks, middleware supported by the system. In addition to supporting evolution, extensible systems also require continuous operation and integration with legacy systems [76].

Extensibility property allows a system to be more than a point solution by allowing the system to dynamically evolve throughout its lifetime. As a result, same system can evolve to provide solutions for different problems. However, not all changes that a system undergoes are pre-meditated, which is why the state of a system after it undergoes any change cannot be guaranteed. Therefore, a key requirement of extensible systems is to be able to guarantee minimal impact on existing system when it undergoes any change; any failure or anomaly should be appropriately handled to preserve system state. In short, it is of utmost importance to ensure any extension does not affect what already exists.

A system's extensibility is not the same as its scalability or elasticity. Scalability relates to a systems' ability to grow or shrink in order to meet varying load; a scalable system is elastic if it can dynamically fit the resources needed to cope with varying load. A scalable system can add or remove hardware resources and/or functionalities. However, an important point to note here is that the increase or decrease in functionalities refers to addition or removal of different instances of existing functionalities; it does not mean addition of new functionalities. As such, a system that is scalable or elastic cannot evolve, and therefore cannot be considered extensible. However, all extensible systems should be able to scale gracefully, while some extensible systems might support elasticity.

Similarly, extensibility also differs from reconfigurability. Saying that a system is reconfigurable means that the system can adapt itself by moving from one configuration to another while preserving all of its existing functionalities, it does not mean that the system can evolve. Optimization, load balancing and fault tolerance are some of the common scenarios where reconfiguration is used.

I.2.2 Evolution of Extensible Systems

To understand the need for extensibility in CPS, it is important to reflect on how extensible systems have evolved. Survey of existing literature suggests that system extensibility has evolved in tandem with evolution of distributed computing paradigm presented earlier in Section I.1. Around mid 90s, initial work on extensible distributed systems were presented in [76, 98]. In [76], authors present the *Information Bus* as extensible distributed system architecture that allowed self-describing objects, dynamically defined types, and anonymous communication with dynamic discovery. The concept of adapters was used to support integration of legacy systems. In [98], authors present the ADAPTIVE Service eXecutive (ASX) framework as an object-oriented framework that provides basic components to construct distributed applications while remaining agnostic to the underlying system. Furthermore, ASX facilitates dynamic update and extension of applications.

In the case of grid computing, heterogeneous resources are managed by grid Resource Management Systems (RMS) and extensibility is supported via resource models that determine how applications and RMS describe resources. In general, these resource models are schema based, or object model based [49]. Schema based extensible resource model allows addition of new schema types that describes the new resource. Object model based extensible resource model facilitates extensibility via extension of object model definitions.

In the case of cloud computing, extensibility is managed differently depending on whether resources are managed by a single Cloud Service Provider (CSP) or multiple CSPs. For single Cloud Service Provider (CSP), extensibility is fairly straightforward in all layers

(infrastructure, platform, software) of services. However, extensibility across multiple CSP is much more complex and requires mechanisms to facilitate interoperability; cloud federation [84] is one approach to solving this issue. In general, cloud federation approaches can be classified into *provider-centric approach*, which requires some form of cloud computing standard [1], and *client-centric approach* [102].

In the case of ubiquitous computing applications, like mobile computing, IoT, and IIoT, facilitating extensibility is challenging because of two primary reasons: (1) possibility of mobile/dynamic hardware resources, and (2) high degree of hardware and software heterogeneity resulting in complex interoperability scenario. When we consider ubiquitous computing comprising CPS, extensibility becomes even more challenging as traditional CPS are not designed to be extensible; this is discussed in detail below.

I.2.3 Extensibility in CPS

So, what are extensible CPS? And how exactly are extensible CPS different than today's CPS. Extensible CPS are next generation CPS [48] comprising loosely connected, multi-domain cyber-physical subsystems that "virtualize" their heterogeneous physical resources to provide an open platform capable of hosting different cyber-physical applications. Behavior of resulting heterogeneous cyber-physical platform is not encoded *a priori*, but it evolves throughout the lifetime of the platform depending on applications hosted on the platform. This approach yields a dynamic cyber-physical platform capable of extending along different planes of evolution as (1) resources with distributed ownership can be dynamically added to or removed from existing subsystems, (2) completely new subsystems pertaining to different domains could be added, and (3) applications can be added or removed dynamically at runtime to add new or remove existing functionalities.

Table 1 summarizes the differences between traditional CPS and extensible CPS. Traditional CPS are designed and built as domain-specific vertical silos of isolated capabilities. In essence, they are black boxes that are verified, validated, and certified at design-time

Table 1: Differences between CPS and Extensible CPS.

CPS	Extensible CPS
Systems are domain-specific vertical silos of isolated capabilities.	Platform of loosely connected CPS pertaining to possibly different physical domains.
Static applications that are composed, verified, validated and sometimes certified at design-time. Lifecycle of such applications are strictly tied to that of the underlying system.	Open platform that can host multiple applications whose lifecycle are not tied to that of the underlying system, so applications (therefore functionalities) can be dynamically added, modified or removed at runtime.
Systems can evolve but not during operation.	Allows continuous evolution and operation resulting in systems with evolving behavior.
A CPS can consist of heterogeneous resource but mostly no distributed ownership even if resources can come from different OEMs.	Each subsystem can consists heterogeneous resources with distributed ownership resulting in high degree of heterogeneity.

before deployment. This implies that applications hosted on these systems are static, *i.e.*, applications are also verified, validated, and certified as part of the system at design-time after which their lifecycle is strictly tied to that of the system. Once deployed, these systems can evolve but not during operation; any change requires the system to go through a stop-change-start cycle. Furthermore, although traditional CPS can comprise heterogeneous resources since resource can come from different Original Equipment Manufacturer (OEM), those resources are not subject to distributed ownership. Therefore, it is easy to manage heterogeneity.

I.3 Challenges for Extensible CPS

In order to identify challenges for extensible CPS, we first need to understand the properties of extensible CPS. As presented in Table 2, there are four key properties: (1) these systems are dynamic with respect to their resources, (2) these systems comprises highly heterogeneous resources, (3) these system host multiple applications simultaneously, and (4) these systems can be remotely deployed. Now that we understand the properties of extensible CPS, we must identify the challenges that arise due to these properties. In order to

do so, it is important to consider different CPS constraints, such as safety, timing, security, resource, and resilience constraints.

Table 2: Properties of Extensible CPS.

Property	Description and Requirements (R)
Dynamic	Hardware and software resources can be added, removed, or updated at any time during the lifetime of an extensible CPS.
Heterogeneous	Each subsystem of a large-scale extensible CPS can belong to different domain and resources of a subsystem itself can have high degree of hardware and software heterogeneity due to distributed ownership.
Multi-tenant	Ability to simultaneously host multiple applications belonging to different organization/client.
Remotely deployed	Hardware resources that comprises extensible CPS can be remotely deployed (for example, UAVs, satellites). Therefore, opportunity for human intervention can be very limited to sometimes non-existent.

Challenge 1: Managing lifecycle of distributed applications

The dynamic and multi-tenant properties of extensible CPS necessitate a management infrastructure capable of managing lifecycle of distributed applications hosted on a cluster. In oder to do so, the management infrastructure must be able to (1) deploy applications, (2) alter states of previously deployed applications, for example from *active* to *passive* or *inactive*, and (3) reconfigure previously deployed applications, for example moving an application component from one node to another.

Challenge 2: Achieving autonomous resilience

More often than not CPS are mission critical, as such, resilience is an important desired property. In the case of traditional CPS, resilience can be hard-coded as these systems are usually static. As such, existing solutions for resilience in traditional CPS rely on offline (design-time) computation of resilience scenarios. However, offline computation is only feasible for static systems. For extensible CPS, offline computation is infeasible as these systems comprise dynamic resources, and therefore, all possible resilience scenarios cannot be forecasted at design-time.

To further elaborate on what resilience exactly means, we must consider entities that comprises an extensible CPS. In general, there are two kinds of entities: (1) user applications, and (2) system services, which includes firmware, OS, platform services such as the management infrastructure mentioned in previous section. Given these entities, a resilient system has to ensure that these entities provide their functionalities for as long as possible. In order to do so, the system must (1) avoid failures if possible, (2) mitigate failures and anomalies that occur, and (3) handle system evolution in a way such that continuous operation is not affected. Furthermore, any resilience mechanism used should be autonomous; this is important as extensible CPS can be remotely deployed.

Challenge 3: Ensuring secure interaction between applications

Security constraint necessitates extensible CPS to provide secure execution environment for different applications they host. If multiple interacting applications are running simultaneously and these applications can belong to different organizations/clients (multi-tenant property), we require some mechanism to ensure that these interactions follow some overarching security policies such that there are no data breaches. It is important to ensure that applications interact with each other if and only if they are allowed to. Therefore, in addition to devising such security policies, some runtime mechanism is required to ensure those policies are followed.

Challenge 4: Allowing heterogeneous applications to be middleware agnostic

As presented in Table 2, extensible CPS comprises heterogeneous hardware and software. Hardware heterogeneities are usually resolved by communication middleware solutions. However, there are multiple middleware solutions currently available; each with their own advantages and disadvantages, each suitable for certain domains. Furthermore, software applications are themselves heterogeneous. For example, a cyber-physical application running one or more edge resources represents a real-time control applications; whereas, a long

running pattern recognition application running on a network of resource-intensive cloud resources represents a non real-time application. Therefore we require a mechanism that allows (1) allows interaction between heterogenous applications while remaining agnostic to the underlying middleware, and (2) applications to be written once and ran anywhere.

Challenge 5: Runtime verification and validation

CPS have strong safety constraint because of which they are usually verified, validated, and certified at design-time. However, due to the dynamic nature and resilience requirement of extensible CPS, these system can evolve dynamically at runtime. Combination of this and safety constraint yields a very significant challenge of runtime verification and validation. There exist composition and integration theories for CPS that are only applicable for design-time verification and validation. However, a significant challenge is to come up with something similar for runtime changes such that a system can be dynamically verified and validated at runtime, when undergoing any changes.

Challenge 6: Runtime resource isolation and utilization

CPS are real-time systems that can have strong timing constraint since these systems interact with the physical world. This results in applications with execution deadlines. Generally, CPS are resource-constrained as well. The combination of timing constraint, resource constraint and multi-tenant property of extensible CPS means these system must support some runtime mechanism to ensure (1) the limited resources available are used efficiently, while (2) all applications get enough resources to meet their deadlines. The latter challenge is one of the most fundamental challenge researchers and developers face when trying to move CPS into cloud settings.

I.4 Overview of Proposed Doctoral Research

This dissertation presents algorithms and techniques to resolve first three (Challenges 1, 2, and 3) of the six challenges previously identified in Section I.3. The reason for initially focusing heavily on these challenges that are related to the management infrastructure is because having a management infrastructure that can manage applications is crucial to solve other challenges. For example, any runtime verification and validation mechanism would need to be part of the runtime management loop. In addition, this dissertation also presents some initial work towards a solution for Challenge 4. Below is the list of contributions and proposed future work presented in this dissertation:

Contribution 1: A resilient deployment and reconfiguration infrastructure to manage distributed applications

The first contribution of this dissertation is a resilient deployment and reconfiguration infrastructure capable of managing lifecycle of remotely hosted distributed applications; this addresses Challenge 1. Furthermore, the deployment and reconfiguration infrastructure is itself resilient; this partly addresses Challenge 2. The details of this contribution is presented in Chapter III. Although the solution presented in this dissertation relies on applications based on Light-weight Corba Component Model (LwCCM) [71] component model, the core idea is applicable to other component models as well.

Most of the exiting component models have a well-defined deployment model, and therefore, solutions (*i.e.*, management infrastructure) to perform initial deployment. However, not all of these solutions are capable of performing runtime reconfiguration. Furthermore, even though previous efforts have resulted in some management infrastructures that support runtime reconfiguration, those efforts do not consider resilience of the management infrastructure itself, which is important for extensible CPS, as explained in Challenge 2.

Contribution 2: Establishing secure interaction across distributed applications

The second contribution of this dissertation is a mechanism to establish secure interaction across distributed applications with varying security requirements. Main focus of this contribution is on a novel participant discovery mechanism that takes into account security requirements of applications during the participant discovery process. This discovery mechanism is designed and implemented as an extension of the Data Distribution Service (DDS) specification [72] provided by the Object Management Group (OMG), resulting in a publish/subscribe middleware capable of ensuring secure interactions. Since this solution is non-invasive, it can work with other implementations of the OMG DDS specification.

The aforementioned discovery mechanism is based on a novel transport mechanism (not a contribution of this dissertation) called *Secure Transport* [80] that uses a lattice of labels to represent security requirements as security classification levels and enforces Multi-Level Security (MLS) [6, 16, 38] policies to ensure strict information partitioning. Chapter IV describes this contribution in detail in the context of a satellite cluster. This contribution addresses Challenge 3.

Contribution 3: Achieving autonomous resilience via self-reconfiguration

The first contribution of this dissertation (described above and presented in Chapter III) is a resilient management infrastructure, which addresses Challenge 1 and partly addresses Challenge 2. In order to completely address Challenge 2, we not only require the management infrastructure to be resilient, we also require the applications hosted on extensible CPS to be resilient. However, for applications to be resilient, we need some mechanism that can dynamically adapt applications at runtime when affected by failures or anomalies. Systems with these kind of capabilities are commonly referred to as *self-adaptive* or *self-reconfiguring* systems.

Although the management infrastructure presented in Chapter III is capable of self-reconfiguring a system by detecting failures and dynamically reconfiguring (*i.e.*, adapting)

applications by migrating them, it does so without any smartness by randomly deciding where to migrate a component. This is not a viable solution as extensible CPS are dynamic and multi-tenant, which means the management infrastructure should take into consideration the entire system configuration state (*i.e.*, existing application components, available resources, required resources, and other constraints) when making adaptation decision to reconfigure a system.

To address above described shortcoming, as the third contribution, this dissertation presents a management infrastructure that implements a novel self-reconfiguration mechanism based on (1) dynamic constraints formed at runtime using system information, and (2) a Satisfiability Modulo Theories (SMT) [15] solver used to solve aforementioned constraints. At the very core, the problem addressed by this contribution is that of dynamic space exploration of the runtime system information. Since extensible CPS are dynamic and multi-tenant, any mechanism used to facilitate reconfiguration cannot be based on design-time computation and should use most up-to-date runtime system state information.

This contribution is broken down into two chapters and it is described in detail in Chapter V and Chapter VI. While Chapter V presents a design-time resilience analysis tool and focuses more on the concept of using SMT solvers for self-reconfiguration, Chapter VI extends it by presenting a holistic solution for managing extensible CPS.

CHAPTER II

BACKGROUND AND MOTIVATING SCENARIO

This chapter presents a target system model, application model, and failure model as background information relevant for contributions presented in the remaining chapters of this dissertation. In addition, this chapter presents a motivational scenario using a Smart Emergency Response System (SERS) as an example of an extensible CPS.

II.1 Target System Model

The target system model for extensible CPS comprises one or more clusters of heterogeneous nodes that provide computation and communication resources. These nodes are also equipped with variety of sensors and actuators. As discussed earlier in Section I.3, dynamic nature of extensible CPS means cluster membership can change over time due to failures or addition and removal of resources. For example, consider a distributed system of fractionated spacecraft [29] that hosts mission-critical applications. Figure 3 shows a typical node of the distributed platform created by these nodes. Each node contains a layered software stack consisting of an operating system (OS), communication middleware, and platform services.

A communication middleware provides mechanism for applications to easily use well-known communication patterns without having to worry about the underlying OS and hardware details. As such, applications do not need to care about OS and communication related hardware heterogeneity. However, as mentioned before in Section I.3, applications do need to care about middleware heterogeneity as there exists different middleware solutions, such as different OMG (Object Management Group) DDS (Data Distribution Service) [72] implementations [47, 69, 89], AllJoyn [5], AMQP (Advanced Message Queuing Protocol) [108], etc.

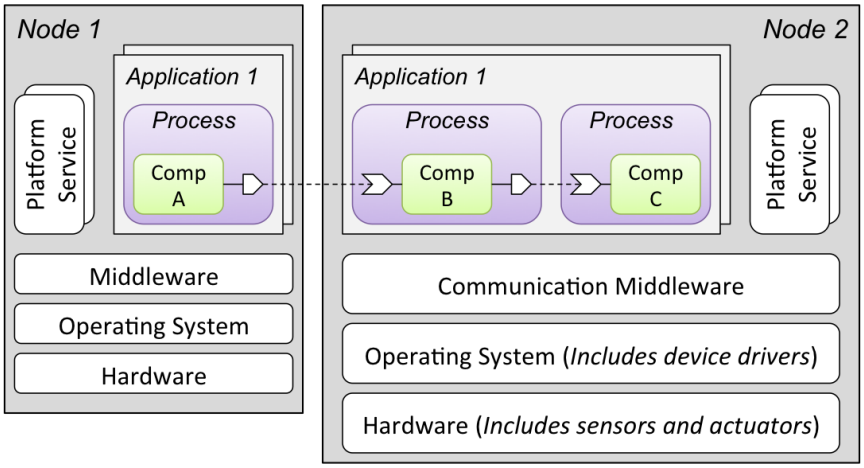


Figure 3: Target System Model comprising Component-based Application Model for Extensible CPS.

The platform services are, in essence, long running services that serve as an extension of the OS by providing generic services for the system to use. These services are what allows us to use this network of heterogeneous nodes as a cyber-physical platform capable of hosting multiple applications. Example of platform services includes monitoring services, resource management services, and application management services.

II.2 Application Model

Since extensible CPS are platform comprising heterogeneous and distributed resources, applications need to be distributed as well. Not all resources required by an application can always be available in same physical node; some nodes may have sensors, some may have actuators and others might have processing and storage capabilities. Therefore, as shown in Figure 3, applications need to be distributed and loosely connected to perform required interactions. Concept of software components, which is based on Component-Based Software Engineering (CBSE) [41] approach, fits very well in this scenario as it allows applications to be composed of re-usable software components that expose well-defined interfaces for interactions.

Assuming component-based applications, a distributed application becomes a graph of

software components that are partitioned into processes; each component runs on its own process, as shown in Figure 3. Edges in this component graph represents component interaction, and therefore, inter-component dependencies. The interaction relationship between the components are defined using established interaction patterns such as synchronous or asynchronous remote method invocation, and anonymous publish-subscribe communication. Process and component creation, deployment, configuration, and re-configuration tasks are considered management tasks, therefore, these tasks are responsibility of a management infrastructure. In order to instantiate an application, the corresponding application graph needs to be mapped to available computing nodes.

II.3 Failure Model

A fault is defined as a defect or problem within a system entity that can manifest itself in observable discrepancies: deviations from expected behavior; or it can remain unobservable. A fault may cause a failure. The failure of a system or a component is the breakdown of its capability to provide required services or functions. Note the distinction between faults and failures: faults cause the loss of function(s), i.e., failure(s). The interconnections between system entities imply that a failure of one entity can also lead to a secondary failure in a connected entity. If the failure propagates to the global level, i.e. the top-level system, it is called a global failure. In a "system of systems", fault-tolerance algorithms are required to detect faults, mask fault effects, and mask lower-level component failures so that they do not lead to a global failure. To be considered fault tolerant, a system must be able to detect occurrences of discrepancies that signify faults, to diagnose and isolate the probable fault sources, to take actions to either contain the faults (and thus stop them from propagating outwards), and/or mitigate their effects on system functions.

State of the art techniques for safety critical systems involve the application of software fault tolerance principles, methods and tools to ensure that a system can survive software defects that manifest themselves at runtime [21, 57, 58, 90, 106]. Alternative approaches

based on system health management techniques exist that are based on runtime fault detection, isolation, and mitigation activities to remove fault effects [103]. In the past we have shown how system-wide mitigation can be performed based on reactive timed state machines specified by the designer at system integration time [62] using the results of a two-level fault-diagnoser [30]. Thereafter, we presented a Boolean encoding for reconfiguring the system using a search based strategy in [60]. Note that in this chapter, we consider system resource constraints and dynamic mission objectives along with the infrastructure required to make this system practical.

One of the problems with these kinds of fault mitigation approaches is the complexity of the specifications required to cover all possible combinations of failure scenarios. Often, it is easier to encode a default behavior to shutdown the faulty entity. This leads to the assumption of a *fail-stop* failure model which means that any failure results in stopping the failed entity, which allows others to detect this failure. In general, these fail-stop failures can be classified into two categories: (1) infrastructure failures, and (2) application failures.

II.3.0.1 Infrastructure failures

Infrastructure failures are failures that arise due to faults affecting a system's (1) network, (2) participating nodes, (3) devices hosted on different nodes, or (4) processes running on different nodes. There exist causality between these four different kinds of infrastructure failures. A network can fail due to various reasons such as increased physical distance between the nodes of a cluster, or due to failure of network related devices. A network failure causes all nodes that are part of the network to fail since those nodes become unreachable after their network failure. A node failure causes all the devices and processes running on that node to fail. A device failure might cause processes using that device to fail, it might even cause the entire node that hosts the device to fail, or if the device is a networking device then it might cause network failure.

However, a process can fail without its host node failing or one of the devices it uses

failing. Similarly, a device can fail without its host node failing, and a node can fail due to reasons other than network separation or device failure. We consider infrastructure failures to be *primary failures* that can result in application failures, ultimately causing the system to lose existing functions.

II.3.0.2 Application failures

Application failures are failures pertaining to the application components. We assume that application components have been thoroughly tested before deployment and therefore classify application failures as *secondary failures* that are caused by to infrastructure failures. However, there can be scenarios where an application component failure becomes a primary source of failure and results in its hosting process, i.e., infrastructure to fail. In this case, application failure becomes a primary failure. Some environmental changes could also lead to application failures, where the changes in the environment can cause an application to receive unexpected input or the environment might not react, as expected, to an application's output.

Failures can be temporary, intermittent or permanent. Temporary failures are failures that have a short duration, while intermittent failures are temporary failures that occur at irregular intervals. The work presented in this dissertation focuses on permanent failures. In case of temporary failures, we can treat them like permanent failures since we follow a fail-stop model. For example, when a node fails temporarily due to network partition, all of its hosted entities are considered failed and appropriate reconfiguration actions will be taken. However, because the failure is temporary, the node comes back online after some time, at which point any existing applications present in the node must be removed after which the node can be treated as a new node joining an existing cluster. A similar approach can be taken to implement a naive solution for intermittent failures.

II.4 Motivating Scenario: Smart Emergency Response System

This sections briefly describes a Smart Emergency Response System (SERS) [110] as a motivating scenario. A SERS is a common smart city application and it is an exemplar of an extensible CPS. A SERS comprises resources of different physical domains. The example presented in Figure 4 comprises of resources of five different physical domains. *Domain A* represents buildings and infrastructures (for example, parking lots) with smart devices such as smart smoke detectors, thermostats, cameras, etc. *Domain B* represents application servers for smart building and infrastructure applications. These application servers are responsible for receiving incident reports from applications in *Domain A* and forwarding associated address to application in *Domain C*. *Domain C* represents a cluster of small satellites that hosts application responsible for receiving incident information from application in *Domain B*, calculating corresponding GPS location, and sending it to smart Road Side Units (RSUs) in *Domain D*. Finally, *Domain D* represents collection of smart RSUs that receive GPS notification from application in *Domain C* and forwards it to nearby emergency response vehicles represented as part of *Domain E*.

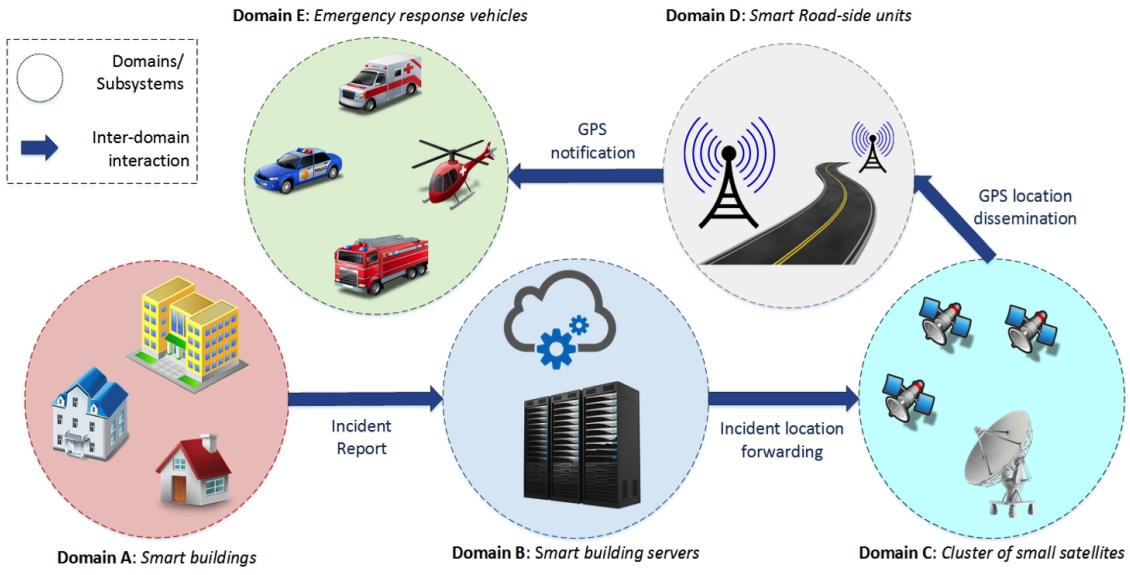


Figure 4: Smart Emergency Response System with Different Physical Domains.

CHAPTER III

A RESILIENT DEPLOYMENT AND RECONFIGURATION INFRASTRUCTURE TO MANAGE DISTRIBUTED APPLICATIONS

III.1 Motivation

In essence, extensible CPS are open cyber-physical platforms that can host multiple applications simultaneously. These applications as well as the resources on which they are deployed are dynamic. Therefore, we require a management infrastructure that can manage lifecycle of remotely hosted distributed applications. Furthermore, since CPS have strong resilience requirement, the management infrastructure itself must be resilient. These requirements have been identified in [86].

To realize a management infrastructure capable of managing applications, we must first understand how these applications are architected. As previously explained in Section II.2, Component-Based Software Engineering (CBSE) [42] approach fits well as an application model for extensible CPS. In this approach applications are realized by composing, deploying and configuring software components using well-defined component models. A component model provides the interaction (components have well-defined ports for interaction) and execution semantics. A number of different component models exist: Fractal [19], CORBA Component Model (CCM) [74], LwCCM [71] etc. Similarly, there exists different Deployment and Configuration (D&C) infrastructures that are compatible with these component models. However, these D&C infrastructures either do not handle dynamic reconfiguration or even if they do, the D&C infrastructure itself is not resilient. Here, it is important to note that the D&C infrastructure is synonymous to a management infrastructure.

Therefore, this chapter presents a novel D&C infrastructure that is not only capable

of initial deployment and configuration, but also capable of runtime reconfiguration of previously deployed applications, and is itself resilient.

III.2 Background and Problem Description

To deploy distributed component-based applications[1] onto a target environment, the system needs to provide a software deployment service. A Deployment and Configuration (D&C) infrastructure serves this purpose; it is responsible for instantiating application components on individual nodes, configuring their interactions, and then managing their lifecycle. Therefore, as mentioned before in Section III.1, a D&C infrastructure is synonymous to a management infrastructure. A D&C infrastructure should be viewed as a distributed infrastructure composed of multiple deployment entities, with one entity residing on each node.

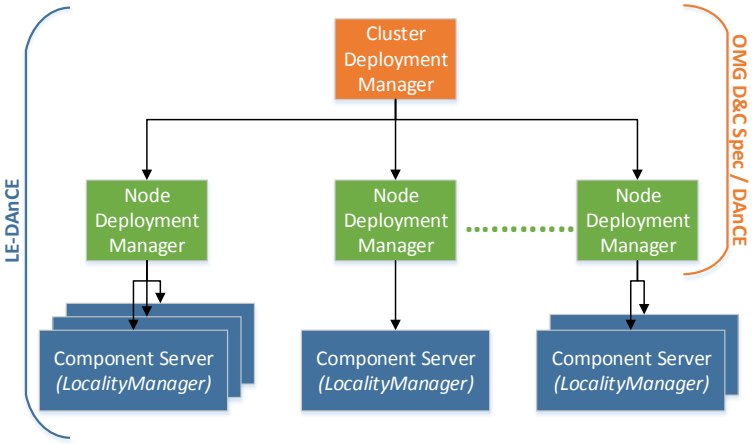


Figure 5: Orchestrated Deployment Approach in LE-DAnCE [82].

The D&C [77] specification provided by the Object Management Group (OMG) is a

[1] Although we use the component model described in [71], our work is not constrained by this choice and can be applied to other component models as well.

standard for deployment and configuration of component-based applications. The Locality-Enabled Deployment And Configuration Engine (LE-DAnCE) [82] is an open-source implementation of this specification. As shown in Figure 5, LE-DAnCE implements a strict two-layered approach comprising different kinds of Deployment Managers (DM). A DM is a deployment entity. The Cluster Deployment Manager (CDM) is the single orchestrator that controls cluster-wide deployment process by co-ordinating deployment among different Node Deployment Managers (NDM). Similarly, a NDM controls node-specific deployment process by instantiating component servers that create and manage application components.

LE-DAnCE, however, is not resilient and it does not support run-time application adaptation as well. Therefore, the contribution presented in this chapter extends LE-DAnCE to achieve a D&C infrastructure that not only performs initial application deployment, it is itself resilient and is also capable of dynamic reconfiguration of existing applications.

III.3 Key Considerations and Challenges

To correctly provide resilient D&C services to an extensible CPS cluster, the D&C infrastructure must resolve the challenges described below:

Challenge 1 (Distributed group membership): Recall that the extensible CPS domain illustrates a highly dynamic environment in terms of resources that are available for application deployment: nodes may leave unexpectedly as a result of a failure or as part of a planned or unplanned partitioning of the cluster, and nodes may also join the cluster as they recover from faults or are brought online. To provide resilient behavior, the DMs in the cluster must be aware of changes in group membership, i.e., they must be able to detect when one of their peers has left the group (either as a result of a fault or planned partitioning) and when new peers join the cluster.

Challenge 2 (Leader election): As faults occur, a resilient system must make definitive

decisions about the nature of that fault and the best course of action necessary to mitigate and recover from that fault. Since extensible CPS clusters often operate in mission- or safety-critical environments where delayed reaction to faults can severely compromise the safety of the cluster, such decisions must be made in a timely manner. In order to accommodate this requirement, the system should always have a *cluster leader* that will be responsible for making decisions and performing other tasks that impact the entire cluster.[2] However, a node that hosts the DM acting as the cluster leader can fail at any time; in this scenario, the remaining DMs in the system should decide among themselves regarding the identity of the new cluster leader. This process needs to be facilitated by a leader election algorithm.

Challenge 3 (Deployment sequencing): Applications in extensible CPS may be composed of several cooperating components with complex internal dependencies that are distributed across several nodes. Deployment of such an application requires that deployment activities across several nodes proceed in a synchronized manner. For example, connections between two dependent components cannot be established until both components have been successfully instantiated. Depending on the application, some might require stronger sequencing semantics whereby all components of the application need to be activated simultaneously.

Challenge 4 (D&C State Preservation): Nodes in extensible CPS may fail at any time and for any reason; a D&C infrastructure capable of supporting such a cluster must be able to reconstitute those portions of the distributed application that were deployed on the failed node. Supporting resilience requires the D&C infrastructure to keep track of the global

[2] Achieving a consensus-based agreement for each adaptation decision would likely be inefficient and violate the real-time constraints of the cluster.

system state, which consists of (1) component-to-application mapping, (2) component-to-implementation mapping[3], (3) component-to-node mapping, (4) inter-component connection information, (5) component state information, and (6) the current group membership information. Such state preservation is particularly important for a new leader.

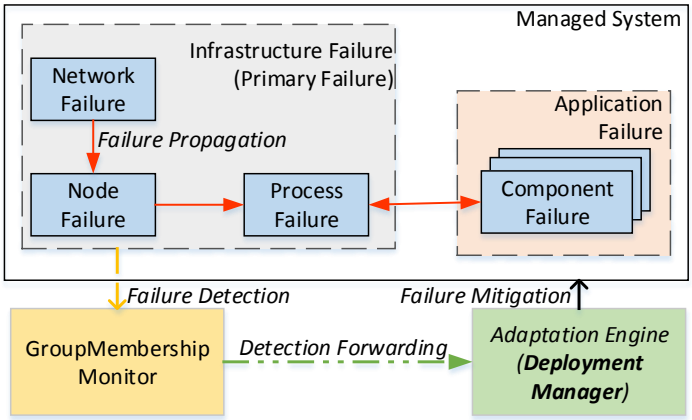


Figure 6: Overview of a Resilient D&C Infrastructure.

III.4 A Resilient Deployment and Reconfiguration Infrastructure

Figure 6 presents an overview of the solution. Infrastructure failures are detected using the Group Membership Monitor (GMM). Application failure detection is outside the scope, however, we refer interested readers to a related publication [63] in this area. The controller is in fact a collection of DMs working together to deploy and configure as well as reconfigure application components. The specific actuation commands are redeployment actions taken by the DMs.

[3] A component can have multiple implementations.

III.4.1 Solution Architecture

Figure 7 presents the architecture of the resilient D&C infrastructure. Each node consists of a single Deployment Manager (DM). A collection of these DMs forms the overall D&C infrastructure. This approach supports distributed, peer-to-peer application deployment, where each node controls its local deployment process. Each DM spawns one or more Component Servers (CSs), which are processes responsible for managing the life-cycle of application components. Note that this approach does not follow a centralized coordinator for deployment actions; rather the DMs are independent and use a publish/subscribe middleware to communicate with each other.

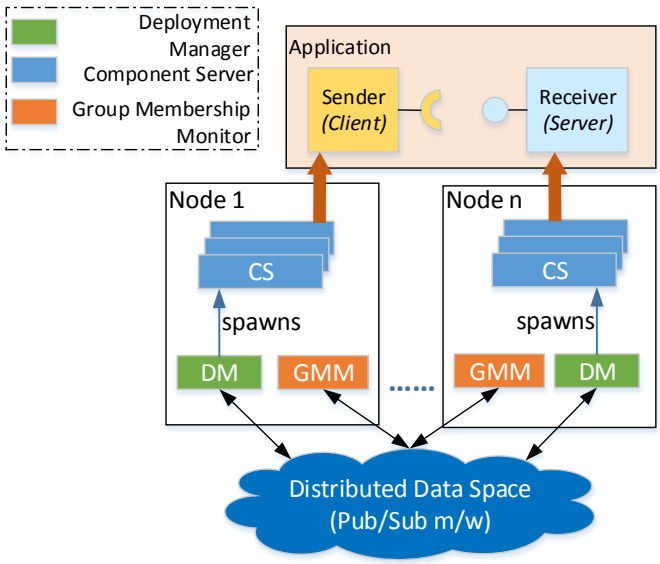


Figure 7: Architecture of a Resilience D&C Infrastructure.

In this architecture, the GMM is used to maintain up-to-date group membership information, and to detect failures via a periodic heartbeat monitoring mechanism. The failure detection aspect of GMM relies on two important parameters – *heartbeat period* and *failure monitoring period*. These configurable parameters allows us to control how often each DM asserts its liveliness and how often each DM monitors failure. For a given failure

monitoring period, a lower heartbeat period results in higher network traffic but lower failure detection latency, whereas a higher heartbeat period results in lower network traffic but higher failure detection latency. Tuning these parameters appropriately can also enable the architecture to tolerate intermittent failures where a few heartbeats are only missed for a few cycles and are established later. This can be done by making the fault monitoring window much larger compared to the heartbeat period.

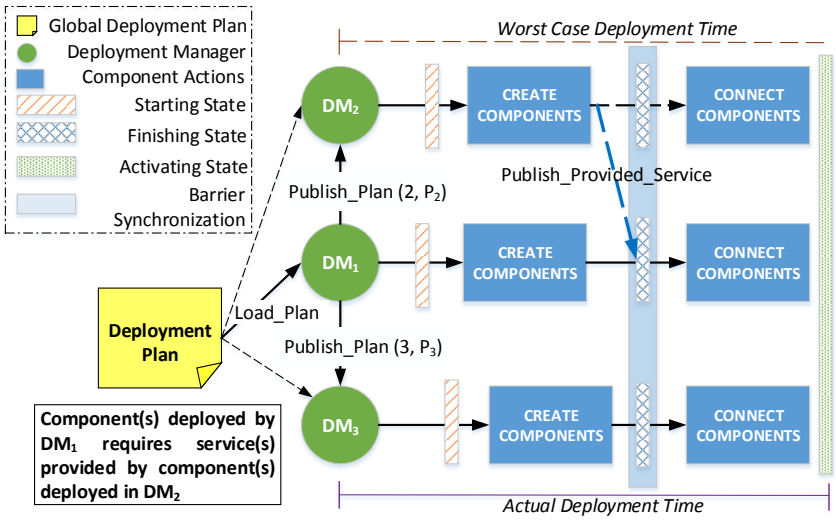


Figure 8: Three-node Deployment and Configuration Setup.

Figure 8 shows an event diagram demonstrating a three node deployment process of the new D&C infrastructure. An application deployment is initiated by submitting a *global deployment plan* to one of the three DMs. This global deployment plan contains information about different components (and their implementation) that make up an application. It also contains information about how different components should be connected. Once this global deployment plan is received by a DM, that particular DM becomes the *deployment leader* for that particular deployment plan. A deployment leader is only responsible for initiating the deployment process for a given deployment plan by analyzing the plan and allocating deployment actions to other DMs in the system. The deployment leader is not

Table 3: Deployment and Configuration Stages

Stage	Description
INITIAL	(1) Global deployment plan is provided to one of the DMs. (2) DM that is provided with a global deployment plan becomes the leader DM and loads that deployment plan and stores it in a binary format.
PREPARING	(1) Plan loaded in the previous stage is split into node-specific plans and they are published to the distributed data space using pub/sub middleware. (2) Node-specific plans published above are received by all DMs and only the ones that are relevant are further split into component server (CS)-specific plans.
STARTING	(1) CS-specific plans created in the previous stage are used to create CSs (if required) and components. (2) For components that provide service via a *facet*, the DM will publish its connection information so that other components that require this service can connect to it using their *receptacle*. This connection however is not established in this stage. (3) In this stage, barrier synchronization is performed to make sure that no individual DMs can advance to the next stage before all of the DMs have reached this point.
FINISHING	(1) Components created in the previous stage are connected (if required). In order for this to happen, the components that require a service use connection information provided in the previous stage to make facet-receptacle connections.
ACTIVATING	(1) Synchronization stage to make sure all components are created and connected (if required) before activation.
ACTIVATED	(1) Stage where a deployment plan is activated by activating all the related components. (2) At this point all application components are running.
TEARDOWN	(1) De-activation stage.

responsible for other cluster-wide operations such as *failure mitigation*; these cluster-wide operations are handled by a *cluster leader*. Two different global deployment plans can be deployed by two different deployment leaders since the solution architecture does not rely on a centralized coordinator.

Deployment and configuration is a multi-staged approach. Table 3 lists the different D&C stages. The `INITIAL` stage is where a deployment plan gets submitted to a DM and ACTIVATED stage is where the application components in the deployment plan is active. The rest of this section describes how information in this table is used to address the key challenges.

III.4.2 Addressing Resilient D&C Challenges

Resolving Challenge 1 (Distributed Group Membership): To support distributed group membership, we require a mechanism that allows detection of joining members and leaving members. To that end the solution presented uses a *discovery mechanism* to detect the former and a *failure detection mechanism* to detect the latter as described below.

Discovery Mechanism: Since the solution approach relies on an underlying pub-/sub middleware, the discovery of nodes joining the cluster leverages existing discovery services provided by the pub/sub middleware. To that end we have used OpenDDS (http://www.opendds.org) – an open source pub/sub middleware that implements OMG's Data Distribution Service (DDS) specification [70]. To be more specific, we use the Real-Time Publish Subscribe (RTPS) peer-to-peer discovery mechanism specified by DDS.

Failure Detection Mechanism: To detect the loss of existing members, a failure detection mechanism is required. In the solution architecture this functionality is provided by the GMM. The GMM residing on each node uses a simple heartbeat-based protocol to detect DM (process) failure. Recall that any node failure, including the ones caused due to network failure, results in the failure of its DM. This means that the failure detection service uses the same mechanism to detect all three different kinds of infrastructure failures.

Resolving Challenge 2 (Leader Election): Leader election is required in order to tolerate cluster leader failure. This is implemented using a rank-based leader election algorithm. Each DM is assigned a unique numeric rank value and this information is published by each DM as part of its heartbeat. Initially the DM with the least rank will be picked as the cluster leader. If the cluster leader fails, each of the other DMs in the cluster will check their group membership table and determine if it is the new leader. Since, a unique rank is associated with each DM, only one DM will be elected as the new leader.

Resolving Challenge 3 (Proper Sequencing of Deployment): The solution D&C infrastructure implements deployment synchronization using a distributed *barrier synchronization* algorithm. This mechanism is specifically used during the STARTING stage of the

D&C process to make sure that all DMs are in the STARTING stage before any of them can advance to the FINISHING stage. This synchronization is performed to ensure that all connection information of all the components that provide a service is published to the distributed data space before components that require a service try to establish a connection. We realize that this might be too strong of a requirement and therefore we intend to further relax this requirement by making sure that only components that require a service wait for synchronization. In addition, the current solution also uses barrier synchronization in the ACTIVATING stage to make sure all DMs advance to the ACTIVATED stage simultaneously. This particular synchronization ensures the simultaneous activation of a distributed application.

Resolving Challenge 4 (D&C State Preservation): In the current implementation, once a deployment plan is split into node-specific deployment plans, all of the DMs receive the node-specific deployment plans. Although any further action on a node-specific deployment plan is only taken by a DM if that plan belongs to the node in which the DM is deployed, all DMs store each and every node-specific deployment plans in its memory. This ensures that deployment-related information is replicated throughout a cluster thereby preventing single point of failure. However, this approach is vulnerable to DM process failures since deployment information is stored in memory. To resolve this issue, the solution presented in this section can be extended to use a persistent backend database to store deployment information.

III.5 Experimental Results

This section demonstrates the autonomous resilience capabilities of the D&C infrastructure by showing how it adapts applications as well as itself after encountering a node failure during deployment-time, and runtime.

III.5.1 Testbed

For all experiments, a cluster of three nodes was used. Each node had a 1.6 GHz Atom N270 processor and 1GB of RAM. Each node ran vanilla Ubuntu 13.04 server image which uses Linux kernel version 3.8.0-19.

The application that was used for the experiments presented in Sections III.5.2 and III.5.3 is a simple two-component client-server experiment presented earlier in Figure 7. The Sender component (client) is initially deployed in node-1, the Receiver component (server) is initially deployed in node-2, and node-3 has nothing deployed on it. For both experiments, node-2 is the node that fails. Furthermore, the infrastructure is configured with heartbeat period set to 2 seconds and failure monitoring period set to 5 seconds.

III.5.2 Node Failure During Deployment-time

Figure 9 presents a time sequence graph of how the D&C infrastructure adapts itself to tolerate failures during deployment-time. As can be seen, node 2 and therefore DM-2 fails at Event 5. Once the failure is detected by both DM-1 in node-1 and DM-3 in node-3, DM-1 being the leader initiates the recovery process (Event 6 - Event 7). During this time, DM-1 determines the part of the application that was supposed to be deployed by DM-2 in node-2, which is the Receiver component. Once DM-1 determines this information, it completes the recovery process by republishing information about the failure affected part of application (Receiver component) to DM-3. Finally, DM-3 deploys the Receiver component in node-3 and after this point, the deployment process resumes normally.

III.5.3 Node Failure During Application Run-time

Figure 10 presents a time sequence graph that demonstrates how the D&C infrastructure adapts applications at run-time to tolerate run-time node failures. Unlike the scenario presented before where the initial deployment of the application has to be adapted to tolerate deployment-time failure, here the initial deployment completes successfully at Event

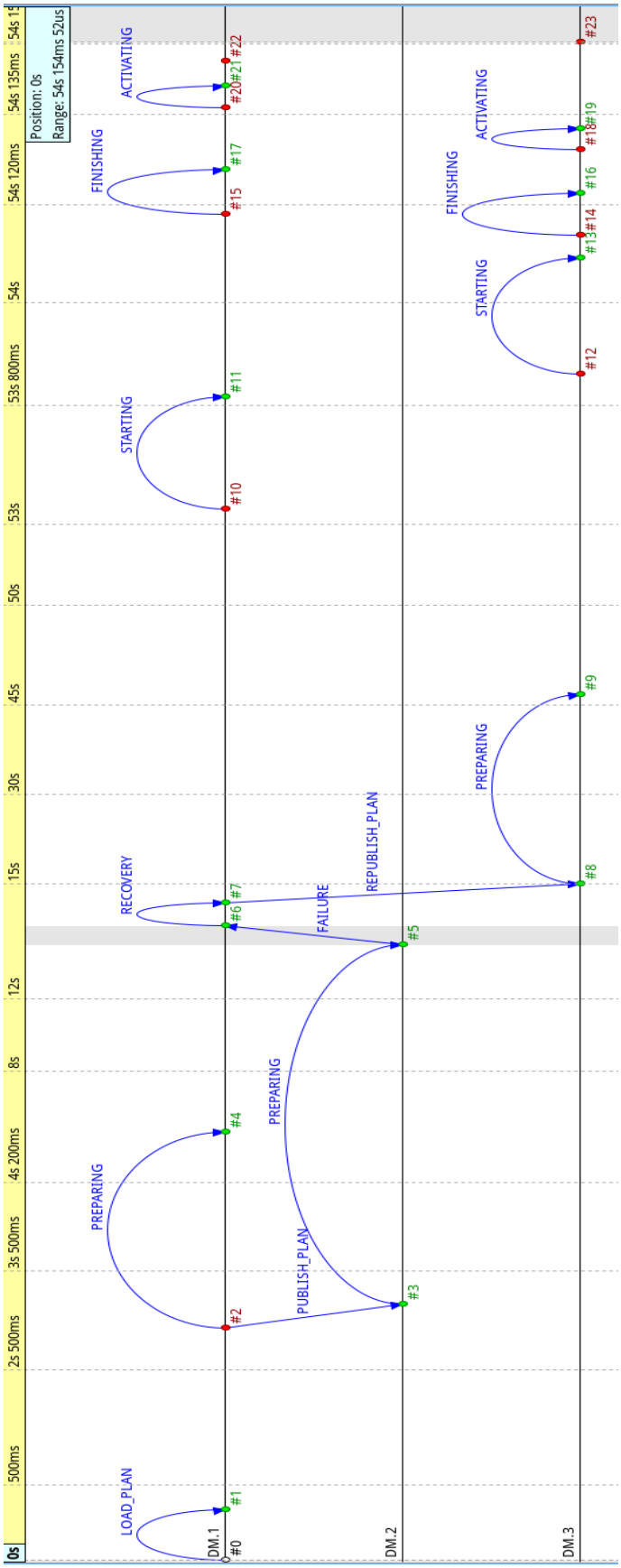


Figure 9: Deployment Time Node Failure.

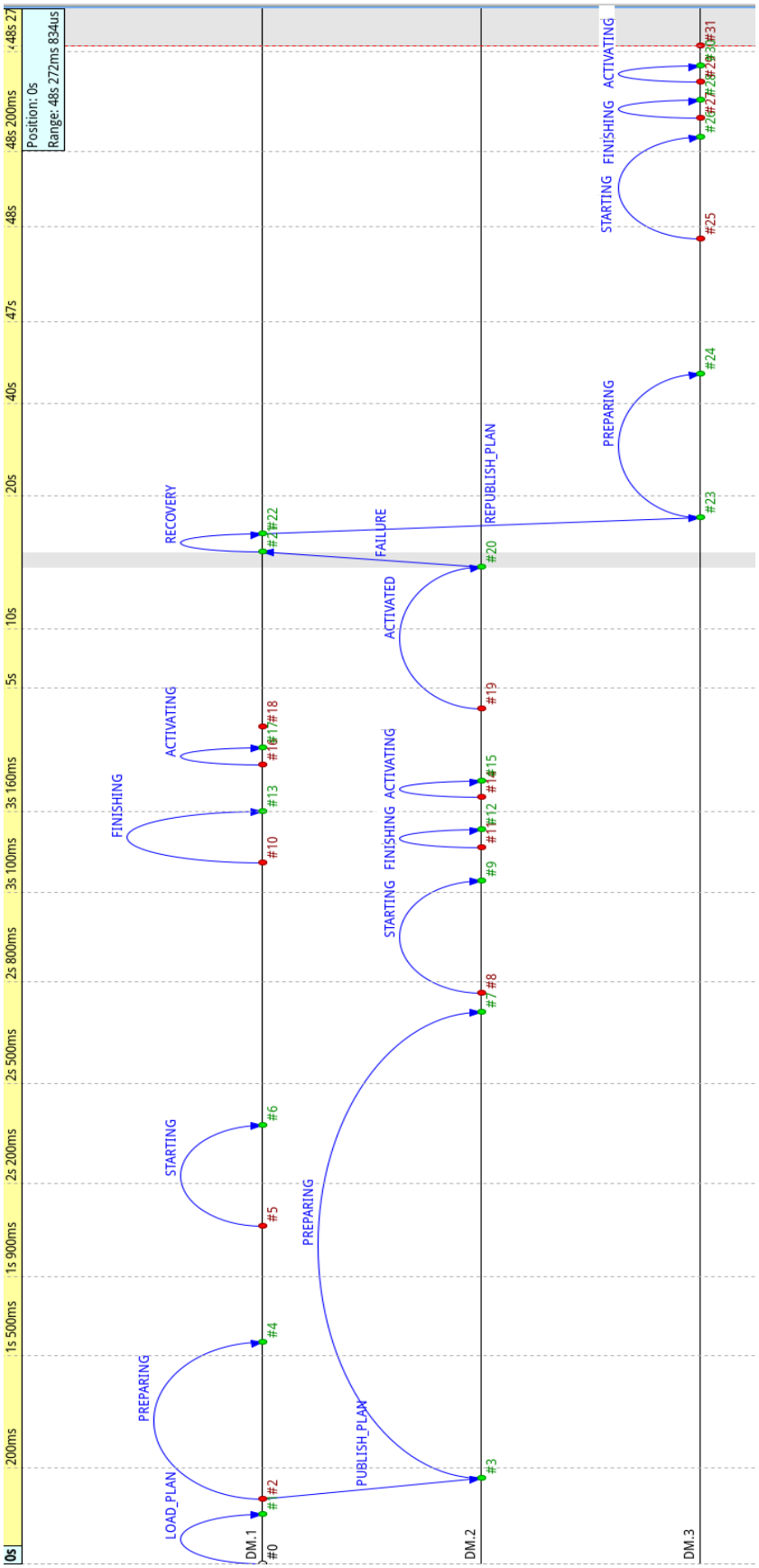


Figure 10: Runtime Node Failure.

19 after which the application is active. However, node-2 and therefore DM-2 fails at Event 20 and the notification of this failure is received by DM-1 at Event 21 after which DM-1 performs the recovery process similar to the way it did for deployment-time failure.

The one significant difference between the deployment-time failure mitigation and run-time failure mitigation is that dynamic reconfiguration of application components is required to mitigate application run-time failure. To elaborate, once DM-3 deploys the Receiver component in node-3 it needs to publish new connection information for the Receiver component allowing DM-1 to update Sender the component's connection.

III.6 Related Work

Deployment and configuration of component-based software is a well-researched field with existing works primarily focusing on D&C infrastructure for grid computing and Distributed Real-time Embedded (DRE) systems. Both DeployWare [35] and GoDIET [23] are general-purpose deployment frameworks targeted towards deploying large-scale, hierarchically composed, Fractal [19] component model-based applications in a grid environment. However, both of these deployment frameworks lack support for application reconfiguration.

The Object Management Group (OMG) has standardized the Deployment and Configuration (D&C) specification [77]. The Deployment And Configuration Engine (DAnCE)[82] describes a concrete realization of the OMG D&C specification for the Lightweight CORBA Component Model (LwCCM) [71]. LE-DAnCE [82] and F6 DeploymentManager [29] are some of our other previous works that extend the OMG's D&C specification. LE-DAnCE deploys and configures components based on the Lightweight CORBA Component Model [71] whereas the F6 Deployment Manager does the same for components based on F6-COM component model [81]. The F6 Deployment Manager, in particular, focused on the deployment of real-time component-based applications in highly dynamic DRE systems, such as fractionated spacecraft. However, similar to the work mentioned above,

these infrastructures also lack support for application adaptation and D&C infrastructure resilience.

A significant amount of research exists in the field of dynamic reconfiguration of component-based applications. In [11], the authors present a tool called Planit for deployment and reconfiguration of component-based applications. Planit uses AI-based planner to come up with application deployment plan for both - initial deployment, and subsequent dynamic reconfigurations. Planit is based on a *sense-plan-act* model for fault detection, diagnosis and reconfiguration to recover from failures. Another work presented in [4], supports dynamic reconfiguration of applications based on J2EE components. Although these solutions support application reconfiguration, none of them are themselves resilient.

The authors in [20] present the DEECo (Distributed Emergent Ensembles of Components) component model, which is based on the concept of Ensemble-Based Component System (EBCS). In general, this approach replaces traditional explicit component architecture by the composition of components into *ensembles*. An ensemble is an implicit, inherently dynamic group of components where each component is an autonomic entity facilitating self-adaptive and resilient operation. In [43], authors present a formal foundation for ensemble modeling. However, they do not focus on the management infrastructure required to deploy and reconfigure these components.

III.7 Concluding Remarks

This chapter presented a resilient Deployment and Configuration (D&C) infrastructure (synonymous to a management infrastructure) for extensible CPS. Since extensible CPS are dynamic and multi-tenant, a management infrastructure is required to manage lifecycle of distributed applications (see Challenge 1 in Section I.3). Furthermore, since resilience is of utmost importance for CPS in general, it is important for the management infrastructure to be resilient. In addition, since extensible CPS are remotely deployed, resilience should

be autonomous. Although CPS are generally built using Component-Based Software Engineering (CBSE) approach and there exists multiple component models with corresponding D&C infrastructure, none of these existing D&C infrastructures can be considered resilient.

The work presented in this chapter incurs a few limitations: (1) As mentioned in Section III.4.2, the current implementation for D&C state preservation is sufficient but not ideal as deployment information should ideally be stored persistently to avoid DM process failure, (2) The D&C infrastructure presented in this chapter performs reconfiguration without any smartness,*i.e.*, we randomly decide where a component should be migrated. However, this is not sufficient for systems that are dynamic and that can host multiple applications. We require the D&C infrastructure to utilize available system information to make a more educated decision on how a system should be reconfigured. This issue is addressed in the solution presented in the next chapter (see Chapter V and Chapter VI).

III.8 Related Publications

1. Subhav Pradhan, Abhishek Dubey, and Aniruddha Gokhale. Designing a Resilient Deployment and Reconfiguration Infrastructure for Remotely Managed Cyber-Physical Systems. *Lecture Notes in Computer Science (LNCS 2016)*, volume 9823. (To be published)

2. Subhav Pradhan, Aniruddha Gokhale, William R. Otte, Gabor Karsai. Real-time Fault Tolerant Deployment and Configuration Framework for Cyber Physical Systems. *Proc. of the RTSS - WiP Session (RTSS-WiP 2012)*, pages 32 - 32, San Juan, Puerto Rico.

3. Subhav Pradhan, William Otte, Abhishek Dubey, Csanad Szabo, Aniruddha Gokhale, and Gabor Karsai. Towards a Self-adaptive Deployment and Configuration Infrastructure for Cyber-Physical Systems. *Institute for Software Integrated Systems (ISIS) Technical Report, ISIS-14-102*, 2014, Nashville, TN, USA.

CHAPTER IV

ESTABLISHING SECURE INTERACTION ACROSS DISTRIBUTED APPLICATIONS

IV.1 Motivation

Consider the fractionated satellites cluster scenario presented as an example of extensible CPS in Section V.1. One notable example for the use of the publish/subscribe pattern in spacecraft software is NASA's Core Flight Executive (CFE), which is a portable platform-independent framework used as the basis for flight software for satellite data systems. The CFE uses publish/subscribe to facilitate communication between multiple applications. A review of the CFE revealed that the publish/subscribe style architecture not only allowed distributed development and easy integration of applications but also allowed applications to be encapsulated, which improved abstraction, flexibility, reuse and division of concerns [34]. Thus, supporting this pattern in space systems is highly desirable.

Unfortunately, not all technologies that support publish/subscribe communication have a comprehensive security model capable of partitioning information flows based on the security classifications of applications. However, security is a key requirement for open and distributed satellite clusters platforms since (1) space systems are extremely expensive and therefore cannot afford security compromises with long term effects on the system, (2) shared space systems are used by companies that are extremely sensitive about their data and therefore require a strict security model.

In order to address this issue, this chapter presents a novel discovery mechanism that ensures strict information partitioning by only allowing applications with compatible security classification levels to discovery, and therefore, interact with each other. This ensures strict information partitioning.

IV.2 Background and Problem Description

In order to better describe the problem at hand, this section first presents the system model. Second, it presents an overview of OMG DDS including its discovery mechanism. This is important since the middleware of choice for this work is OpenDDS [69], which is an open source implementation of the OMG DDS specification. Third, this section presents the problem statement in context of OpenDDS middleware.

IV.2.1 System Model

We consider each node of a satellite cluster to run a copy of the **D**istributed**RE**altime **M**anaged **S**ystem (DREMS) platform [29, 33]. The only difference between DREMS architecture and that presented in Section II.1, is that DREMS considers application components to be hosted inside actors. Actors are the building blocks of this information system and are similar to processes in traditional operating systems except that the Actor identifiers are unique across nodes and are not lost even after the death of the Actor. Actors can be of two types: (1) Application Actors, and (2) Platform Actors. Application Actors make up the mission-specific application functionality and can be dynamically installed or removed. Platform Actors are actors related to platform services and they are part of the Trusted Computing Base (TCB) [94, 95]. Applications hosted in our platform cannot bypass the TCB and access resources, such as the network.

IV.2.2 OMG DDS Overview

The OMG Data Distribution Service (DDS) specification [72] defines a data-centric communication standard for communication between DDS entities (data producers and consumers) in a wide variety of environments. A DDS application consists of *publishers* and *subscribers*, where publishers use *data writers* to produce data while subscribers use *data readers* to consume data. The DDS specification also supports Quality of Service

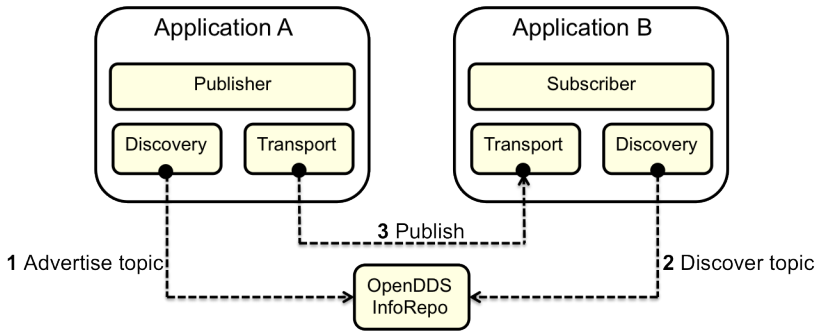


Figure 11: OpenDDS Centralized Discovery Mechanism

(QoS) policies which allows application developers to fine tune non-functional properties of a DDS middleware, and hence the communication between publishers and subscribers.

From an application's perspective, publishers and subscribers are anonymous; yet they need to communicate with each other. This necessitates a discovery mechanism. To discover and match publishers and subscribers (and therefore data writers and data readers), the DDS middleware uses a *discovery service*. Even though the exact implementation of this discovery service varies from one implementation to another, a common requirement for this service is to be able to discover matching publishers and subscribers and to establish connections between them. To perform this matching, the discovery service uses *topics*. A topic is a data type that serves the purpose of matching publishers and subscribers. Communication between a data writer and a data reader does not occur unless the topic published by the writer matches the topic subscribed to by the reader. Figure 11 illustrates the centralized discovery mechanism used by OpenDDS.

IV.2.3 Problem Statement

Since we use OpenDDS to provide publish/subscribe capabilities to applications with different security classifications, we require it to support appropriate information partitioning mechanisms. However, OpenDDS, as it stands currently, does not support any specific security policy. It is important to note here that there is a DDS security specification in development [75] and RTI DDS [47], which is another implementation of OMG DDS,

has recently implemented this specification. However this specification relies on the correct operation of the application and middleware to configure and enforce these policies. Furthermore, relying on security model supported by the middleware itself requires us to consider the entire middleware as part of the TCB [94, 95].

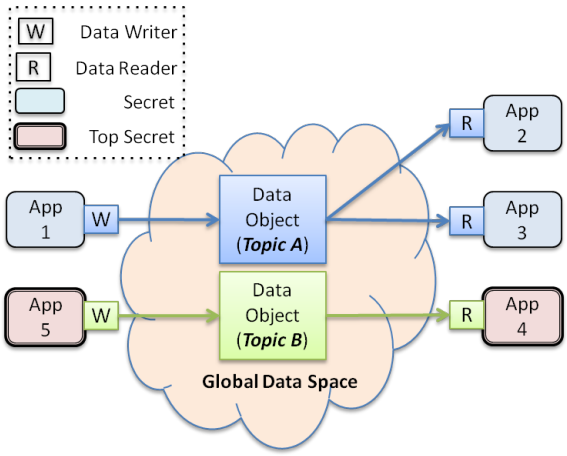


Figure 12: Topic based application interaction in OMG DDS

Existing DDS entities, such as topics and partitions cannot be used as mechanisms to enforce information partitioning based on security labels since applications associated with the same topic can have different security classifications. A naive solution would be to create a topic for each security label, as shown in Figure 12. However, this approach has a number of problems. First, it makes the applications responsible to subscribe to topics that are appropriate to their security level. Second, this approach also relies on higher security level applications to correctly refrain from publishing samples to topics to which lower security level applications are subscribed to. Both these shortcomings are unworkable, as we cannot trust applications to behave correctly.

IV.3 Solution Approach

This section presents the solution. To do so, this section first presents the target system model as variance of the system model presented in Section II.1. Second, this section

presents brief description of the underlying Secure Transport (ST) mechanism[1], since our solution leverages capabilities of the ST. Finally, this section presents detailed description of the novel discovery mechanism.

IV.3.1 Secure Transport

Secure Transport (ST) is a novel transport mechanism implemented in the OS kernel that (1) restricts the communication pathways that can exist between any two processes on the same computing node or on different computing nodes, (2) supports both unicast as well as multicast transfers, (3) supports message authentication before transmission and reception according to rules of a Multi-Level Security (MLS) policy [16, 29, 101], and (4) provides packet level encryption for messages using IPSec [2].

MLS defines a policy based on partially ordered security labels that assign classifications and need-to-know categories to all information that may pass across process boundaries. This policy ensures that information is allowed to flow from a producer to a consumer in DDS if and only if the label of the consumer is greater than or equal to that of the producer. Both the allowed communication topology and the MLS policy labels must be configured for each task by the secure discovery mechanism, which uses processes with elevated system privileges to do so. By designing a solution that resides at the level of a transport mechanism, we shield higher-level middleware, such as OMG DDS, from invasive changes while at the same time providing them an opportunity to leverage these new mechanisms.

Secure Transport (ST) comprises two key concepts: (1) endpoints, and (2) flows and message transfer rules. These concepts are described below.

[1] Detailed description of ST mechanism is not part of this dissertation and can be found in [80].
[2] The IPSec implementation in ST is the subject of ongoing work

IV.3.1.1 Endpoints

Endpoints are the basic communication resources used by applications to transmit and receive messages; they are analogous to socket handles in the traditional BSD socket APIs. Like traditional sockets, user space programs pass an endpoint identifier to the `send` and `receive` system calls. Unlike traditional sockets, however, unprivileged tasks may not arbitrarily construct endpoints that allow for inter-process communication with other tasks; such endpoints must be explicitly configured by a privileged Actor that is part of a trusted system configuration infrastructure. All endpoints are configured with a set of security labels that can be used for sending messages through that endpoint.

Endpoints are separated into four different categories with different restrictions on their creation and use; for the purposes of this discussion, we will describe only two endpoint classes that are used for Inter-Process Communication (IPC):

- **Local Message Endpoints (LME)**: Local message endpoints are the basic method for IPC and may be used to send messages to other actors. These endpoints must be configured by the trusted system configuration infrastructure and are subject to restrictions placed by flows and security rules.

- **Remote Message Endpoints (RME)**: Similar to LMEs, RMEs are a mechanism for network IPC between Actors, but may be used to communicate with Actors hosted by different operating system instances.

IV.3.1.2 Flows and Message Transfer Rules

Communication in ST is allowed between two LMEs or RMEs if and only if there exist mutually compatible *flows* on each endpoint. A flow can be thought of as a logical pipe between two endpoints and determines the direction in which messages can travel. It provides system integrators the ability to specify the actors that are allowed to share

messages. The actual transfer of the message is further restricted by the MLS rules (see below).

More concretely, a flow that is assigned to an endpoint is a connectionless association with an endpoint owned by a designated Actor. This association determines if the local endpoint is allowed to send or receive messages with the remote endpoint. Unicast flows connect a source endpoint to a destination endpoint; multicast flows connect a source endpoint to multiple destination endpoints.

In all cases, the flow assignment between two endpoints must be mutual in order for communication to succeed. Additionally, each message must be marked with the specific label that indicates the security classification of that message. Message transmission is allowed if and only if the following rules are satisfied. We refer the readers to [33] for a full list of formal MLS rules.

- The label of the message must be within the label set of the sender endpoint.
- The sender must have an outbound flow to the recipient, and the recipient must have a inbound flow from the sender.
- The receiver's endpoints label must be either at the same classification level or at a higher classification level of the received message. Thus, a lower classification application cannot extract information from a higher classification application on the reply path for a two-way communication because the labels on the return path do not satisfy the MLS rules.

Performing message exchange via endpoints and flows enables decoupling between senders and receivers, which operate only on their local endpoints without explicit knowledge of the flows attached to those endpoints. For example, the flow connecting a client to a failed server can be switched over to an alternative server transparently to the client.

IV.3.2 A Secure Discovery Mechanism

In order to describe the discovery mechanism in detail, we first need to understand how the Deployment and Configuration (D&C) infrastructure in DREMS works because it is responsible for assigning the security labels, setting up endpoints and the flows between communicating actors and ultimately playing a key role in the secure discovery. The DREMS D&C is almost identical to the D&C infrastructure described in Chapter III. The only difference is that the former extends the latter by adding aforementioned capabilities related to the secure discovery mechanism.

IV.3.2.1 Overview of the D&C Infrastructure

The D&C infrastructure is responsible for the deployment and configuration of component-based applications. Once an application is deployed, the D&C infrastructure is also responsible for managing the application's lifecycle throughout its lifetime. The D&C infrastructure is an implementation of the OMG D&C specification [78][3].

In a cluster there is exactly one Cluster Deployment Manager (CDM), which is responsible for orchestrating the deployment and configuration (D&C) of applications across multiple nodes in the cluster. Each node has a single Node Deployment Manager (NDM) that is responsible for taking node-specific actions. The CDM and NDM are Platform Actors and are therefore considered to be part of the TCB. Finally, each node can have multiple Component Servers (CS), which are spawned by NDMs as per requirement. All parts of an application, *i.e.*, component servers, components, and secure transport endpoints are created by the D&C infrastructure according to a deployment plan, which is created by a trusted system integrator. The trusted system integrator is also responsible for assigning MLS labels to different applications.

[3]This is not the same as the D&C infrastructure presented previously in Chapter III

IV.3.2.2 An Architecture for Secure Discovery Mechanism

The discovery mechanism discussed in this section leverages existing discovery capabilities provided by OpenDDS. OpenDDS supports two forms of discovery mechanisms: (1) using a centralized information repository called the *InfoRepo*, and (2) using a peer-to-peer approach where participating DDS applications discover each other in a collaborative way rather than using a centralized information repository.

The peer-to-peer discovery approach requires all applications in a network be able to communicate each other's existence in order to perform discovery. This is not a workable solution for our purpose as the communication restrictions enforced by ST mechanism preclude any two unprivileged application processes spontaneously connecting with each other. In addition, an application with lower security label must not be able to discover the existence of other applications with a higher security label. Since we cannot use the peer-to-peer discovery mechanism, our solution extends the centralized discovery service provided by OpenDDS. Our extended capabilities require the following functionalities:

- The discovery mechanism should be able to establish Secure Transport information flows between data writers and data readers of applications with matching security labels. Since ST is a transport mechanism implemented in the kernel itself, it requires the discovery mechanism to have elevated system privileges to create ST endpoints and establish ST information flows.
- In addition to the discovery mechanism itself having system privileges, it should only interact with other processes with system privileges. This prevents the centralized repository from being a target of "data-at-rest" attacks.
- Normally, a discovery mechanism only checks for topic and relevant Quality of Service (QoS) parameters when matching data writers and data readers. However, since we are using the concept of security classification represented by security labels, we require that the discovery mechanism also check these security labels during the discovery process.

Table 4: Entities involved in the Secure Discovery Mechanism.

Entity	Functionality
DDS Entity	This represents the various DDS related entities such as domain participants, data writers and data readers. These entities are part of a user's component-based applications and therefore hosted inside their respective Component Servers (CSs).
DCPSInfo	A singleton used to keep track of various DDS entities created by different applications and inform the DDS middleware.
CS ORB	This is the default CORBA Object Request Broker (ORB) [73] that is created when a CS is instantiated by a Node Deployment Manager (NDM). This ORB is used by the CS to communicate with its parent NDM.
Discovery Callback	All new data readers and data writers register a callback object, which is used by the discovery mechanism to provide information regarding data reader/data writer matches.
DictM Proxy	Since NDMs do not have access to the Dictionary Manager (DictM), this proxy is used for communicating with the DictM, which is collocated with the CDM.
Callback Proxy	The Callback proxy is created by the DictM proxy. Upon creation of the Callback proxy, the DictM proxy provides this information to the DictM. This is important because the DictM provides the data reader/data writers match information to the Callback proxy, which in turn uses this information to establish the ST flows between endpoints used by matching data readers and writers. The Callback proxy uses the ST interfaces to create these flows. Note that the ST flows must be established before the DDS middleware can establish connection between data readers and data writers by using their respective callback objects.
DM ORB	This is the ORB used by the NDM and CDM to communicate with each other.
DictM	The Dictionary Manager (DictM) is a Platform Actor collocated with the CDM. It acts as a central information repository, which is notified every time a new data reader or data writer is created. Upon creation of a new data writer, the DictM updates information content and upon creation of a new data reader, the DictM finds a matching writer (if any) and propagates this information to the callback objects of the created data readers.

To address these challenges and since we build on top of OpenDDS' centralized approach, a centralized discovery mechanism called the *Dictionary Manager (DictM)* is used. The DictM is a Platform Actor and therefore has system privileges to establish Secure Transport information flows and it only interacts with other Platform Actors.

Figure 13 presents the architecture for the secure discovery mechanism showing how it leverages the D&C infrastructure (and hence the TCB). Table 4 enlists the functionalities of these entities. Figure 14 presents sequence diagrams illustrating (1) creation of a data writer, and (2) association of a data reader with an existing data writer.

As shown in Figure 14, to create a data writer, first the Component Server creates a DDS domain participant which in turn is used to create the data writer. Both the domain

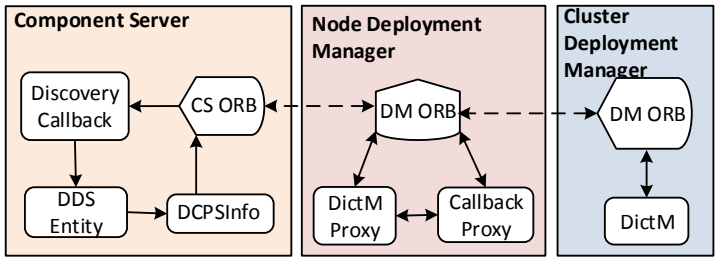


Figure 13: Discovery Architecture. Table 4 describes the entities shown in this figure.

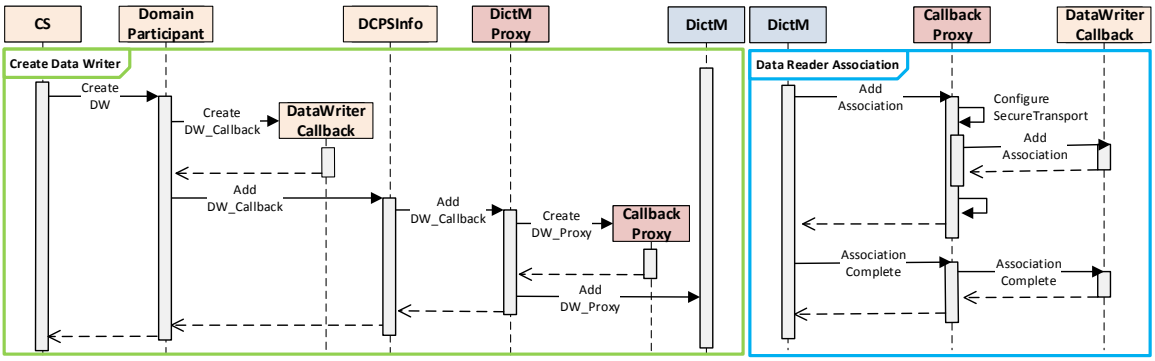


Figure 14: Sequence Diagram illustrating the process of (1) Data Writer Creation, and (2) Data Reader Association.

participant and data writer are DDS Entities. The domain participant also creates a data writer callback, which is the Discovery Callback that will later be used to inform the data writer about matching data readers. Once the data writer callback object is created, this information is propagated to the DCPSInfo and DictM Proxy, which in turn creates a Callback Proxy and sends this information to be stored in the DictM.

Data reader creation follows the same pattern as that of a data writer. Once the data reader is created and this information is propagated to the DictM, it finds the matching data writer and adds the association. This process is also shown in Figure 14. Adding an association consists of configuring a ST flow between endpoints of the matched data reader

and data writer. Once the ST flow is established, the association is complete and now the DDS middleware can establish a connection between the data writer and the data reader.

IV.4 Experimental Evaluation

This section evaluates our solution in the context of a use case scenario. Since the Secure Transport (ST) leverages IPv6, we also compare the effective performance of ST against native IPv6; both transmitted over the same physical medium. This evaluation is important since ST will be used for all the secure communication by our system and hence the cost of using such a mechanism must be understood prior to its use.

IV.4.1 Experimental Setup

Figure 15 presents the setup of our experiment comprising two applications. These applications use DDS for communication. Each application consists of a *publisher* and *subscriber*. App-1 is hosted on node-1 and has security label *unclassified*, whereas, App-2 is hosted on node-2 and has the security label *secret*. App-2's security label thus dominates the label of App-1, and hence only App-1 is allowed to send information to App-2.

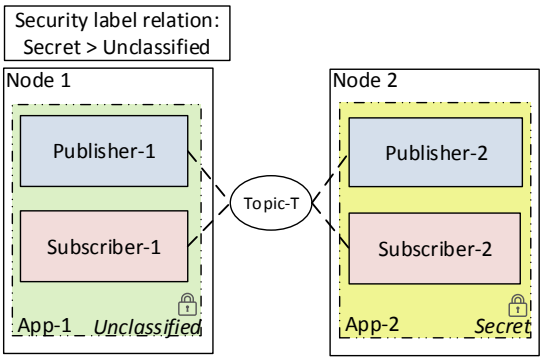


Figure 15: Use case scenario: Two DDS Applications with Different Security Labels.

Based on the setup mentioned above, the subscriber in App-2 should be able to receive messages published by publishers in both App-2 and App-1. However, the subscriber in

```
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <0>
[LM_DEBUG] - 23:45:17.824504 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:18.707008 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <1>
[LM_DEBUG] - 23:45:18.708406 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:19.707905 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <2>
```

Figure 16: App-1 Log Snippet which shows that App-1 only receives messages published by itself and not from App-2 since the latter has higher Security Label.

```
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App2> Hello World.  Test message from Provider <12>
[LM_DEBUG] - 23:45:17.183886 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:17.738411 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <0>
[LM_DEBUG] - 23:45:17.739916 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:18.180700 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App2> Hello World.  Test message from Provider <13>
[LM_DEBUG] - 23:45:18.182083 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:18.706913 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <1>
[LM_DEBUG] - 23:45:18.708378 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:19.180884 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App2> Hello World.  Test message from Provider <14>
[LM_DEBUG] - 23:45:19.183357 - MessageDispatcher::execute_message - Message executed
[LM_DEBUG] - 23:45:19.706862 - MessageDispatcher::execute_message - Deadline_type = DLT_NONE. Execute CMObject.
CONSUMER EVENT: Consumer_Message_data_listener_exec_i::on_one_data: received message <App1> Hello World.  Test message from Provider <2>
```

Figure 17: App-2 Log Snippet which shows that App-2 receives messages published by both itself and App-1 since it has higher Security Label than App-1.

App-1 should only be able to receive messages published by a publisher in App-1 since App-2 is publishing messages with higher security label. To demonstrate this behavior, Figures 16 and 17 present log message snippets[4] captured during the execution of the above-described use case with the appropriate App shown circled.

IV.4.2 Secure Transport Network Utilization

The Secure Transport (ST) mechanism presented previously in Section IV.3.1 is built on top of IPv6. With any communication protocol, performance is a key concern, so the effective performance (i.e., network utilization) of ST versus native IPv6 transmitted over Ethernet was evaluated. First the overhead of the protocol and its average and maximum

[4]These log message snippets have been slightly modified in order to exclude irrelevant log messages.

throughput were calculated and compared to native IPv6. Since ST is built on top of IPV6, each ST packet on the network incurs the same header overhead as an IPv6 packet.

Table 5: Network Utilization Calculations for IPv6 and for Secure Transport tunneled through an IPv4 network.

	Message Utilization (8192B)
IPV6	0.927956502
Minimum ST Header	0.924396299
Average ST Header	0.921692169
Maximum ST Header	0.820348488

Additionally, each message includes a ST-specific header containing information about the sending actor, the flow, the security labels, etc. This ST header is a minimum of 34 bytes for the smallest security label, averages around 60 bytes for most security label lengths, and has a maximum of 1,052 bytes for the longest security labels. Since a ST message can be up to 8 Kilobytes and an Ethernet packet is at most 1500 bytes, only one transmitted packet of each message will have the ST header. Since our test network on which we run IPv6 and ST is a tunneled 6-to-4 network, we must add the IPv4 header length to our total packet header. Finally, we choose UDP as our transport protocol for both IPv6 and the underlying ST protocol, so UDP's 8 byte header must be taken into account. The network utilization calculations are presented in Table 5. These calculations are based on experiments executed on a private testbed of nodes connected to each other through a gigabit Ethernet switch.

IV.5 Related Work

The OMG DDS specification, as currently specified, lacks an extensive security specification and therefore all DDS implementations lack a well-established security model. However, RTI [47] and PrismTech [89] have combined their efforts to put forward a DDS security proposal [75]. This proposal focuses on providing fine-grained, data-centric security by providing (1) access control per DDS topic, (2) read/write permissions for related

DDS entities, and (3) field-specific permissions, which allow different fields of a particular topic to have different permissions.

Even though this proposal is critical to the advancement of the state of the art in DDS, however, a key issue that we have identified is that it relies on applications to correctly configure the security policies required, and the middleware to correctly enforce them. This requirement is fundamentally incompatible with a threat model where applications cannot be trusted. Furthermore, unlike our approach, this proposal is directed towards a solution that involves the entire DDS middleware to be part of the security model and therefore the TCB. Since the TCB is assumed to be trusted, care should be taken to keep its size small. Thus, maintaining the entire DDS middleware in the TCB is infeasible.

Similarly, prior efforts [14, 93] also require the entire DDS middleware to be part of the TCB. In [93], the authors present an approach in which Authentication and Authorization (AA) is embedded in the discovery mechanism which is implemented as a special network application located within the DDS Real-time Pub/Sub (RTPS) layer. This approach differs from ours since we place the centralized repository, used for discovery, outside of the DDS middleware. The work presented in [14], focuses on integrating Role-based Access Control (RBAC) with pub/sub communications. RBAC is similar to MLS in that the different roles (security labels) provide principals (actors) with different services (access restrictions). However, RBAC allows for the roles, in our case security labels, of a principal to change during the lifetime of the application, something that we do not support as we consider such flexibility as a potential source of attack.

[83] presents the notion of microguards for data access restrictions. Microguards are distinct from the pub/sub middleware and are placed on domain boundaries to facilitate information sanitization via transitioning policies between any two domains. The authors argue that these microguards can be configured to perform checks that realize MLS policies. A limitation with guards is that they tend to be very specific to a data type and do not support generic data communications. Also, in their network configuration, the guards sit

between networks or systems and connects them. They are not part of an actual system so it is possible to use a different communication path to bypass the security enforced by these guards. Such bypassing is not feasible in our solution. Furthermore, in our approach, all of the MLS-related label checks are done by a single entity that provides the discovery service rather than by distributing the task among multiple guards which introduces unnecessary complications and leads to an increase in the number of possible points of attack.

The Component Information Flow (CIF) framework presented in [3] provides a way of achieving data integrity and confidentiality during both intra- and inter-component communication. Labels are assigned to component ports at design-time via a policy file. However, that work has some limitations with the type of systems considered here because it supports label checking only at design and compile time.

IV.6 Concluding Remarks

This chapter presented a novel discovery mechanism that helps establish secure interaction between applications with varying security levels. This contribution is important for extensible CPS, such as a satellite cluster, because of the open nature of these systems in which applications from different vendors are likely to be simultaneously hosted on the shared resource. As such, it is of utmost importance to devise a mechanism that facilitates strict information partitioning between different applications to prevent data breaches by ensuring only compatible applications entities can communicate with each other.

To that end this chapter presented (1) Secure Transport (ST), which is a transport mechanism that supports Multi-Label Security (MLS) labels and policies to represent and validate security classifications, and (2) a secure discovery mechanism that is capable of establishing Secure Transport flows between DDS publish/subscribe applications with matching security classifications. The use of a transport-level security mechanism ensures that no invasive changes need to be made to the middleware. The results show that our system provides the necessary information partitioning and that the overhead of the ST is negligible.

IV.7 Related Publication

1. Subhav Pradhan, William Emfinger, Abhishek Dubey, William Otte, Daniel Balasubramanian, Aniruddha Gokhale, Gabor Karsai, and Alessandro Coglio. Establishing Secure Interactions Across Distributed Applications in Satellite Clusters. *Proc. of the 5th IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT 2014)*, pages 67 - 74, Laurel, Maryland, USA.

CHAPTER V

ACHIEVING RESILIENCE IN EXTENSIBLE CPS VIA SELF-RECONFIGURATION

V.1 Motivation

This chapter focuses on resilience of extensible CPS. Consider a mobile cyber-physical platform of fractionated satellite, which is a cluster of independent satellite modules flying in formation and communicating with each other via ad-hoc wireless networks. Each independent satellite that is part of a fractionated satellite cluster, can come from different organization. This architecture can realize the functions of monolithic satellites at a reduced cost and with improved adaptability and robustness [18]. Several existing and future missions use this type of architecture, including NASA's Edison Demonstration of SmallSat Networks, TANDEM-X, PROBA-3, and PRISMA from Europe. In each of these missions, the cooperating fractionated satellites are expected to provide the foundation for applications running simultaneously using shared resources.

Each satellite modules of a fractionated satellite cluster are present in the Low Earth Orbit (LEO), where one of the basic requirements is to be able to maintain orbital flight so that they can overcome the atmospheric drag and orbit the Earth while remaining in the LEO. Each individual satellite achieves this objective by periodically using their thrusters to adjust their position. In addition to this critical objective, other objectives can be added by hosting different applications. Figure 18 presents an overview of a fractionated satellite cluster hosting two different component-based applications with mixed criticality. The first application is a high-priority *Cluster Flight Application* (CFA), which is responsible for maintaining flight control. The second application is lower priority *Image Processing Application* (IPA), which is responsible for capturing and processing real-time images.

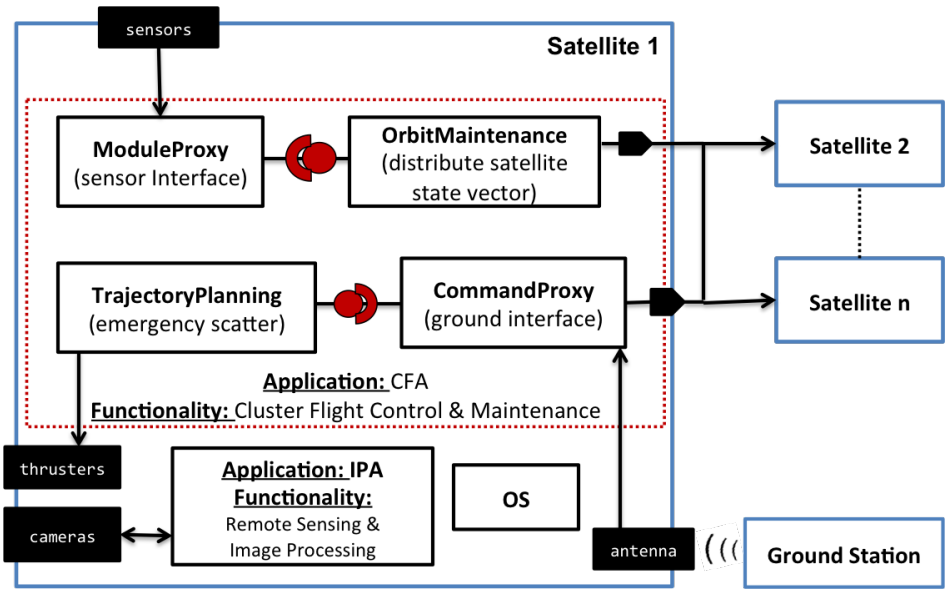
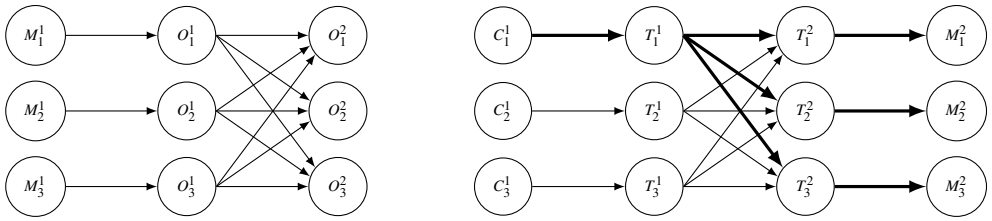


Figure 18: Distributed Deployment of Applications with mixed-criticality on a Fractionated Satellite Cluster.

As shown in Figure 18, the high-priority CFA application comprises four different components. Next, we briefly describe the different functions provided by these components. A schematic overview of the associated tasks performed by these components is presented in Figure 19.

- **ModuleProxy**: This component behaves as an interface between different satellite sensors and the *OrbitMaintenance* component, allowing the *OrbitMaintenance* component to access available sensors.
- **OrbitMaintenance**: This component is responsible for tracking the state of a cluster satellite. To perform this task, it uses the *ModuleProxy* component to acquire the latest information, such as location co-ordinates. Once appropriate information is collected, this component is also responsible for disseminating this information as a packaged structure to all other satellites in the cluster. As every satellite runs an instance of CFA, each node periodically receives updates from the other nodes.
- **CommandProxy**: This component performs the task of receiving commands from a ground station. When a command is received, it sends the command to its local



Task	Component	Activity
M^1	*ModuleProxy*	Inform O^1 of new state
M^2		Activate engine
O^1	*OrbitalMaintenance*	Publish new state
O^2		Subscribe to new state
T^1	*TrajectoryPlanning*	Publish new command
T^2		Subscribe to new command
C^1	*CommandProxy*	Inform T^1 of command

Figure 19: Tasks performed by components of the *Cluster Flight Application*. For these tasks, the subscript represents the ID of the node onto which a task is deployed. The total latency of the interaction $C_1^1 \rightarrow M_N^2$ represents the total latency between receiving the *scatter* command and activating the thrusters. This interaction pathway is in bold.

TrajectoryPlanning component. Furthermore, commands received from a ground station are also forwarded to other satellite nodes in a cluster.

- **TrajectoryPlanning**: This component is responsible for performing the task of receiving commands from the local *CommandProxy* component and responding to those commands using satellite thrusters, if required, to perform highly critical, hard real-time tasks.

The lower priority IPA is a comparatively simpler application. It comprises a component that uses the camera to capture real-time images (sensing) and another component that processes the captured images. These are periodic CPU-intensive tasks that are temporally isolated [88] from each other. As mentioned before, the IPA is a lower priority application when compared to the CFA. As such, the IPA tasks are executed by application threads that have lower priority than that of the CFA.

Extensible CPS like the fractionated satellites host mission critical applications that

necessitate support for resilience mechanisms. In addition to hosting mission critical applications, platforms like fractionated satellites are remotely deployed and therefore require autonomous resilience. Self-reconfiguration is one way to achieve autonomous resilience. In addition to runtime self-reconfiguration mechanisms, design-time analysis and verification are also important since they can be used to perform admittance checks on applications at design-time before they are deployed on the target system. It is important to find errors and anomalies as quickly as possible since a small error at design-time, such as a Quality-of-Service (QoS) requirement mismatch, can propagate and quickly affect other applications, sub-systems, or an entire system.

V.2 Background and Problem Description

In order to describe the problem at hand, this section first presents a mechanism used to describe extensible CPS. Then the resource and deployment models are presented. Finally, this sections presents the problem statement.

V.2.1 Goal-based System Description

Extensible CPS are dynamic in nature and therefore require a generic way to represent system goals expected to be satisfied by a system during a given time interval. A time interval sequence consisting of high-level system objectives that must be available during those intervals is called a mission *goal*. Different systems associated with a cyber-physical platform are mission oriented and therefore have specific mission goals. Since objectives are essentially functions, system *objectives* can be defined using the concept of functional decomposition, which is the process of decomposing high-level functions into a set of sub-functions, until a set of leaf-level functions is reached. Leaf-level functions are functions that cannot be decomposed, and they are mapped to components [52, 61] that provide these functions as *services*. Services are provided or required by components through their

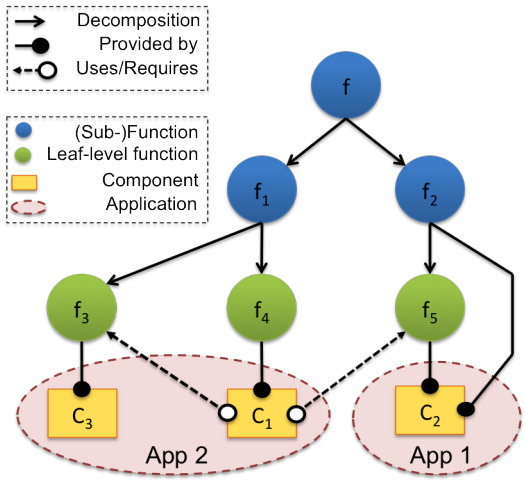


Figure 20: Functional Decomposition Graph for a simple two-application System.

ports. This approach of goal-based system description is not novel as it has been previously presented in [24, 92]. However, the work presented in this chapter, as well as, the next (see Chapter VI) uses the goal-based system description approach for management of distributed applications.

Components are the basic unit of system composition. As shown in Figure 20, a component can provide one or more functions (leaf-level or non leaf-level) via its ports. Furthermore, different components can provide the same functionality. If a functionality is provided by multiple components, then any of those component can be deployed; this allows more flexibility. Similarly, a component can also require one or more functions via its ports. This provided and required relations between components and functions allow us to establish dependencies between components. In addition to functions, a component can also require resources in order to be considered available. As such, we classify a component's requirement into *functional requirements* and *resource requirements*.

Figure 20 presents the functional decomposition graph of a simple two-application system. As shown in the figure, function f is a high-level function that represents a system's objective. Function f can be decomposed into sub-functions f_1 and f_2. Sub-function f_1 can be further decomposed into leaf-level functions f_3 provided by component C_3 and f_4

provided by component C_1. Similarly, sub-function f_2 can be decomposed into leaf-level function f_5 provided by component C_2.

Definition 1. *A functional decomposition is a directed acyclic graph (DAG), $FD = (F, DE)$, where F is the set of functions, and $DE = F \times F$ is the set of dependency edges. The functions with zero indegree are called functions while the others are called sub-functions.*

Definition 2. *A software component is a collection, $C = (P, S, R)$, where P is a set of ports associated with a component, S is a set of functions provided by a component, and R is a set of requirements.*

Definition 3. *An application is a graph of components, $G = (C, E)$, where $E \subseteq C \times C$ represent the control/data flow dependencies between components. These dependencies impose operational requirements on components. That is, unless specified otherwise, a component requires all other components to which it is connected to be available.*

V.2.2 Resource Model

The physical computing infrastructure provides *computation* and *communication* resources. Computation resources correspond to hardware facilities required to execute computation tasks at a given computation node. These include processing speed (number of instructions per second), memory size (amount of memory required), and specific hardware required for certain tasks such as sensing or signal processing. Communication resources on the other hand correspond to facilities required for interaction between tasks executing on different computation nodes. This includes communication bandwidth, available security measures such as encryption, etc.

The resource model represents the capabilities and evolution of resources that are used to carry out a mission, as a function of control inputs (actions) applied to the resources. For example, the resource specification for a network link would include capability specifications like the maximum data flow capacity of the link. It would also include the possible discrete states of the link, such as whether it is in service or broken.

V.2.3 Deployment Model

Deployment means instantiating a set of components and mapping them to available physical resources. Given a set of currently deployed and active applications and a set of components included in the application, we can deduce the set of system functions that can be supported.

Definition 4. *A deployment $D = (d_V)$ is a function that maps software structure SC, which is a set of component instances and their inter-dependencies, to a hardware network $HC = (N, L)$, which is a DAG, where N is the set of nodes, and $L = N \rightarrow N$ is the set of links between these nodes. A communication link resource function is a function $N \times L \Rightarrow \mathbb{N}$ that represents the capacity of a specific communication link on a node. $d_V : C \rightarrow N$, where C is a set of components.*

V.2.3.1 Alternate Deployment Configurations

Two deployment configurations are considered to be alternatives if they deploy the same set of applications on the same physical architecture within the same resource constraints while satisfying the same set of goals. Alternate deployment configurations could be compared against each other on the basis of resource cost and performance.

V.2.3.2 Configuration Space and Configuration Points

The configuration space of a platform represents the state space of the platform. This includes (1) goal-based system description of different systems hosted on the platform, (2) resource requirements of different components that are part of the system description, (3) nodes that comprises the platform and their corresponding resources, such as memory, storage, and devices, and (4) deployment constraints that determine whether components should be collocated on the same node, distributed across different nodes, or always deployed on a specific node. A configuration space can expand or shrink depending upon addition or removal of related entities.

A configuration space can contain multiple configuration points. A configuration point represents valid configurations of all systems that are part of the associated configuration space. A valid configuration of a system represents component to node mappings (deployment) for all components that are required to satisfy the system's goal. We always begin with a valid configuration point, which we call the initial configuration point. Initial configuration point represents the initial deployment of different systems. Similarly, current configuration point represents the current deployment. A configuration point, since it is a component-to-node mapping, can be represented using a component-to-node matrix defined below.

Definition 5 (C2N matrix)**.** *A C2N matrix comprises rows that represent component instances and columns that represent nodes; the size of this matrix is $\alpha \times \beta$, where α is the number of component instances and β is the number of available nodes (Equation V.1). Each element of the matrix is encoded as a Z3 integer variable whose value can either be 0 or 1 (Equation V.2). A value of 0 for an element means that the corresponding component instance (row) is not deployed on the corresponding node (column). Conversely, a value of 1 for an element indicates deployment of the corresponding component instance on the corresponding node. For a valid C2N matrix, a component instance must not be deployed more than once (Equation V.3).*

$$C2N = \begin{bmatrix} c2n_{00} & c2n_{01} & c2n_{02} & \dots & c2n_{0\beta} \\ c2n_{10} & c2n_{11} & c2n_{12} & \dots & c2n_{1\beta} \\ c2n_{20} & c2n_{21} & c2n_{22} & \dots & c2n_{2\beta} \\ & & \dots\dots\dots\dots\dots & & \\ c2n_{\alpha 0} & c2n_{\alpha 1} & c2n_{\alpha 2} & \dots & c2n_{\alpha\beta} \end{bmatrix} =$$

$$c2n_{cn} : c \in \{0 \dots \alpha\}, n \in \{0 \dots \beta\}, (\alpha, \beta) \in \mathbb{Z}^{+} \tag{V.1}$$

$$\forall c2n_{cn} \in C2N : c2n_{cn} \in \{0,1\} \tag{V.2}$$

$$\forall c : \sum_{n=0}^{\beta} c2n_{cn} <= 1 \tag{V.3}$$

At any given point in time only one of the configuration point reflects the reality of the deployed system; this is the current configuration point. All other configuration points are implicitly present in the configuration space, but have to be computed dynamically at runtime. This is precisely what happens when a failure is detected. When a failure occurs, current configuration point is marked as faulty, specifically some component(s) or node(s) are marked as faulty, rendering corresponding row (s) or column (s) of the the *C2N* matrix with 0 markings and a constraint that it cannot be used in future unless the fault has been removed. For example, consider a scenario where multiple configuration points maps one or more components to a node. If this node fails, then all aforementioned configuration points are rendered faulty. Given these concepts of configuration space and points, recovering from failure essentially involves self-reconfiguration of the system by finding a new valid configuration point and determining actions required to transition from current (faulty) configuration point to the new (desired) configuration point. As such, configuration points and their transitions form the very core of our self-reconfiguration mechanism.

For a more detailed description of a configuration space and its configuration points, please refer to our previous work [85], which presents a feature model that we use to represent a configuration space.

V.2.4 Problem Statement

Extensible CPS can host numerous mission critical cyber-physical applications. Each application consists of components providing different functions to meet various objectives and therefore the mission goal. As such, it is of utmost importance to make sure that all

functions and their corresponding components required to maintain a system's goal are preserved in the face of failures and anomalies. Therefore, for cyber-physical platforms, such as the fractionated satellite cluster described as a motivating scenario in Section II.4, resilience is a key requirement. We adopt the definition of resilience from [54]: "The persistence of the avoidance of failures that are unacceptably frequent or severe, when facing changes." Although a truly resilient system needs to be resilient against failures, changes (intended or unintended), and updates, this dissertation focus only on resilience against failures.

We identify the following as requirements that need to be satisfied to achieve cyber-physical platforms that are capable of supporting autonomous resilience:

Requirement 1 - Design-time analysis tools for admittance checking: Application requirements, such as timing and network QoS requirements, and properties like resilience should be analyzed and validated at design-time.

Requirement 2 - Runtime mechanism to facilitate autonomous resilience: We require a distributed runtime mechanism capable of providing autonomous resilience. Any such mechanism should be able to monitor, detect, diagnose, and mitigate failures.

There exists multiple solutions to satisfy *Requirement 1* [32, 51]. As a minor contribution associated with *Requirement 1*, this chapter presents a novel design-time tool capable of performing resilience analysis. Most of the work presented in this chapter focuses on *Requirement 2*. There exists significant amount of research literature related to failure monitoring, detection, diagnosis, and mitigation. Most of this can be leveraged for extensible CPS, however, existing solutions for failure mitigation cannot be used as they do not take into account the scale and the dynamic nature of these platforms. As such, the contribution of this chapter is a novel self-reconfiguration mechanism that facilitates autonomous resilience.

V.3 Solution Approach

This section presents the solution in detail. First, an overview of the solution approach is presented. Second, the design-time resilience analysis tool is presented. Third, the runtime infrastructure for self-reconfiguration mechanism is presented.

V.3.1 Overview of the Solution Approach

An overview of our solution approach is shown in Figure 21; it comprises design-time and runtime aspects. The design-time aspect of the solution includes a graphical modeling tool developed using the Generic Modeling Environment (GME) [55], associated model interpreters, a design-time resilience analysis tools (described in Section V.3.2), and a database to store artifacts generated and analyzed by aforementioned interpreters and analysis tools. The database is also part of the runtime aspect. We can view this database as a medium through which relevant information is shared between entities of the design-time and runtime entities. In addition to the database, the runtime aspect also includes a management infrastructure, a managed system, a monitoring infrastructure, and a resilience infrastructure. These runtime entities form an autonomous resilience loop akin to a *sense-plan-act* loop, which is the basis of our approach to realizing a self-reconfiguring system.

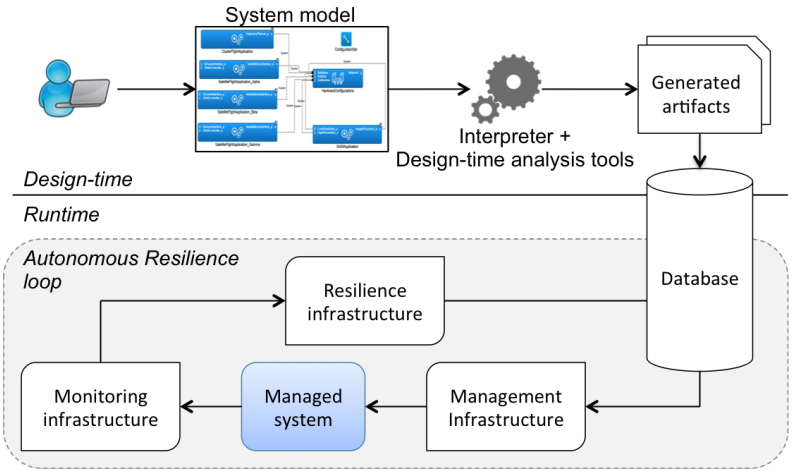


Figure 21: Overview of the Solution Approach.

The monitoring infrastructure performs the task of sensing; it is responsible for monitoring a managed system to detect and diagnose failures. The resilience infrastructure performs the task of planning; it is responsible for covering the self-reconfiguration mechanism. Finally, the management infrastructure performs the task of acting; it is responsible for undertaking actions computed (planned) by the resilience infrastructure. In our implementation, which is described in detail in Section V.3.3, the monitoring infrastructure comprises distributed monitors for failure detection, the resilience infrastructure comprises a Satisfiability Modulo Theories (SMT) [15] based solver, and the management infrastructure comprises distributed Deployment Managers (DMs), where a single DM is deployed on every node.

A typical workflow is as follows. The user begins by creating a model and defining components, which provide the basic units of functionality. The definition of a component includes its communication ports and timing requirements. Next, one or more applications are created by assembling components together and configuring their communication. For instance, the output port of one component may be connected to the input port of another component. Based on applications that need to be deployed on the target platform, mission goals (see Section V.2.1) are defined. At this point design-time analysis tools and model interpreters are used to analyze the design-time model and generate appropriate artifacts that represent a configuration space and initial configuration point (see Section V.2.3.2) for the modeled system. These are stored in the database and is later used at runtime; the initial configuration point is used for initial deployment and the configuration space is used to compute new configuration points at runtime in order to reconfigure the system. We describe this process in detail in Section V.3.3.2.

V.3.2 Design-time Resilience Analysis Tool

The section describes in detail a novel design-time resilience analysis tool. This tool is useful in the context of extensible CPS for which resilience is of utmost importance. In

general, the task of a resilience analysis tool is to provide feedback to the system integrator about how resilient a system design is, before the system is actually deployed. The resilience analysis tool, presented in this section, calculates two fundamental resilience metrics as a pair of integers: a lower bound and an upper bound on the degree of resilience. When these bounds are calculated, all possible remedial actions are considered. The lower bound measures the least number of faults that can (but not necessarily) lead to a complete system failure. The upper bound is the maximum number of faults the system can possibly tolerate due to the remedial actions of the reconfiguration engine; a higher number of faults will lead to a system failure, regardless of redundancy.

In simple terms, the upper bound is an optimistic resilience metric and the lower bound is a pessimistic resilience metric. If we are designing a safety critical system, the system designer will evaluate design choices based on the pessimistic criteria. However, for a regular enterprise system, a number within the two bounds will be used. It can be argued that the system requires a larger degree of redundancy around critical components to achieve a larger lower bound, increasing the overall cost of the system. Below we provide a formal definition of these two resilient metrics.

Definition 6. *A reliability block diagram* $RBD(Src, Snk, C, N, Dep)$ *is a directed graph whose nodes are the system components or source/sink nodes* ($Src \cup Snk \cup C \cup N$)*. An edge between a node A and a node B means that B depends on A.* $Dep : Src \cup C \cup N \times Snk \cup C \cup N$.

Definition 7. *The worst-case resilience is defined as the least number of failures that will render one or more system goals unachievable. Alternatively, the worst-case resilience is the number of the node disjoint paths in the RBD.*

Definition 8. *The best-case resilience is defined as the maximum number of failures that can be sustained while the system goals are met. Alternatively, the best-case resilience is the number of parallel paths in the RBD.*

At design-time, we compute these metrics for a system design. We consider a system

design as a pair: (1) an initial design i.e. the initial configuration point, and (2) the configuration space. While the initial design describes the initial state of the system without any failure, the configuration space implicitly describes all the feasible designs. If a primary fault causes secondary faults of other system entities, it is captured by the logical constraints. For example, to enforce that the failure of a component brings down its host process, we can add a constraint that enforces that. However, our current implementation only considers node and component failures.

Primitive	Description
Assign(i, j)	**Input:** A component instance and a node. **Effect:** A constraint that assigns component *i* to node *j*
TurnToBinaryResource(c, n, c_list)	**Input:** a component instance, a node, and a set of components that are using the resource. **Effect:** a constraint that assigns component c to node n, and collocates all the client components present in c_list with c.
Enabled(i)	**Input:** a component instance. **Effect:** a Boolean expression that is true if the component is assigned to a node; false otherwise. The constraint sums the row of the component instance and checks if it is greater than zero.
CollocateComponents(c1, c2)	**Input**: two component instances. **Effect:** a constraint that ensures that the component instances must be assigned to the same node.
DistributeComponents(c_list)	**Input:** a list of component instances. **Effect:** a constraint that ensures that the component instances must be assigned to different nodes.
Communicates(i,j)	**Input:** two component instances. **Effect**: a constraint that makes sure that there is a link between the nodes,the components are deployed on. If the,two components are on the same node, the constraint is still satisfied.
ForceExactly(f, c_list, n)	**Input:** a function and a list of components; a positive integer n. **Effect:** a constraints that makes sure that exactly n of the components in the list must be enabled, to provide the function.
ForceAtleast(f, c_list, n)	**Input:** a function and a list of components; a positive integer n. **Effect:** a constraints that makes sure that at least n of the components in the list must be enabled to provide the function.
ForceAtmost(f, c_list, n)	**Input:** a function and a list of components; a positive integer n. **Effect:** a constraints that makes sure that at most n of the components in the list must be enabled to provide the function.

Table 6: Constraint Primitives implemented using Z3 Solver [26] Python APIs.

In order to perform resilience metrics computation, we formulate the problem as a SMT problem, and use the Z3 solver [26] to solve the SMT problem. We describe the deployment

as an adjacency matrix (see Definition 5). The constraints are defined in Table 6. These primitives are translated to equations over the adjacency matrix. For example, the primitive *Enabled* and *Assign* are mapped as shown in Listing V.1. The *Enabled* function returns true if a component with index i is assigned to any node. To do this it checks if the sum of the row corresponding to that component is greater than 0. The *Assign* function ensures a component is assigned to a particular node. The assignment is valid only if the component is not in faulty state. Thus, the component being enabled implies the assignment, which means that the element in the component's row and the node's column must be one. The variable *c2n* represents the adjacency matrix in Z3, and *Implies* is the Python wrapper around the implication in the Z3 library.

Listing V.1: Sample implementation of primitive constraints *Enabled* and *Assign*.

```
# num_comp: Number of components.
# num_nodes: Number of nodes.
# c2n: A num_comp X num_nodes adjacency matrix, where values
#       are 0 or 1. 0 meaning not enabled and 1 meaning enabled.
# i: Index of a component to enable.
def Enabled(self, i):
    return Sum([self.c2n[i][j] for j in range(self.num_nodes)])>0

# i: Index of a component to enable.
# j: Index of a node on which the component should be enabled
def Assign(self, i, j):
    return Implies(self.Enabled(i), self.c2n[i][j] ==1)
```

Algorithm 1 Worst Case Metric Computation | Phase 1: Calling BFS

INPUT: Adjacency Matrix and Constraints
OUTPUT: Worst case metric

1: min = 0
2: **for** e 0 to $|nodes \bigcup components| - 1$ **do**
3: res = $get\_min\_faults\_bfs\_r(0, [], e)$
4: **if** res == true **then**
5: return

Once the components and the constraints have been generated, the solver is able to compute solutions. As shown in Algorithm 1 and Algorithm 2, we find the worst case resilience metric by performing a breadth-first search in the search space of injected faults.

We inject faults in the solver by specifying constraints, typically disabling one or more components or nodes. The second phase of the algorithm is the recursive Breadth-First Search (BFS). Essentially, we increase the number of faults each round in which we call the BFS. The BFS combines together all the variations of faults, and when the level counter reaches zero, the current state is evaluated by making all the components/nodes in the list fail and checking if there is a solution. We save the solver state before this computation (*push*) and restore it afterward on each control path (*pop*). Since the order is provided by a BFS, whenever we cannot find a solution, we have found a minimal number of faults. This is our worst case faults.

Algorithm 2 Worst Case Metric Computation | Phase 2: BFS Traversal | $get\_min\_faults\_bfs\_r$

```
INPUT: start, list, level
OUTPUT: Worst case metric
 1: if level == 0 then
 2:     solver.push()
 3:     for each element e in list do
 4:         fail e
 5:     solver.check()
 6:     if no solution then
 7:         save min as metric
 8:         solver.pop()
 9:         return true
10:     solver.pop()
11:     return false
12: for e in range of start and |nodes ⋃ components| − 1 do
13:     res = get_min_faults_bfs_r(n + 1, list + [e], level − 1)
14:     if res == true then
15:         return true
16: return false
```

The computation of the best-case metric is rather indirect. Instead of finding the maximum number of faults, we find a minimal configuration, and then subtract its number of elements from the maximum number of elements in the initial model. This makes our computation much more efficient because we can phrase this problem as a set of constraints for Z3. We express the number of nodes and components as an integer variable n for the solver,

and we keep calling the solver by requesting a solution with a smaller n. If the solver cannot find a solution, the previous solution is the smallest model.

We have introduced several metrics, such as, a weighed metric $w = WM$, where $M = (m_{worst},\ m_{best})$, and W is an appropriate weighing vector. We extended the notion of this metric for subsystems. The vector M for the system can be expressed as $(min(m^i_{worst}),\ sum(m^i_{best}))$. The first element takes the minimum of m^i_{worst} for all critical subsystems i. The second element adds all the m^i_{best}. Based on the distance in Definition 9, it is possible to assign distance metric to the worst and best case metrics. If the distance is weighed, we need to modify the BFS algorithm to Dijkstra's path finding algorithm to compute the worst case, and instead of the number of nodes, the distance must be expressed for the solver for the best case metric.

V.3.3 Runtime Infrastructure for Self-Reconfiguration

This section presents the runtime self-reconfiguration infrastructure. First, we provide an architectural overview of our distributed infrastructure. Then, we present the reconfiguration mechanism.

V.3.3.1 Architecture overview

Figure 22 presents an overview of our resilient reconfiguration infrastructure. There are two kinds of nodes - a computation node, and a solver node. Each computation node hosts (1) applications, (2) an instance of the distributed database to store the configuration space, the initial configuration point, the current configuration point, and deployment actions, (3) a Deployment Manager (DM) that is responsible for managing lifecycle of different applications, and (4) a monitor to detect failures. There is a notion of a *leader* among different computation nodes and we use the existing capabilities of the distributed database to determine a leader.Unlike a computation node, a solver node only hosts an instance of the distributed database and a Resilience Engine (RE) that can compute a new configuration

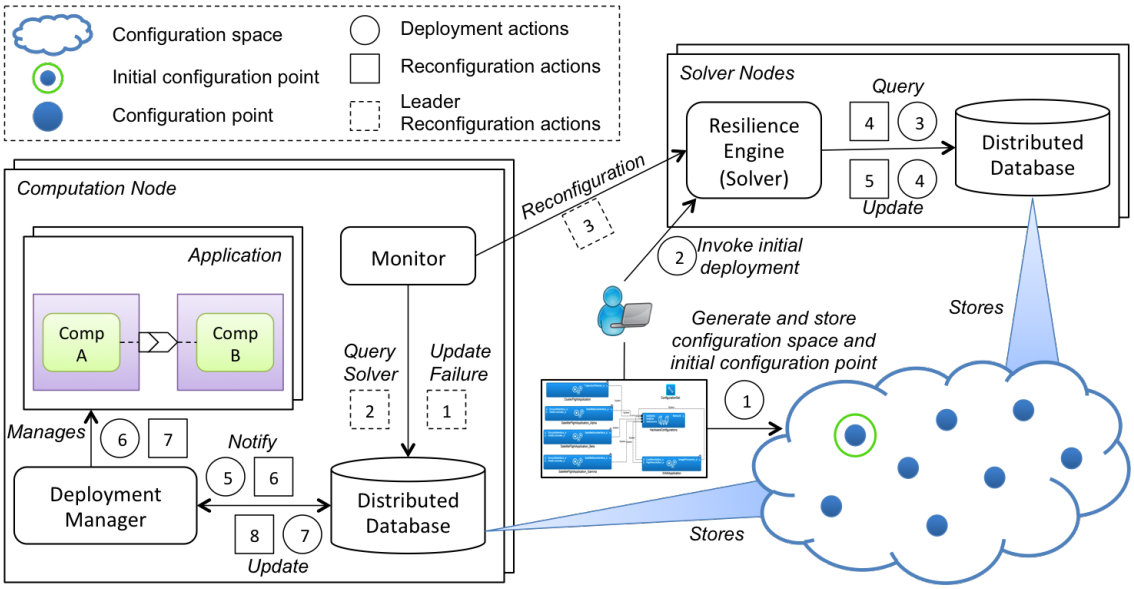


Figure 22: Overview of the distributed self-reconfiguration infrastructure with *Deployment* and *Reconfiguration* action sequences. Initial deployment is triggered when a user/system integrator generates and stores the configuration space and the initial configuration point for a system using the design-time modeling tool. Once this is done, a Resilience Engine (RE) is invoked to instigate initial deployment. The RE then computes the required deployment actions and stores them in the database. At this point, the Deployment Managers (DMs) that are responsible for taking these actions are notified after which they execute those commands locally to complete initial deployment. Reconfiguration is similar, however, unlike a user/system integrator instigating the process, it is a monitor that instigates the process by logging information about any detected failure to the database and invoking the RE. This should only be done by a single monitor, as such we dedicate this task to the leader monitor, i.e., the monitor running on the leader node.

point when a system needs to migrate from one configuration point to another to mitigate failures. Further descriptions of these are provided below.

***Applications*:** As mentioned in section II.1, we assume component-based applications. Therefore, each application is a set of components that interact with each other or with components of different applications. All information required to deploy and configure these applications on the target system is stored in a distributed persistent backend.

***Distributed Database*:** A distributed database is required to store relevant information such as (1) the configuration space, (2) the current configuration point, and (3) the initial

configuration point. The initial configuration point is provided by a system architect and is used as the baseline for further reconfiguration when required. Well known faults are also stored in the database as part of the configuration space. We use MongoDB [66] as our choice of database and deploy multiple instances of this in a replica set.

***Monitor*:** A monitor is responsible for monitoring, detecting and diagnosing failures. This is an important aspect of a resilient system. However, there exists significant amount of existing work in this particular research area, including works published by my collaborators in [30, 62]. As such, the work presented in this chapter does not focus on failure monitoring, detection and diagnosis. For our experiments presented in Section VI.4, we simply inject failures by updating system configuration stored in the database. In essence, monitors in our architecture, as shown in Figure 22, are responsible for reporting diagnosed failures to the database and invoking the Resilience Engine (RE) in order to initiate system reconfiguration.

***Resilience Engine*:** A Resilience Engine (RE) is primarily responsible for computing a new configuration point at runtime when faults occur in the current state. This is important because once a new configuration point is computed, reconfiguring the system involves moving the system from the current configuration point, which is considered faulty, to the new configuration point. The mechanism used to calculate a new configuration point is described in Section V.3.3.2. In general, a RE first determines different entities affected by the failure, and then it uses the Z3 solver to compute a new configuration point, considering various constraints and available resources. If a new configuration point is successfully computed, the local database instance is updated accordingly. This updated information is later used by appropriate DMs to reconfigure the system.

***Deployment Manager*:** In our architecture, Deployment Managers (DMs) running on each node are used as local adaptation engines that are responsible for managing the life-cycle of application components deployed on its node. Therefore, collectively, these DMs

form a distributed deployment and configuration infrastructure that manages various distributed applications by performing (1) initial deployment and configuration, (2) runtime adaptation via reconfiguration, and (3) termination. In previous chapter (see Chapter III), we identified key requirements for resilient deployment and configuration infrastructure and implemented a prototype. Here we address the same requirements but our implementation is different and relies heavily on capabilities already provided by the distributed database. For example, dynamic group membership is one of the key requirements identified and implemented in Chapter III (see Section III.4.1). However, for the work presented in this chapter, we simply make use of group membership capability (i.e., replica set) supported by MongoDB.

As shown in Figure 22, DMs in our architecture simply listen for notification from their local database instance. Although MongoDB does not include notification service, we implement a simple notification mechanism based on MongoDB replica set Oplog, which is a database collection that stores every database event. Once a DM is notified of an event of its interest, it queries the database to obtain a set of application management actions that it should perform. These actions will be related to application components hosted on locally on the same node; a DM in one node cannot manage application components deployed on a different node. Once a DM takes required actions, it updates the database accordingly.

V.3.3.2 Reconfiguration

Once a failure is detected, our two-phase resilient recovery mechanism outlined in algorithms 3 and 4 ensures that the system undergoes the required reconfiguration. The different actions involved in this mechanism are also illustrated in Figure 22.

Phase 1 | *Computing a new configuration point:* The first phase of the reconfiguration mechanism is instigated once a RE is invoked after detection of a failure. In this phase, the RE computes a new configuration point by using information about the failure, the

current configuration point, and relevant deployment and resource constraints in the configuration space. In order to do so, the RE uses aforementioned information to form a SMT problem and feeds it to the Z3 solver as we did for the design-time resilience analysis (Section V.3.2).

Algorithm 3 presents the Configuration Point Computation (CPC) algorithm. In the beginning of this algorithm (step 1), a component-to-node (C2N) matrix (see Definition 5) is constructed using information about different available components and nodes. The next step (step 2) creates a SMT constraint over the C2N matrix such that a component is only deployed in a single node. This constraint is encoded in a way to ensure that the sum of each row of the C2N matrix is exactly one.

Algorithm 3 Configuration Point Computation (CPC) Algorithm.

Input: functions (fn), components (c), nodes (n), failure (fl)
Output: a valid configuration point

1: $c2n$ = a C2N matrix constructed using c and n ▷ See Definition 5.
2: cst_1 = an assignment constraint over $c2n$ ▷ Ensures that a component is only deployed in a single node
3: $r2n$ = a R2N matrix constructed using nodes in n and resources provided by each node ▷ R2N matrix is a resource-to-node matrix.
4: $r2c$ = a R2C matrix constructed using components in c and resources required by each component ▷ R2C matrix is a resource-to-component matrix.
5: cst_2 = a resource constraint over $r2n$ and $r2c$ ▷ Ensures that resource requirements of components are met.
6: cst_3 = a failure constraint using fl ▷ Ensures that a failed node is empty or failed a component is not re-deployed.
7: $solver = create\_Z3\_solver$ ()
8: add constraint to $solver$ using fn ▷ Ensures that all functions are provided.
9: add constraint cst_1, cst_2, and cst_3 to $solver$
10: $solution = null$
11: **while** true **do**
12: $result = solver.check$ ()
13: **if** $result$ == unsat **then**
14: $solver.pop()$
15: **if** $solution$ == null **then**
16: **return** null
17: **else**
18: **return** $solution$
19: **else**
20: $solution = solver.model$ ()
21: add distance constraint to the solver using $solution$

The next step (step 3) creates a resource-to-node (R2N) matrix using information about different nodes and resources provided by those nodes. The R2N matrix comprises resources as rows and nodes as columns, and each element of the matrix is the value of a particular resource provided by the corresponding node. Similarly, a resource-to-component

(R2C) matrix is created in the next step (step 4) using information about different components and resources required by those components. The R2C matrix comprises resources as rows and components as columns, and each element of the matrix is the value of a particular resource required by the corresponding component. The next step (step 5) of this algorithm is to create a resource constraint using the aforementioned R2N and R2C matrices. This constraint ensures that the resources required by components deployed on a node is satisfiable.

Once the assignment and resource constraints are encoded, the next step (step 6) in Algorithm 3 is to encode a failure constraint related to the failure that was initially detected. If the failure was a node failure, we encode the constraint such that no components are deployed on the failed node. Whereas, if the failure was a component failure, then we encode the constraint such that the component is not re-deployed. The failure constraint related to component failure could be relaxed by ensuring that a component gets re-deployed but not on nodes where it has previously failed. At this point, all constraints are encoded and the next few steps (steps 7 - 9) involves creating a Z3 solver and adding different constraints to the solver.

Definition 9 (Least Distance Constraint)**.** *The "least distance" constraint is used to ensure that we find a valid configuration point that is closest to the current configuration point. The distance between two configuration points is the distance between their corresponding C2N matrices. This distance is computed as shown in Equation V.4; the distance between two valid configuration points A and B is the sum of the absolute difference between each element of the C2N matrices corresponding to the two configuration points.*

$$config\_distance = \sum_{n=0}^{\beta} |c2n\_A_{cn} - c2n\_B_{cn}| \tag{V.4}$$

After adding constraints to the solver, the next set of steps (steps 10 - 21) is responsible for computing a configuration point that is the least distance (see Definition 9) away from

the current configuration point. In order to do so, we use a recursive logic, which upon every successful solution computation (step 20) adds a distance constraint (step 21) and invokes the solver again. The distance constraint is encoded using distance between computed solution and the current configuration point. It is encoded to ensure a new solution (one that will be computed in the next round of iteration) is lesser distance away from the current configuration point in comparison to the solution computed in this iteration. As such, by adding this constraint, we are asking the solver to find a better solution in every iteration of successful solution computation. There will come a point when the solver will not be able to find a better solution (step 13), in which case we check if the solution from previous step is valid (step 15) and return that as the closest configuration point (step 18). This is an important heuristic as we do not want the system to deviate too much from its current configuration. It also guarantees minimal reconfiguration time as the number of changes required will be minimal due to the fact that the distance between the configuration points is the least possible.

Once a new configuration point is computed, it is stored in the database as a desired state. The next phase of our self-reconfiguration mechanism is responsible for using this configuration point to compute reconfiguration commands required to transition from the current configuration point to the new configuration point; we discuss this is detail below. Here, it is important to note that our current implementation of the runtime self-reconfiguration mechanism does not analyze or verify different properties (timing, network QoS) of the configuration points computed at runtime. As mentioned before, this is an important processes, specially for extensible CPS that host mission critical applications. However, our work presented in chapter demonstrates our initial effort towards achieving autonomous resilience; integrating analysis and verification of different properties with the runtime reconfiguration loop is part of our future work.

Phase 2 | *Computing reconfiguration commands and reconfiguring the system using*

those commands: The second phase of our reconfiguration mechanism, shown in algorithm 4, is responsible for computing reconfiguration commands and performing the reconfiguration itself. In order to compute the reconfiguration commands required to transition from one configuration point to another, the *compute reconfiguration commands* procedure of Algorithm 4 is used. As shown, this procedure takes C2N matrices of newly computed configuration point (step 3) and current configuration point (line 4) to determine different reconfiguration commands (steps 5 - 13). To determine reconfiguration commands, we check how each element of the aforementioned matrices are different when compared to each other (steps 7 and 10). Depending on the difference we either create a *start* command or a *stop* command. The former results in creation of a new process, whereas, the latter results in termination of an existing process.

Algorithm 4 Reconfiguration Commands Computation and Reconfiguration Execution Algorithm.

```
1:  procedure COMPUTE RECONFIGURATION COMMANDS          ▷ Executed by the RE that computes a new configuration point.
2:      commands = null
3:      c2n_new = C2N matrix of the new configuration point          ▷ This is computed using Algorithm 3
4:      c2n_cur = C2N matrix of the current configuration point
5:      for component c in c2n_new do
6:          for node n in c2n_new do
7:              if c2n_curr_cn < c2n_new_cn then                    ▷ Component missing in current
8:                  create start command for component c in node n
9:                  add command to commands list
10:             if c2n_curr_cn > c2n_new_cn then                    ▷ Component missing in new
11:                 create stop command for component c in node n
12:                 add command to commands list
13:     store commands in the database
14:
15: procedure RECONFIGURATION EXECUTION                 ▷ Runs infinitely in each DM.
16:     if reconfiguration notification received then               ▷ One per command.
17:         retrieve the reconfiguration_command from the database
18:         if reconfiguration_command is for this node then
19:             if reconfiguration_command == START then
20:                 create a new process and save pid in the database
21:             if reconfiguration_command == STOP then
22:                 use component name to retrieve pid from the database
23:                 kill the process using pid
24:             mark reconfiguration_command as executed in the database
```

Once all reconfiguration commands are computed and stored in the database, the *reconfiguration execution* procedure of Algorithm 4 is used to ensure all reconfiguration commands are executed. This procedure is executed infinitely by each DM.

When a DM is notified about a reconfiguration command (step 16), it checks if it should execute that command (step 17). A DM should only execute commands that are targeted for its host node. Once a DM determines a command that it should execute, it will check whether the command is a start or stop command and execute the command accordingly (steps 19 - 23). Finally, after executing a command, the DM updates the database to acknowledge that the command has been executed. Once this happens for all reconfiguration commands pertaining to a configuration point transition, we can claim that the system has successfully self-reconfigured.

V.4 Case Study: Fractionated Satellite Cluster

In this section, we first present our use case scenario comprising three applications deployed on a cluster of fractionated satellite. Second, we demonstrate the design-time resilience metrics computation. Finally, we demonstrate the runtime self-reconfiguration mechanism using a small scale system, and evaluate it using a larger system.

V.4.1 Scenario

In order to perform different demonstrations and evaluation, we use a fractionated satellite scenario where we have a simple system with the following objectives: (1) satellite flight applications to control the position of each satellite, (2) an imaging application to capture images, and (3) a cluster flight planning application to coordinate the flight paths and positions of the different satellites. The software (application) model for this system is shown in Figure 23. We use a GME [55] based modeling front-end that allows a user to model complex systems using a graphical modeling language.

As shown in Figure 23, this system is comprised of three different kinds of applications: (1) a single instance of*ClusterFlightApplication*, which is responsible for satisfying the objective of coordinated flight planning, (2) three different instances of a flight control

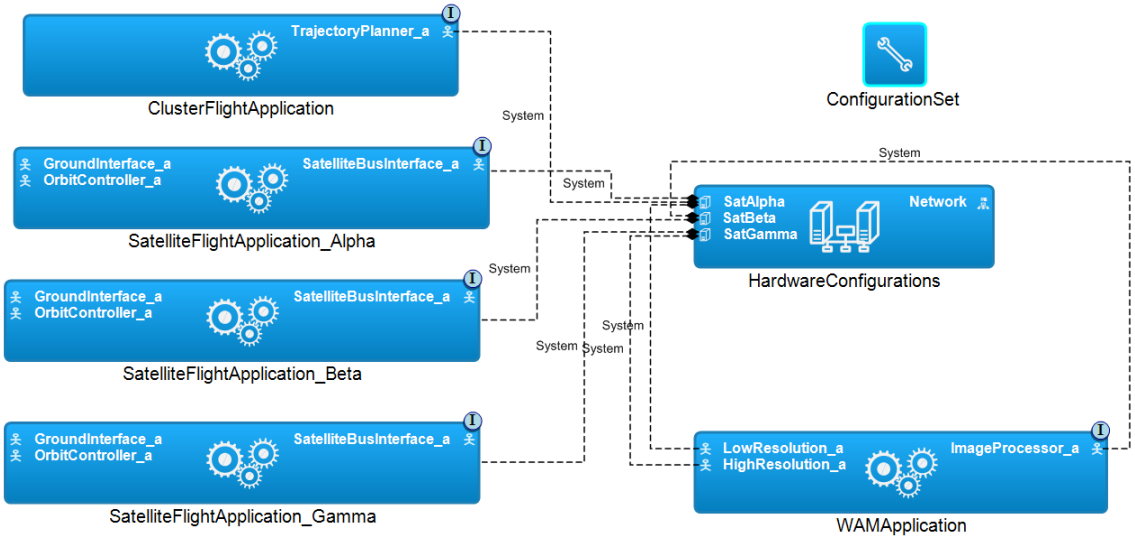


Figure 23: Software Model Design using GME [55] based Modeling Language.

application called *SatelliteFlightApplication*, one for each node for a three-node initial deployment scenario, and (3) a single instance of *WAMApplication*, which is responsible for satisfying the imaging objective. The *HardwareConfigurations* for this application suggest the requirements for the three nodes, which are named *SatAlpha*, *SatBeta*, and *SatGamma* in the model. The initial deployment maps the *ClusterFlightApplication* to node *SatAlpha*, the *SatelliteFlightApplication* instances to all three nodes, and three different components of the *WAMApplication* to the three different nodes.

Each instance of the *SatelliteFlightApplication* is composed of three components (1) an *OrbitController* component, which is responsible for manipulating thrusters to control satellite movement and position, (2) a *GroundInterface* component, which is responsible for communicating with a ground station, and (3) a *SatelliteBusInterface* component, which is responsible for interacting with the satellite bus. The *ClusterFlightApplication* contains a single component, a *TrajectoryPlanner* component, which is responsible for planning and co-ordinating flights paths of the different satellites. The *WAMApplication* is composed a *HighResolutionImageGrabber* component, a *LowResolutionImageGrabber* component,

and a *ImageProcessor* component; the first two components are responsible for capturing images of varying resolution while the third component is responsible for processing different images.

Not shown in Figure 23 are the different devices present on each node. For our scenario, all three nodes host a *BusController* device to control the satellite bus and a *GroundInterface* device to communicate with a ground station. In addition, node *SatAlpha* also hosts an *HR_Camera* device to capture high resolution images, an *LR_Camera* device to capture low resolution images, and a *GPU* device to process captured images. Similarly, node *SatBeta* also hosts a *GPU* device, and node *SatGamma* also hosts an *HR_CAMERA* device. In addition to representing the system configuration after the initial deployment, Figure 24 also shows all these different devices with respect to their hosting nodes.

V.4.2 Resilience Metrics Calculation

Our current implementation of the design-time resilience analysis tool only considers software component (application) failures and node failures. As such, the resulting resilience metrics are true only for component failures and node failures. In other words, the minimum and maximum number of failures tolerable are strictly component failures or node failures. Resilience analysis of system configuration presented in Figure 24 results in resilience metrics of $(1, 12)$, where 1 is the worst-case metric and 12 is the best-case metric. This means that the system is capable of tolerating at least one failure, regardless of what the failure is, and at most twelve failures. Again, these failures are either component or node failures. The thirteenth failure, regardless of which node or component it is, will definitely cause the system to fail.

To further explain the computed resilience metrics, let us examine the worst-case metric. Since the worst-case metric of 1 tells us that the system is always capable of tolerating a single failure, let us come up with a scenario where two failures result in the system to be non recoverable. If node *SatGamma* fails followed by the failure of node *SatAlpha*, we lose

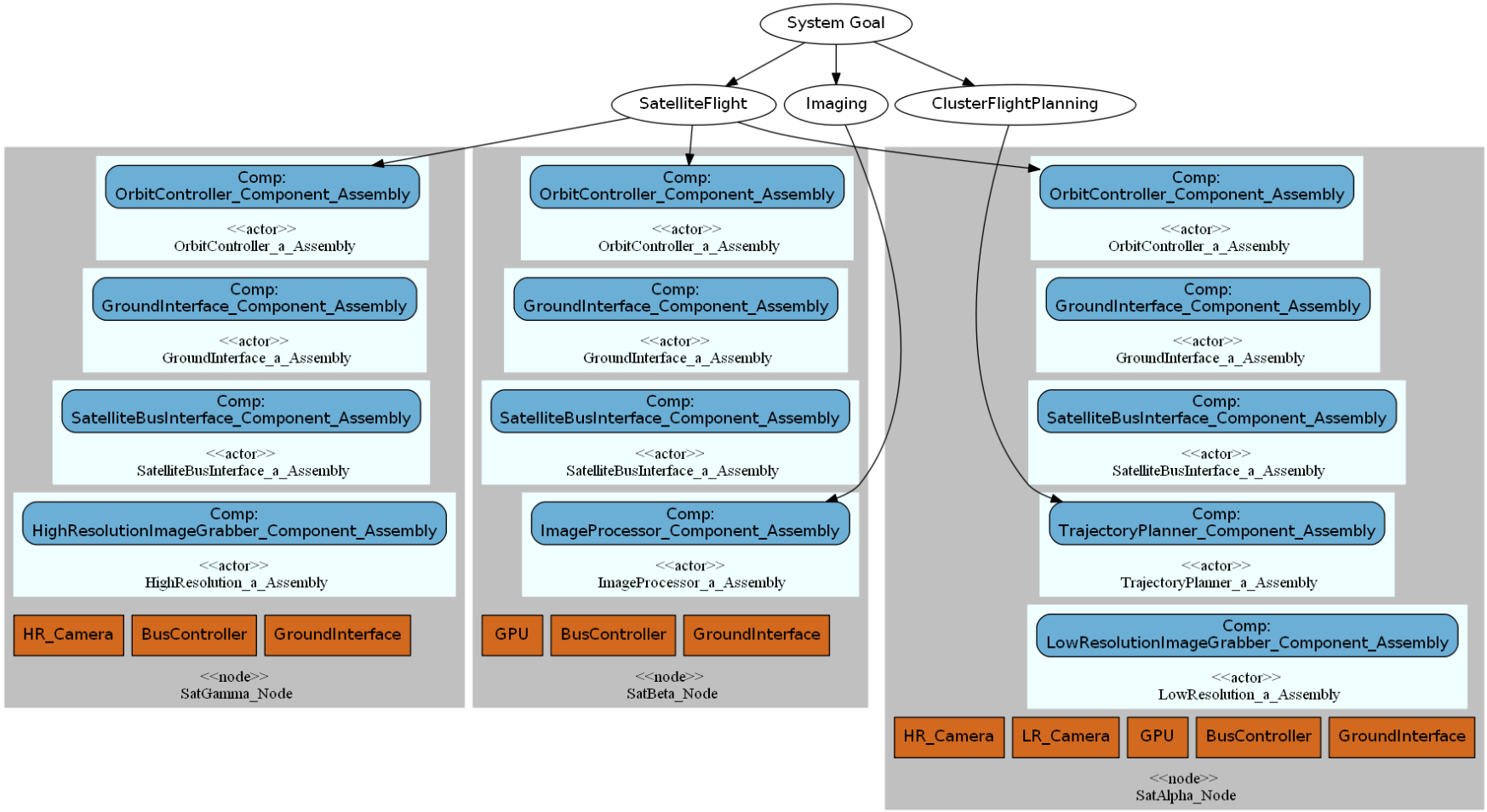
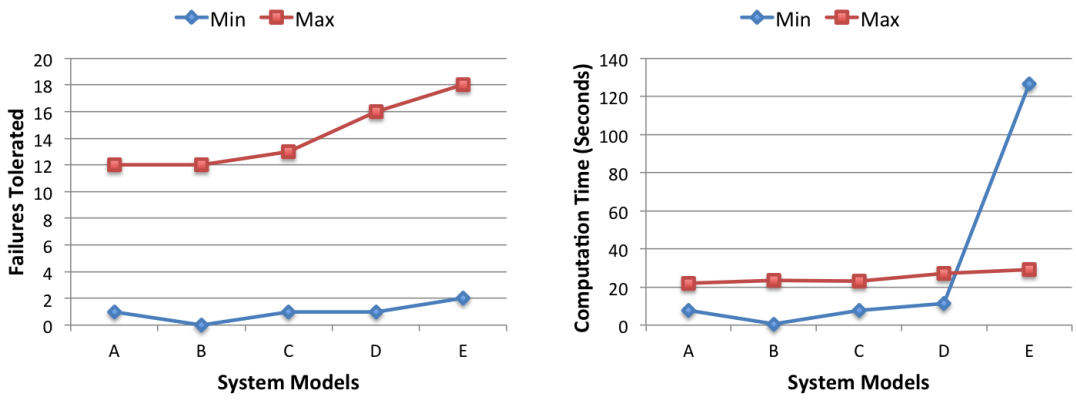


Figure 24: System Configuration after Initial Deployment of Model in Figure 23.

both image capturing components of which at least one is required by the *ImageProcessor* component on node *SatBeta*. Therefore, in this scenario, the two node failures was enough to render the system non recoverable.

Similarly, we can evaluate the best-case metric by coming up with one or more scenarios that shows how the system can tolerate twelve failures. One such scenario is as follows - (1) failure of the *GroundInterface* component on node *SatGamma*, which has no effect as there are two other *GroundInterface* components, (2) failure of the *GroundInterface* component on node *SatAlpha*, which doesn't require instantiation of the component on another node but it does result in the *TrajectoryPlanner* component being restarted on node *SatBeta* since this node has a functioning *GroundInterface* component to receive important commands from ground station, (3) failure of the *HighResolutionImageGrabber* component on node *SatGamma*, which results in this component being restarted on node *SatAlpha*, (4) failure of the *SatelliteBusInterface* on node *SatGamma*, (5) failure of the *OrbitController* component on node *SatGamma*, (6) failure of node *SatGamma* itself, (7) failure of the *TrajectoryPlanning* component on node *SatBeta* resulting in it being restarted on node *SatAlpha*, (8) failure of the *ImageProcessor* component on node *SatBeta* resulting in it being restarted on node *SatAlpha*, (9) failure of the *LowResolutionImageGrabber* on node *SatAlpha*, which has no affect as the *ImageProcessing* component only requires one out of two image capturing components, (10) failure of the *GroundInterface* on node *SatBeta*, which results in system still being functional but not able to receive any new ground commands, (11) failure of the *SatelliteBusInterface* component on node *SatBeta*, and finally (12) failure of the entire node *SatBeta*, which results in all remaining components being hosted on node *SatAlpha*.

The purpose of computing these resilient metrics is to quantify the resilience of a system. Using these metrics we can compare between different deployments or versions (for example, with different resources) of the same system and determine the most resilient.



(a) Resilience metrics for different system models.

(b) Resilience metrics computation time for different system models.

Figure 25: Resilience Metrics (left) and corresponding computation time (right) for different variation of system model presented in Figure 23. A represents the default model (shown in Figure 23), B represents a model in which a *GPU* device is removed from *SatAlpha*, C represents a model in which a *HR_Camera* is added to *SatBeta*, D represents a model in which a new node similar to *SatGamma* is added to the system, and E represents a model in which a new node similar to *SatAlpha* is added to the system.

Based on this analysis, we can judge the tradeoffs between resilience and the different system designs, and make a well-informed decision before deploying a system.

Figure 25 presents resilience metrics (Figure 25a) and corresponding computation time (Figure 25b) for different variations of system model presented in Figure 23. As shown in the figure, maximum failure computation time ranges between 20 - 30 seconds. Similarly, minimum failure computation time ranges between 0 - 20 seconds for system models *A* - *D*. However, minimum computation time for system model *E* is considerably higher at 126.63 seconds. This is because when a new node with five different devices is added to the default model, the search space expands considerably for each failure scenario considered. However, this is acceptable as this analysis is done during design-time.

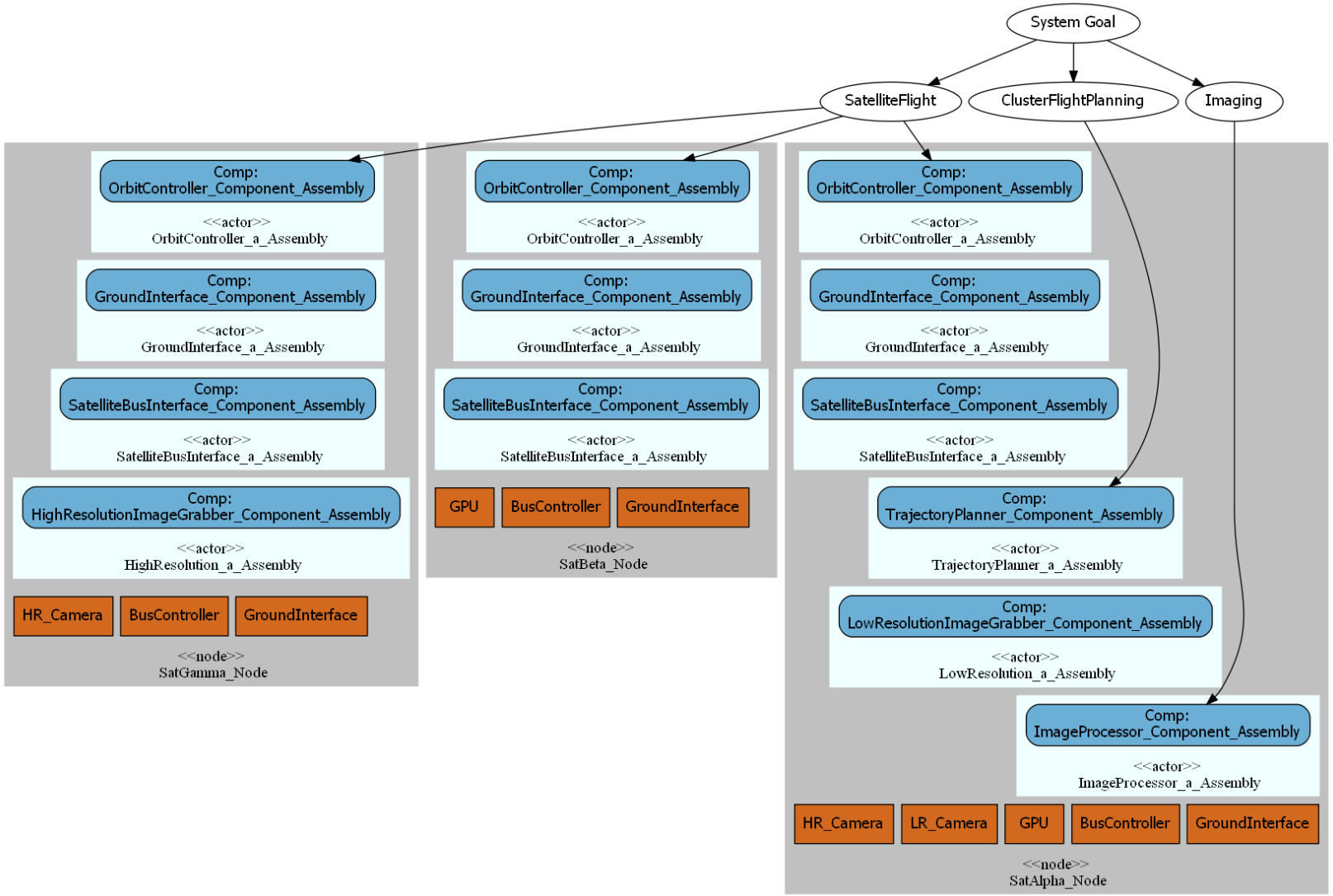


Figure 26: System configuration after recovering from *ImageProcessor* component failure in node *SatBeta*. Compare it to the initial configuration shown in Figure 24.

V.4.3 Runtime Self-Reconfiguration Mechanism Demonstration

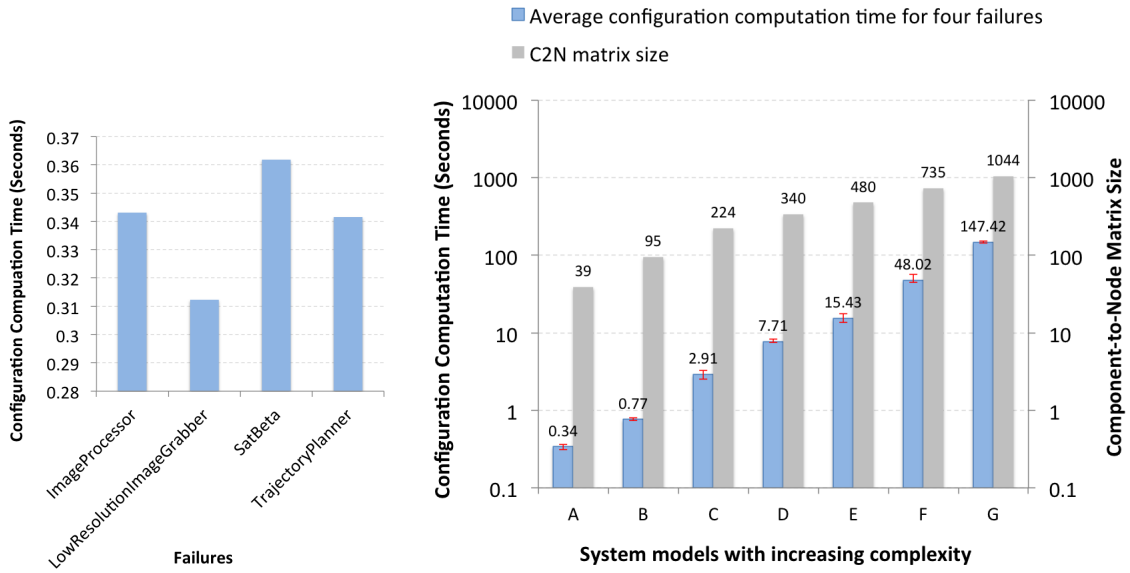
In this section, we demonstrate the self-reconfiguration capability provided by our runtime infrastructure. Figure 24 shows the system configuration after the initial deployment. From this figure, it is clear that the system requires three different objectives – *SatelliteFlight*, *Imaging*, and *ClusterFlightPlanning* – to satisfy its high-level goal. To test resilience, we first inject a component failure [1] by failing the *ImageProcessor* component in node *SatBeta*. Once a *Resilience Engine* receives this failure report, it computes a new configuration point and a list of reconfiguration commands to transition the system from its current configuration point (faulty) to the new configuration point. In this particular scenario, the *Resilience Engine* computes a solution that requires the *ImageProcessor* component to be moved from node *SatBeta* to *SatAlpha*; this makes sense because the *ImageProcessor* component requires *GPU* device and the only other node with a *GPU* device is node *SatAlpha*. The resulting configuration is presented in Figure 26.

V.4.4 Runtime Self-Reconfiguration Mechanism Evaluation

Figure 27 presents result of two experiments we performed to evaluate our self-reconfiguration mechanism. First, we compare the time taken to compute new configuration points after failures in the system model presented in Figure 23. As shown in the Figure 27a, we consider four failures; first two failures are component failures (*ImageProcessor* and *LowResolutionImageGrabber*), third failure is a node failure (*SatBeta*), and fourth failure is another component failure (*TrajectoryPlanner*). The time taken to compute a new configuration point for all four failure cases is 0.34 seconds on average, with minimum 0.31 seconds and maximum 0.36 seconds. The range here is 50 milliseconds. This is because all four failures are invoked in the same system, which means the size of the C2N matrix will be the same.

Second, we compare the time taken to compute new configuration points for different

[1] Failure injection is as simple as changing the status of the device to mark it as failed.



(a) Configuration computation time for failures in the simple system model presented in Figure 23.

(b) Average configuration computation time for four failures in different system models. Both y-axis are in logarithmic scale.

Figure 27: Configuration computation time for failures in a simple model (left) and average configuration computation time for four failures in different system models (right). The different system models have increasing complexity; A has 3 nodes and 13 components, B has 5 nodes and 19 components, C has 8 nodes and 28 components, D has 10 nodes and 34 components, E has 12 nodes and 40 components, F has 15 nodes and 49 components, and G has 18 nodes and 58 components.

system models. As shown in Figure 27b, we use seven different system models and for each system model we compute the average configuration computation time with regards to the same four failures that we used for our first evaluation experiment (Figure 27a). Although all seven system models comprise similar nodes and components, the number of nodes and components in each system model is different. System model A is the simplest and resembles the basic system model shown in Figure 23; it comprises of 3 nodes and 13 components. System model B comprises 5 nodes and 19 components. System model C comprises 8 nodes and 28 components. System model D comprises 10 nodes and 34 components. System model E comprises 12 nodes and 40 components. System model F comprises 15 nodes and 49 components. System model G comprises 18 nodes and 58

components. So we can see that these system models have increasing complexity. As we can clearly see in Figure 27b, systems with higher complexity have higher average configuration computation time. This is because of the size of the C2N matrix over which all constraints are encoded. Furthermore, the size of the C2N matrix also tells us about the size of the resource matrices (R2C and R2N). Since, we are considering increasing scale of the same system model, we can argue that the size of the R2C and R2N matrices will also increase as the system complexity increases. So, the more complex a system, the larger its configuration space (all three different matrices and corresponding constraints) and therefore the increase in time taken by the underlying Z3 solver to find a solution.

Here, we would like to state that, although Figure 27b presents result based on single iteration of the experiment, we were able to reproduce similar results for multiple iterations of the same experiment.

From these results we can see that configuration computation time increases with increase in system complexity. As such, we have to be careful when choosing what classes of systems this solution is applied to. For example, it might not be feasible to use this solution as it is to large-scale hard real-time systems. A variation of this approach, which relies on solution pre-computation, can used to resolve this issue. Details of this solution pre-computation approach is presented in Chapter VI.

V.5 Related Work

Significant amount of prior work has been done in order to achieve dynamically reconfiguring systems. [7, 12, 97] presents different policy-based approaches to achieving dynamic reconfiguration. In [12], the authors present a policy-based framework that requires mission specification, which describes how specific roles are assigned to different nodes based on their credentials and capabilities, and how these roles should be re-assigned in response to changes or failures. As such, this mission specification explicitly encodes

reconfiguration actions, i.e., role re-assignments, during design-time. [97] also follows similar approach where declarative policies are used to specify adaptation. In [7], the authors present a policy-based approach where each adaptation policy comprises rules, actions, and the rate at which each rule should be evaluated. These approaches are different from ours, as we do not explicitly encode reconfiguration actions at design-time; it is impossible to cover all possible combinations of failure scenarios at design-time.

Alternative approaches to achieving dynamic reconfiguration include use of system health management techniques [103]. Existing work that follows this approach includes [64], which shows how system-wide mitigation can be performed based on reactive timed state machines specified at design-time, using the results of a two-level fault-diagnoser [28]. A boolean encoding for reconfiguration using a search based strategy is presented in [61]. These approaches have similar limitations to aforementioned policy-based approaches since the runtime reconfiguration mechanism depends on design-time specifications.

In [39, 107], the authors present a middleware that supports timely reconfiguration in distributed real-time systems. *Application Graph*, which contains information about what services are required and how they depend on each other, and *Expanded Graph*, which contains information about different service implementations, are studied *a priori* at design-time. As such, these solutions also have similar limitations to aforementioned solution since runtime reconfiguration mechanism relies on artifacts computed at design-time.

In [11], the authors present a tool called *Planit* for deployment and reconfiguration of component-based applications. Planit uses a temporal planner and is based on a *sense-plan-act* model for fault detection, diagnosis, and reconfiguration to recover from runtime application failures. As such, it is similar to our work presented in this chapter. In order to facilitate the runtime planning, Planit allows modeling of both, implicit and explicit configurations at design-time. Although our reconfiguration mechanism is also based on implicitly encoded configuration (we call this configuration space), we capture this encoding in a very generic manner. To be precise, we use a goal-based system description approach to

ensure loose coupling between requirements and actual software entities that fulfill those requirement. However, in Planit, implicit encoding is defined in terms of low-level software artifacts such as components and their connections. We believe that a solution for extensible CPS needs to provide better flexibility to account for dynamism.

V.6 Concluding Remarks

This chapter presented a self-reconfiguration mechanism that can be used to facilitate autonomous resilience, which is important for extensible CPS. The self-reconfiguration mechanism, presented in this chapter, is based on dynamic constraints that represent a system and a Satisfiability Modulo Theories (SMT) solver that makes use of those constraints to compute valid system state in order to reconfigure a system.

The work presented in this chapter has couple of shortcomings. First, the self-reconfiguration mechanism is non-deterministic since it uses a SMT solver, which essentially searches a dynamic search space (*i.e.*, collection of constraints that represents a system) at runtime. On one hand, this technique is important as extensible CPS are dynamic and any reconfiguration mechanism used should execute at runtime rather than at design-time when all possible failures cannot be forecasted. While, on the other hand, this technique results in long reconfiguration time when used for large-scale systems; this becomes problematic for real-time systems as they have to be highly available, and therefore, cannot incur long reconfiguration times. To address this issue, next chapter (Chapter VI) presents a pre-computation-based variation of the mechanism presented in this chapter.

Second shortcoming of this work is that the design-time resilience analysis tool is not part of the runtime self-reconfiguration mechanism. In an ideal solution, it is essential to incorporate design-time analysis and validation tools to the runtime self-reconfiguration mechanism because it is important to ensure that any reconfiguration solution computed at runtime, by the self-reconfiguration mechanism, is valid. This is a complex problem and will be part of the future work.

Note of Acknowledgement: *The initial part of this work, which includes the underlying idea of using various Satisfiability Modulo Theories (SMT) constraints and computing resilience metrics, was performed by Dr. Tihamer Levendovszky when he was a Research Assistant Professor at Vanderbilt University. This work presents extension of his initial contribution, as well as, a complete implementation and experiments for validation. His contribution and guidance have been instrumental in completing this work.*

V.7 Related Publications

1. Subhav Pradhan, Abhishek Dubey, Tihamer Levendovszky, Pranav Kumar, William Emfinger, Daniel Balasubramanian, William Otte, and Gabor Karsai. Achieving Resilience in Distributed Software Systems via Self-Reconfiguration. *Journal of Systems and Software (JSS 2016)*.

2. Subhav Pradhan, William Otte, Abhishek Dubey, Aniruddha Gokhale, and Gabor Karsai. Towards a Resilient Deployment and Configuration Infrastructure for Fractionated Spacecraft. *Proc. of the 5th Workshop on Adaptive and Reconfigurable Embedded Systems (APRES 2013)*, pages 29 - 32, Philadelphia, PA, USA.

3. Subhav Pradhan, Abhishek Dubey, Aniruddha Gokhale, and Martin Lehofer. WiP Abstract: Platform for Designing and Managing Resilient and Extensible CPS. *Proc. of the 7th International Conference on Cyber-Physical Systems (ICCPS 2016)*, pages 1 - 1, Vienna, Austria.

CHAPTER VI

A HOLISTIC SOLUTION FOR MANAGING EXTENSIBLE CPS

VI.1 Motivation

This chapter presents a holistic solution, called CHARIOT (*Cyber-pHysical Application aRchItecture with Objective-based reconfiguraTion*), for managing extensible CPS. The motivation for the work presented in this chapter is the same as that of the previous chapter (see Section V.1). This is because the work presented in this chapter extends the work presented in the previous chapter by (1) using the concept of generic component types during design-time and adding the capability to compute exact component instances from available component types at runtime, (2) encoding redundancy patterns using Satisfiability Modulo Theory (SMT) constraints, and (3) adding the capability to use a finite horizon look-ahead strategy that pre-computes solution to significantly improve the performance of the Configuration Point Computation (CPC) algorithm presented in previous chapter (see Section V.3.3.2).

Furthermore, instead of using the same motivating scenario of a fractionated satellite cluster, this chapter uses a different motivating scenario. Consider an indoor parking management system installed in a garage. This case study focuses on the vacancy detection and notification functionality. This system is designed to make it easier for clients to use parking facilities by tracking the availability of spaces in a parking lot and servicing client parking requests by determining available parking spaces and assigning a specific parking space to a client. We use this system as a running example throughout the rest of this chapter to explain various aspects of CHARIOT. Figure 28 visually depicts this system; it consists of a number of pairs of camera nodes (wireless camera) and processing nodes

(Intel Edison module mounted on Arduino board)[1] placed on the ceiling to provide coverage for multiple parking spaces. Each pair of a camera and a processing node is connected via a wired connection. In addition, the parking lot has an entry terminal node that drivers interact with to as they enter the parking lot.

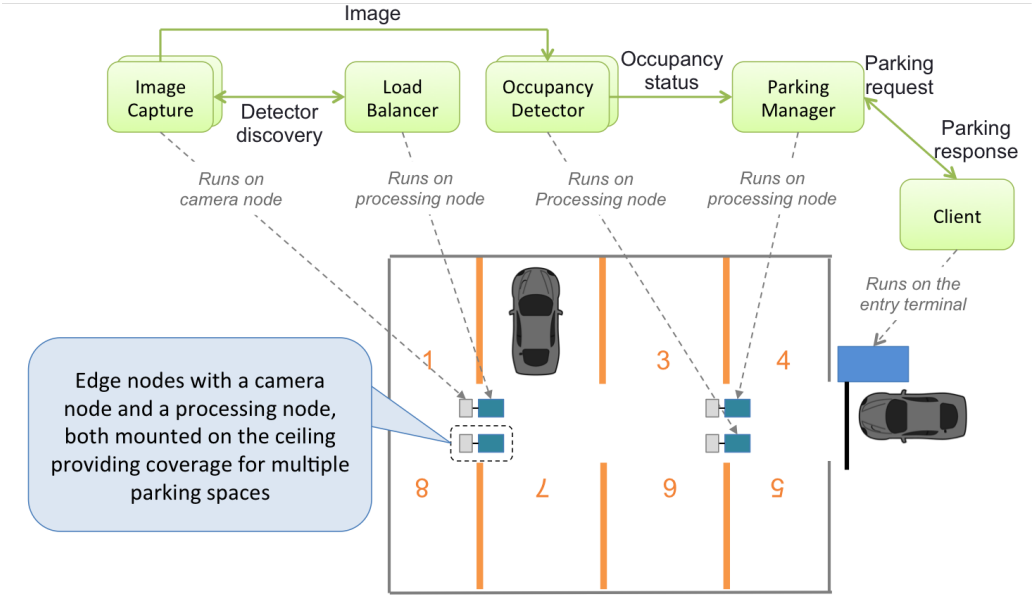


Figure 28: An Overview of the Parking Management System Case Study.

In addition to the hardware devices that comprises the system, Figure 28 also shows a distributed application consisting of five different types of components deployed on the hardware outlined above. An *ImageCapture* component runs on a camera node and periodically captures an image and sends it to an *OccupancyDetector* component that runs on a processing node. An *OccupancyDetector* component detects vehicles in an image and determines occupancy status of parking spaces captured in the image. For an *ImageCapture* component to send images to an *OccupancyDetector* component, it must first find the *OccupancyDetector* by using the *LoadBalancer* component, which also runs on

[1] https://www.arduino.cc/en/ArduinoCertified/IntelEdison

a processing node. The *LoadBalancer* component keeps track of the different *OccupancyDetector* components available. After an *OccupancyDetector* component analyses an image for occupancy status of different parking spaces, it sends the result to the *ParkingManager* component, which keeps track of occupancy status of the entire parking lot. The *ParkingManager* component also runs on a processing node. The fifth and final component comprising the smart parking application is the *Client* component, which runs on the entry terminal and interacts with users to allow them to query, reserve, and use the parking lot.

VI.2 Problem Description

Similar to the previous chapter, the work presented in this chapter also focuses on the problem of autonomous resilience for extensible CPS. The case study shown in Section VI.1 motivates the need for orchestration middleware like CHARIOT to manage deployment, execution, and update phases. For example, middleware capable of deploying distributed applications is quite useful in a large multi-level parking garage. Likewise, managing the life-cycle of previously deployed applications during the execution phase is also important. Factors that could trigger execution phase management actions vary from optimization to resilience. For example, it is essential to ensure that the *ParkingManager* component is not a single point of failure, *i.e.*, the smart parking system should not fail if the *ParkingManager* component fails. We therefore require middleware that can detect failures, determine if a failure affects the *ParkingManager* component, and if it does, then autonomously reconfigure the system so that a *ParkingManager* component is always available. Reconfiguration of an extensible CPS requires a certain amount of time, which might not be acceptable for safety-critical, real-time systems. In such scenarios, the only viable solution is to have redundant copies of applications.

Addressing the problems described above requires a solution that holistically addresses

both (1) the design-time challenges of capturing the system description, and (2) the run-time challenges of implementing the dynamic reconfiguration strategies. In particular, the following key factors must be considered by such a solution:

1. ***Failure avoidance***, which is necessary since failures can cause downtime. Extensible CPS consist of hardware components that degrade over time and hence eventually fail. Likewise, software applications can also fail due to various defects. Since these types of failures cannot be avoided altogether in an extensible CPS, one approach to handling failure is to minimize its impact.
2. ***Failure management***, which is needed to minimize downtime due to failures that cannot be avoided, including failures caused by unanticipated changes. The desired solution should ensure all application goals are satisfied for as long as possible, even after failures.
3. ***Operations management***, which is needed to minimize the challenges faced when intentionally changing or evolving an existing extensible CPS, *i.e.*, these are *anticipated* changes. A solution for this should consider changes in hardware resources and software applications.

VI.3 Solution Approach

This section presents detailed description of CHARIOT. First, an overview of the solution approach is presented, after which detailed description of the three different layers of CHARIOT is presented.

VI.3.1 Overview of the Solution Approach

CHARIOT implements a three-layered architecture stack consisting of a design layer, a data layer, and a management layer, as shown in Figure 29. The design layer is implemented via a generic system description language that captures system specifications in terms of different kinds of available hardware resources, software applications, and

the resource provided/required relationship between them. As described later in Section VI.3.2, CHARIOT implements this layer using a *domain-specific modeling language* (DSML) called CHARIOT-ML whose goal-based system description approach yields a generic means of describing complex extensible CPS.

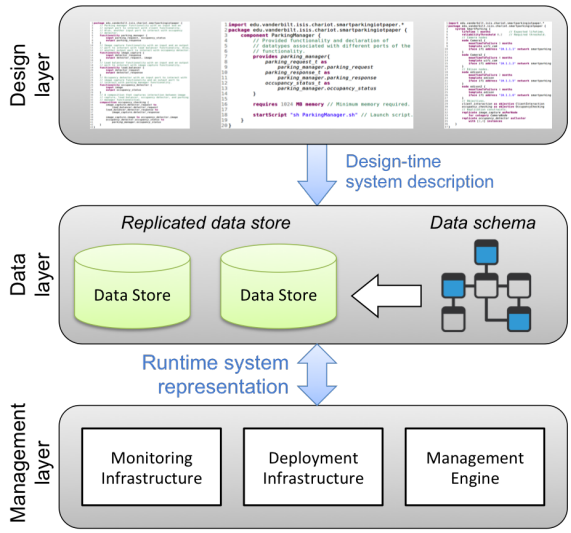


Figure 29: The Layered Architecture of CHARIOT.

In the middle of CHARIOT's stack is a data layer implemented using a persistent data storage and the corresponding well-defined schema to store system information, which includes a design-time system description and a runtime representation of the system. This layer canonicalizes the format in which information about extensible CPS is represented. We present the details of this contribution in Section VI.3.3.

The bottom of CHARIOT's stack is a management layer that comprises monitoring and deployment infrastructures, as well as a novel management engine that facilitates application (re)configuration as a mechanism to support autonomous resilience. As described later in Section VI.3.4, this management engine uses system information stored in the persistent storage to formulate Satisfiability Modulo Theories (SMT) constraints that encode system

properties and requirements, enabling the use of SMT solvers (such as Z3 [26]) to dynamically compute optimal system (re)configuration at runtime. Here it is important to note that the underlying technology and concept used for reconfiguration is similar to that presented in the previous chapter (Chapter V). However, as previously mentioned in Section VI.1, the work presented in this chapter is an extension of the previous chapter and has distinct novel contributions.

CHARIOT handles failure avoidance via functionality redundancy and optimal distribution of redundant functionalities. The general idea here is to be able to tolerate more failures by strategically deploying redundant copies of components that provide critical functionalities, such that more failures are avoided/tolerated without having to reconfigure the system; further description of functionality redundancy is presented in Section VI.3.2.2.

Failure management is handled using the above-described sense-plan-act loop. The *Monitoring Infrastructure* is responsible for detecting failures; this is the *sensing* phase. After failure detection, it is the responsibility of the *Management Engine* to determine the actions needed to reconfigure the system such that failures are mitigated; this is the *planning* phase and is based on Z3 [26], which is an open source Satisfiability Modulo Theories (SMT) solver. Once reconfiguration actions are computed, the *Deployment Infrastructure* is responsible for taking those actions to reconfigure the system; this is the *acting* phase. Since failure detection and diagnosis have been extensively studied in existing literature, the focus of this chapter is strictly on the second (planning) and third (acting) phases of the self-reconfiguration loop; this is presented in Section VI.3.4. We use capabilities supported out-of-the-box by ZooKeeper [46] to implement a monitoring infrastructure based on a group membership mechanism (see Setion VI.4.1.2).

Operations management is required to handle anticipated changes (*i.e.*, planned update or evolution). These changes include both hardware and software changes carried out at runtime. Addition of new nodes and removal of existing nodes are example of hardware changes. Similarly, addition of new applications, removal of existing applications, and

modification of existing applications are example of software changes. While failure management is triggered by detection of failures, operations management can be triggered for various reason. A software related change is always instigated from changes made to the appropriate design-time system model. So, for a software related change there is no detection mechanism; the trigger has to be human/manual invocation of the management engine. However, in the case of a hardware related change, since hardware nodes are not modeled explicitly as part of a design-time system model, some external entity is required to detect these changes and invoke the management engine. This detection is also done by the group membership mechanism presented in Section VI.4.1.2.

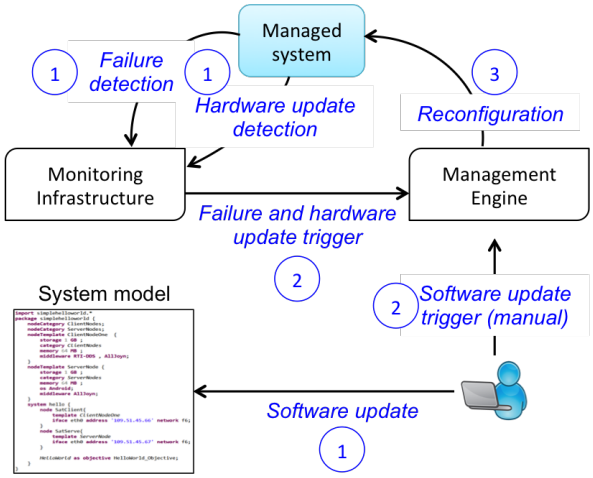


Figure 30: Reconfiguration Triggers associated with Failure Management and Operations Management.

To summarize detection and reconfiguration trigger mechanisms associated with failure management and operations management, we present Figure 30 as an overview. As shown in the figure, reconfiguration for failure management and hardware update (operations management) is triggered by the monitoring infrastructure. Whereas, reconfiguration for software update (operations management) is manually triggered once the system model is updated.

VI.3.2 The CHARIOT Design Layer

This section describes the CHARIOT design layer, which addresses the requirement of a design-time entity to capture system descriptions. CHARIOT's design layer allows implicit and flexible system description prior to runtime. In general, an extensible CPS can be described in terms of required components or it could be described in terms of functionalities provided by components. The former approach is inflexible since it tightly couples specific components with the system. CHARIOT therefore supports the latter approach, which is more generic and flexible since it describes the system in terms of required functionalities, so that different components can be used to satisfy system requirements, depending on their availability.

A key challenge we faced when creating CHARIOT was to devise a design-time environment whose system description mechanism could capture system information (*e.g.*, properties, provisions, requirements, and constraints) *without* explicit management directives (*e.g.*, *if node A fails, move all components to node B*). The purpose of this mechanism is to enable CHARIOT to manage failures by efficiently searching for alternative solutions at runtime. Another challenge we faced was how to devise abstractions that ensure both correctness *and* flexibility so CHARIOT can easily support operations management.

To meet the challenges described above, CHARIOT's design layer allows application developers to model extensible CPS using a generic system description mechanism supported by CHARIOT-ML, which is our design-time modeling environment. We implement this mechanism leveraging the goal-based system description approach described in previous chapter (see Section V.2.1). As shown in Figure 31, the key entities modeled as part of a system's description using CHARIOT-ML are: (1) hardware resource categories and templates, (2) different types of components that provide various functionalities, and (3) goal descriptions corresponding to different applications that must be hosted on available resources. Since extensible CPS applications are generally mission-specific, their goals

should be satisfied during a specified amount of time. CHARIOT defines a *goal* as a collection of *objectives*, where each objective is a collection of *functionalities* that can have inter-dependencies.

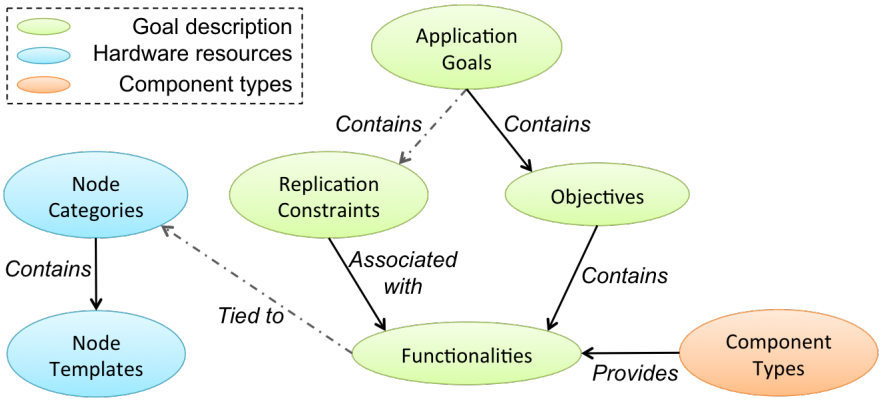


Figure 31: CHARIOT-ML Modeling Concepts and their Dependencies.

CHARIOT's design layer concretizes the functionality tree described in Section V.2.1. It currently enforces a two-layer functionality hierarchy, where *objectives* are high-level functionalities that satisfy goals and *functionalities* are leaf nodes associated with component types. When these component types are instantiated, each component instance provides associated functionalities. To maximize composability and reusability, a component type can only be associated with a single functionality, though multiple component types can provide the same functionality.

To further elaborate CHARIOT's design layer the remainder of this section presents the system description of the smart parking system initially presented in Section VI.1. Figure 32 shows the corresponding functionality tree, which is used below to describe the different entities comprising the system's description using snippets of models built using CHARIOT-ML.

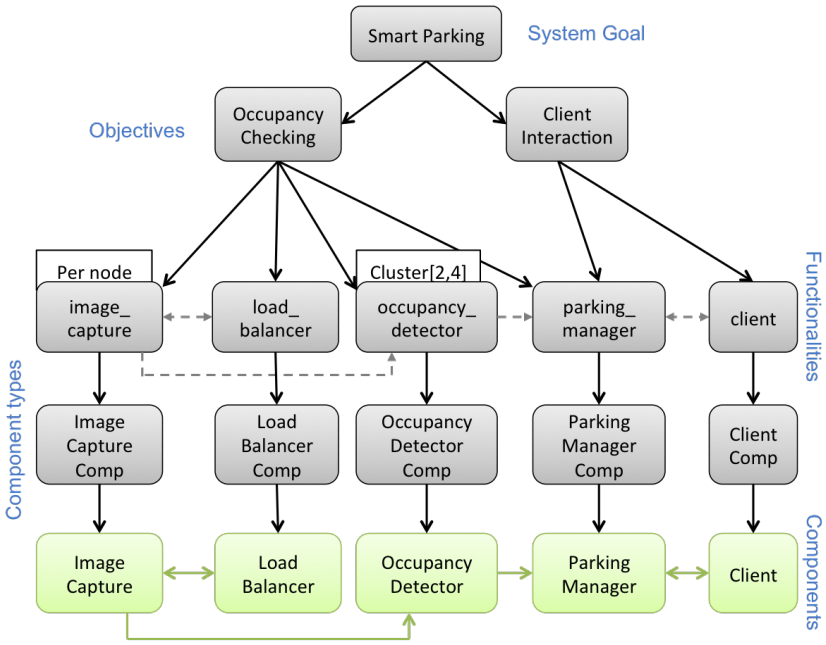


Figure 32: Parking System Description for the example shown in figure 28.

VI.3.2.1 Node Categories and Templates

Since physical nodes are part of an extensible CPS, CHARIOT-ML models them using categories and templates. The nodes are not explicitly modeled since the group of nodes comprising a system can change dynamically at runtime. The degree of dynamicity varies from one system to another; for example, a smart parking system is far less dynamic when compared to a fractionated satellite cluster. As such, in CHARIOT we only model *node categories* and *node templates*. A node category can be defined as a logical concept used to establish groups of nodes; every node that is part of a extensible CPS belongs to a certain node category.

Since we do not explicitly model nodes at design-time, we use the concept of node templates to represent the kinds of nodes that can belong to a category. Therefore, a node category is a collection of node templates and a node template is a collection of generic information (such as memory, CPU, devices, etc) that can be associated with any node that is an instance of the node template. When a node joins a cluster at runtime the only information it needs to provide (beyond node-specific network information) is which node

```
1 import edu.vanderbilt.isis.chariot.smartparkingiotpaper.*
2 package edu.vanderbilt.isis.chariot.smartparkingiotpaper {
3     nodeCategory CameraNode {
4         // Template for Wi-Fi enabled (wireless IP)
5         // camera nodes.
6         nodeTemplate wifi_cam {
7             memory 32 MB
8             storage 1024 MB     // 1 GB external
9         }
10    }
11
12    nodeCategory ProcessingNode {
13        // Template for Edison nodes.
14        nodeTemplate edison {
15            memory 1024 MB      // 1 GB
16            storage 4096 MB     // 4 GB
17        }
18    }
19
20    nodeCategory TerminalNode {
21        // Template for entry termial nodes.
22        nodeTemplate entry_terminal {
23            memory 1024 MB      // 1 GB
24            storage 8192 MB     // 8 GB
25        }
26    }
27 }
```

Figure 33: Snippet of Node Categories and Node Templates Declarations.

template it is an instance of. The concept of node categories becomes important when assigning a per-node replication constraint (discussed in Section VI.3.2.2), which requires that a functionality be deployed on each node of the given category.

Figure 33 presents the node categories and templates for the smart parking system. As shown in this figure, there are three categories of nodes: *CameraNode* (line 3-10), *ProcessingNode* (line 12-18), and *TerminalNode* (line 20-26). Each category contains one template each. The *CameraNode* category contains a *wifi_cam* template that represents a Wi-Fi enabled wireless IP camera. The *ProcessingNode* category contains an *Edison* template that represents an Edison board. The *TerminalNode* category contains an *entry_terminal* template that represents a parking control station placed at an entrance of a parking space. This scenario is consistent with the smart parking system described in Section VI.1.

VI.3.2.2 Goal Description

The goal description for the smart parking application is shown in Figure 34 . The goal itself is declared as *SmartParking* (line 3). Following the goal declaration is a list

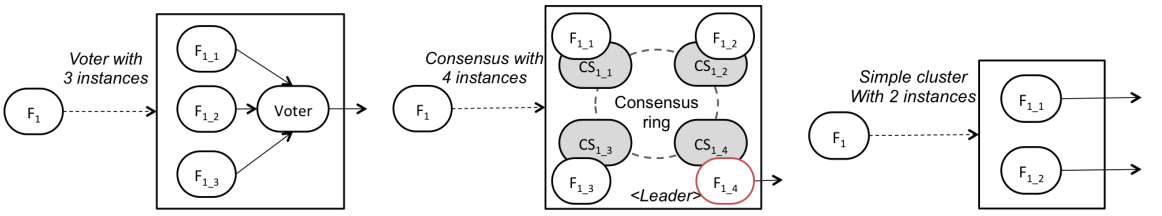
of the objectives required to satisfy the goal (line 5-6). Two objectives are defined in this example: the *ClientInteraction* objective and the *OccupancyChecking* objective. The *ClientInteraction* objective is related to the task of handling client parking requests, whereas the *OccupancyChecking* objective is related to the task of determining the occupancy status of different parking spaces.

```
1 import edu.vanderbilt.isis.chariot.smartparkingiotpaper.*
2 package edu.vanderbilt.isis.chariot.smartparkingiotpaper {
3     goalDescription SmartParking {
4         // Objectives.
5         client_interaction as objective ClientInteraction
6         occupancy_checking as objective OccupancyChecking
7
8         // Replication constraints.
9         replicate image_capture asPerNode
10            for category CameraNode
11        replicate parking_client asPerNode
12            for category TerminalNode
13        replicate occupancy_detector asCluster
14            with [2,4] instances
15    }
16 }
```

Figure 34: Snippet of Smart Parking Goal Description Comprising Objectives and Replication Constraints.

In CHARIOT-ML, objectives are instantiations of compositions (see Section VI.3.2.3). The *ClientInteraction* objective instantiates the *client_interaction* composition (line 5) and the *OccupancyChecking* objective instantiates the *occupancy_checking* composition (line 6). A description of how we model these compositions in CHARIOT-ML is presented in Section VI.3.2.3. After the objectives are modeled as part of a system, CHARIOT-ML allows the association of those objectives's functionalities with replication constraints. For example, Figure 34 shows the association of the *image_capture* functionality with a per-node replication constraint (line 9-10), which means this functionality should be present on each node that is an instantiation of any node template belonging to *CameraNode* category. Similarly, the *parking_client* functionality is also associated with a per-node replication

constraint (line 11-12) for *TerminalNode* category. Finally, the *occupancy_detector* functionality is associated with a cluster replication constraint (line 13-14), which means this functionality should be deployed as a cluster of at-least 2 and at-most 4 instances.



(a) Voter pattern with factor = 3. (b) Consensus pattern with factor = 4. (c) Cluster pattern with factor = 2.

Figure 35: Example Redundancy Patterns for Functionality F_1. The CS_{n_m} entities represent consensus service providers.

CHARIOT-ML supports functionality replication using four different redundancy patterns: the (1) voter pattern, (2) consensus pattern, (3) cluster pattern, and (4) per-node pattern, as shown in Figure 35. The per-node pattern (as described above for the *image_capture* functionality) requires that the associated functionality be replicated on a per-node basis. Replication of functionalities associated with the other three redundancy patterns is based on their redundancy factor, which can be expressed by either (1) explicitly stating the number of redundant functionalities required or (2) providing a range. The latter (as previously described for the *occupancy_detector* functionality) requires the associated functionality to have a minimum number for redundancy and a maximum number for redundancy, *i.e.*, if the number of functionalities present at any given time is within the range, the system is still valid and no reconfiguration is required.

Figure 35 presents a graphical representation of voter, consensus, and cluster redundancy patterns (the case of the consensus pattern, *CS* represents consensus services). Different redundancy factors are used for each. As shown in the figure, the voter pattern involves a voter in addition to the functionality replicas; the consensus pattern involves

a consensus service each for the functionality replicas and these consensus services implement a consensus ring; and the cluster pattern only involves the functionality replicas. Implementing the consensus service is beyond the scope this dissertation. We envision using existing consensus protocols, such as Raft [79], for this purpose.

VI.3.2.3 Functionalities and Compositions

Functionalities in CHARIOT-ML are modeled as entities with one or more input and output ports, whereas compositions are modeled as a collection of functionalities and their inter-dependencies. Figure 36 presents four different functionalities (*parking_manager*, *image_capture*, *load_balancer*, and *occupancy_detector*) and the corresponding composition (*occupancy_checking*) that is associated with the *OccupancyChecking* objective (see line 6 in Figure 34). This figure also shows that composition is a collection of functionalities and their inter-dependencies, which are captured as connections between input and output ports of different functionalities.

VI.3.2.4 Component Types

CHARIOT-ML does not model component instances, but instead models component types. As discussed earlier in Section VI.3.2, each component type is associated with a functionality. When a component type is instantiated, the component instance provides the functionality associated with its type. A component instance therefore only provides a single functionality, whereas a functionality can be provided by component instances of different types. Two advantages of modeling component types instead of component instances include the flexibility it provides with respect to (1) the number of possible runtime instances of a component type and (2) the number of possible component types that can provide the same functionality.

Figure 37 shows how the *ParkingManager* component type is modeled in CHARIOT-ML. As part of the component type declaration, we first model the functionality that is

```
package edu.vanderbilt.isis.chariot.smartparkingiotpaper {
    // Parking manager functionality with an input and an
    // output port to interact with client functionality.
    // Also, another input port to interact with occupancy
    // detector.
    functionality parking_manager {
        input parking_request, occupancy_status
        output parking_response
    }
    // Image capture functionality with an input and an output
    // port to interact with load balancer functionality. Also,
    // another output port to interact with occupancy detector.
    functionality image_capture {
        input detector_response
        output detector_request, image
    }
    // Load balancer functionality with an input and an output
    // port to interact with image capture functionality.
    functionality load_balancer {
        input detector_request
        output detector_response
    }
    // Occupancy detector with an input port to interact with
    // image capture functionality and an output port to
    // interact with parking manager functionality.
    functionality occupancy_detector {
        input image
        output occupancy_status
    }
    // A composition that captures interaction between image
    // capture, load balancer, occupancy detector, and parking
    // manager functionalities.
    composition occupancy_checking {
        image_capture.detector_request to
            load_balancer.detector_request
        load_balancer.detector_response to
            image_capture.detector_response

        image_capture.image to occupancy_detector.image
        occupancy_detector.occupancy_status to
            parking_manager.occupancy_status
    }
}
```

Figure 36: Snippet of Functionalities and Corresponding Composition Declaration.

```
import edu.vanderbilt.isis.chariot.smartparkingiotpaper.*
package edu.vanderbilt.isis.chariot.smartparkingiotpaper {
    component ParkingManager {
        provides parking_manager  // Provided functionality.

        requires 128 MB memory // Minimum memory required.

        startScript "sh ParkingManager.sh" // Launch script.
    }
}
```

Figure 37: Snippet of Component Type Declaration.

provided by the component (line 4). After the functionality of a component type is modeled, we model various resource requirements (Figure 37 only shows memory requirements in line 6) and the launch script (line 8), which can be used to instantiate an instance of the component by spawning an application process.

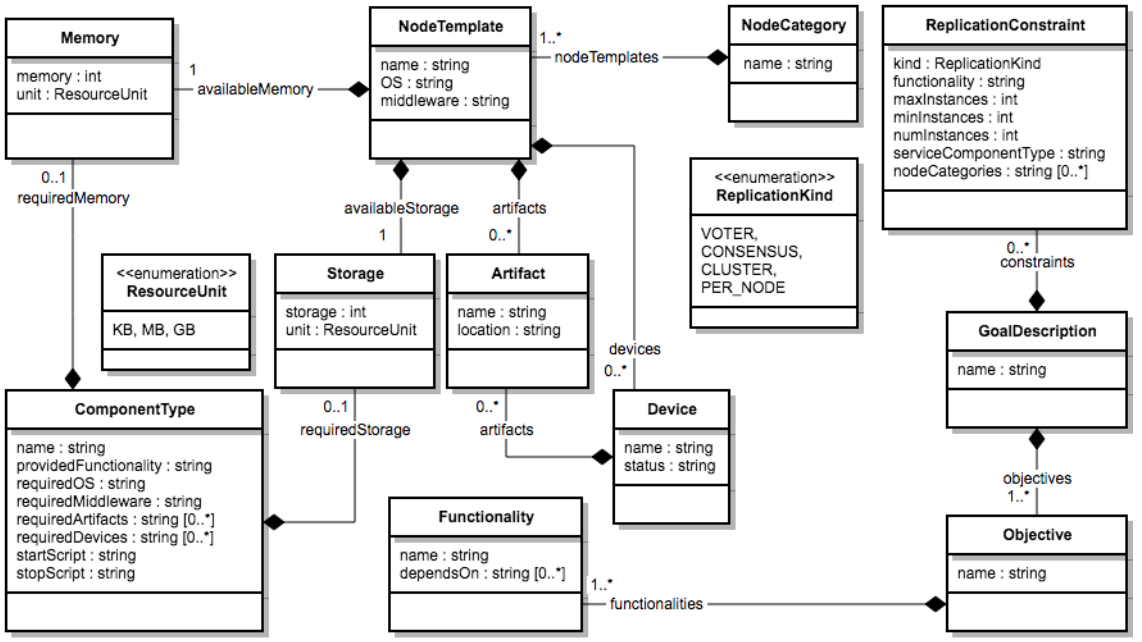
CHARIOT supports two different types of component types: hardware components and software components. The component type presented in Figure 37 is an example of a software component. Hardware components are modeled in a similar fashion, though we just model the functionality provided by a hardware component and nothing else since a hardware component is a specific type of component whose lifecycle is tightly coupled to the node with which it is associated. A hardware component is therefore never actively managed (reconfigured) by the CHARIOT orchestration middleware. The only thing that affects the state of a hardware node is the state of its hosting node, *i.e.*, if the node is on and functioning well, the component is active and if it is not, then the component is inactive.

In context of the smart parking system case study presented in this chapter, the *ImageCapture* component is a hardware component that is associated with camera nodes. As a result, an instance of the *ImageCapture* component runs on each active camera node. We model this requirement using the per-node redundancy pattern (see line 32-33 in Figure 34). Likewise, the failure of a camera node implies failure of the hosted *ImageCapture* component instance, so this failure cannot be mitigated.

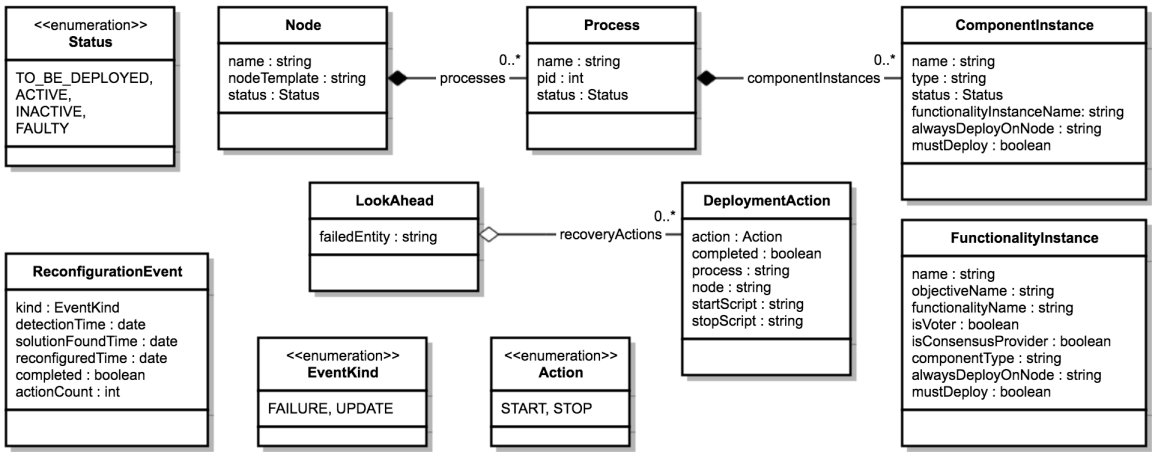
VI.3.3 The CHARIOT Data Layer

This section presents the CHARIOT data layer, which defines a schema that forms the basis for persistently storing system information, such as design-time system description and runtime system information. This layer codifies the format in which system information should be represented. A key advantage of this codification is its decoupling of CHARIOT's design layer (top layer) from its management layer (bottom layer), which yields a flexible architecture that can accommodate varying implementations of the design

layer, as long as those implementations adhere to the data layer schema described in this section.



(a) Schema to Store Design-time System Descriptions.



(b) Schema to Store Runtime System Representations.

Figure 38: UML Class Diagrams for Schemas Used to Store System Information.

Figure 38 presents UML class diagrams as schemas used to store design-time system description and runtime system information. These schemas are designed for document-oriented databases. An instance of a class that is not a child in a composition relationship

therefore represents a root document. Below we describe CHARIOT's design-time and runtime schemas in detail.

VI.3.3.1 Design-time System Description Schema

The schema for design-time system description comprises entities to store node categories, component types, and goal descriptions, as shown in Figure 38a. As discussed in Section VI.3.2.1, a node category is a concept used to establish logical groups of nodes that form part of an extensible CPS. It contains a collection of node templates, which provide a generic specification of a type of node. The *NodeCategory* class therefore consists of a unique name and a list of node templates. Likewise, the *NodeTemplate* class consists of a unique name and a set of specification attributes, such as available operating system, middleware, memory, storage, software artifacts, and devices.

In addition to node categories, a design-time system description schema also captures component types available for extensible CPS applications. Neither node categories nor component types are application-specific since multiple applications can be simultaneously hosted on nodes of an extensible CPS and a component type can be used by multiple applications.The *ComponentType* class consists of a unique name and a set of other attributes such as (1) name of the functionality provided, (2) required operating system, middleware, memory, storage, software artifacts, and required devices, and (3) scripts that can be used to start and stop an instance of the component type, as shown in Figure 38a.

A design-time system description schema also consists of goal descriptions. As discussed in Section VI.3.2, a goal description is application-specific and it describes the goal of an application in terms of objectives and functionalities required to satisfy the goal. The *GoalDescription* class consists of a unique name and a set of objectives and constraints, as shown in Figure 38a. Moreover, objectives are represented by the *Objective* class,w hich consists of a unique name and a set of functionalities.

In addition to objectives and functionalities, a goal description can also contain replication constraints. The *ReplicationConstraint* class represents replication constraints, as shown in Figure 38a. As described in Section VI.3.2.2, a replication constraint has a kind, which can either be a voter, consensus, cluster, or per-node. A replication constraint should always be associated with a functionality. The *maxInstances*, *minInstance*, and *numInstances* attributes are related to the degree of replication. The latter attribute is used if a specific number of replica is required, whereas the former two attributes are used to describe a range-based replication. The *nodeCategories* attribute is used for per-node replication constraints. The *serviceComponentType* attribute is related to specific component types that provide special replication services, such as a component type that provides a voter service or a consensus service.

VI.3.3.2 Runtime System Information Schema

The schema for runtime system information comprises entities to store functionality instances, nodes, deployment actions, reconfiguration events, and look-ahead information, as shown in Figure 38b. The *FunctionalityInstance* class consists of a unique name, name of the associated functionality and objective, boolean flags to indicate whether a functionality instance corresponds to the voter of a voter replication group (*isVoter* attribute) or a consensus service provider of a consensus replication group (*isConsensusProvider*). The *FunctionalityInstance* class also consists of a *ComponentType* attribute to store exact component type of a functionality instance; this attribute is only relevant for voter and consensus service providing functionality instances as they are not associated with a separate functionality that is part of a goal description. Furthermore, the *FunctionalityInstance* class also consists of an *alwaysDeployOnNode* attribute, which ties a functionality instance to a specific node and is only relevant for functionality instances related to per-node replication groups. Finally, a *mustDeploy* boolean attribute of the *FunctionalityInstance* class indicates whether a functionality instance should always be deployed.

The *Node* class consists of a unique name, associated node template, node status, and a list of hosted processes. For the latter, the *Process* class is used and it consists of a unique name, process ID, status, and a list of hosted component instances. Similarly, the *ComponentInstance* class represents component instances and it consists of a unique name, name of the component type it implements, status, name of the corresponding functionality instance as a component instance is always associated with a functionality instance (see Section VI.3.4.2), node name (*alwaysDeployOnNode*) if a component instance needs to be always deployed on that node as part of a per-node replication constraint, and a *mustDeploy* boolean attribute to determine if a component instance must always be deployed.

The *DeploymentAction* class represents runtime deployment actions that are computed by the CHARIOT management engine to (re)configure a system. The *DeploymentAction* class consists of an action, a *completed* boolean flag to indicate if an action has been taken or not, process affected by the action, node on which the action should be performed, and scripts to perform the action. CHARIOT supports two kinds of actions: start actions and stop actions. The *LookAhead* class represents pre-computed solutions related to CHARIOT's finite-horizon look-ahead strategy described in Section VI.3.4.3. It consists of attributes that represents a failed entity, and a set of recovery actions (deployment actions) that must be performed to recover from the failure.

Finally, the *ReconfigurationEvent* class represents runtime reconfiguration events. It is used to keep track of different failure and update events that triggers system reconfiguration. It consists of *detectionTime*, *solutionFoundTime*, and *reconfiguredTime* to keep track of when a failure or update was detection, when a solution was computed, and when the computed solution was deployed. It also consists of a *completed* boolean attribute to indicate whether a reconfiguration event is complete or not and an *actionCount* attribute to keep track of number of actions required to complete a reconfiguration event.

VI.3.4 The CHARIOT Management Layer

The CHARIOT management layer comprises a monitoring infrastructure, deployment infrastructure, and a management engine, as shown in Figure 29. The monitoring, deployment, and configuration of distributed applications are well studied, so CHARIOT implements these capabilities using existing technologies, as described in Section VI.4.1. This section therefore focuses on CHARIOT's management engine, which is a novel contribution that facilitates self-reconfiguration of extensible CPS managed via CHARIOT.

VI.3.4.1 Configuration Space and Points

The general idea behind CHARIOT's self-reconfiguration approach is similar to that presented in the previous chapter (see Section V.2.3.2). As such the self-reconfiguration approach relies on the concepts of *configuration space* and *configuration points*. If a system's state is represented by a configuration point in a configuration space, then reconfiguration of that system entails moving from one configuration point to another in the same configuration space. The remainder of this section describes these concepts and presents CHARIOT's core reconfiguration mechanism and configurable look-ahead strategy.

For the work presented in this chapter we consider a configuration space to include (1) goal descriptions of different application, (2) replication constraints corresponding to redundancy patterns associated with different applications, (3) component types that can be used to instantiate different component instances and therefore applications, and (4) available resources, which includes different nodes and their corresponding resources, such as memory, storage, and computing elements. At any given time a configuration space of an extensible CPS can represent multiple applications associated with the system. A configuration space can therefore contain multiple configuration points, which represent valid configurations of all applications that are part of the system represented by the configuration space.

A configuration point is a valid configuration of a system which represents component-instance-to-node mappings (*i.e.*, a deployment) for all component instances needed to realize different functionalities essential for the objectives required to satisfy goals of one or more applications. The initial configuration point represents the initial (baseline) deployment, whereas, current configuration point represents the current deployment.

VI.3.4.2 Computing the Configuration Points

Given the description of configuration space and points, a valid reconfiguration mechanism should be based on transitions between configuration points. The *Configuration Point Computation* (CPC) algorithm serves this purpose and thus defines the core of CHARIOT's self-reconfiguration mechanism. Although a version of the CPC algorithm is presented in the previous chapter (see Section V.3.3.2), the version of the CPC algorithm presented in this section (1) extends the prior version by accounting for the concept of abstract component types and generating concrete component instances out of them, and (2) describes the SMT constraint encodings in much more detail. As such, the CPC algorithm presented in this section can be decomposed into three phases: the (1) instance computation phase, (2) constraint encoding phase, and (3) solution computation phase, as described below.

Phase 1, Instance Computation Phase:

The first phase of a CPC computes required instances of different functionalities and subsequently components, based on the system description provided at design-time. Each functionality can have multiple instances if it is associated with a replication constraint. Each functionality instance should have a corresponding component instance that provides the functionality associated with the functionality instance. Depending upon the number of component types that provide a given functionality, a functionality instance can have multiple component instances. Only one of the component instances will be deployed at runtime, however, so there is always be a one-to-one mapping between a functionality instance and a deployed component instance.

The CPC algorithm first computes different functionality instances using Algorithm 5, which is invoked for each objective. Every functionality is initially checked for replication constraints (line 3). If a functionality does not have a replication constraint, a single functionality instance is created (line 32). For every functionality that has one or more replication constraints associated with it, we handle each constraint depending on the type of the constraint. A per-node replication constraint is handled by generating a functionality instance and an *assign* constraint each for applicable nodes (line 6-11). An application node is a node that is alive and belongs to the node category associated with the per-node replication constraint.

Algorithm 5 Functionality Instances Computation.

Input: objective (*obj*), nodes (*nodes_list*), computed functionalities (*computed_functionalities*)
Output: functionality instances for *obj* (*ret_list*)

```
1:  for func in obj.functionalities do
2:      if func not in computed_functionalities then                ▷ Make sure a functionality is processed only once.
3:          if func has associated replication constraints then
4:              constraints = all replication constraints associated with func
5:              for c in constraints do
6:                  if c.kind == PER_NODE then                      ▷ Handle per node replication.
7:                      for node_category in c.nodeCategories do
8:                          nodes = nodes in nodes_list that are alive and belong to category node_category
9:                          for n in nodes do
10:                             create functionality instance and add it to ret_list
11:                             add assign (functionality instance, n) constraint
12:                 else
13:                     replica_num = 0          ▷ Initial number of replicas, which will be set to max value if range given.
14:                     range_based = False      ▷ Flag to indicate if a replication constraints is range based.
15:                     if c.numInstances != 0 then
16:                         replica_num = c.numInstances
17:                     else
18:                         range_based = True
19:                         replica_num = c.maxInstances
20:                     for i = 0 to replica_num do                 ▷ Create replica functionality instances.
21:                         create replica functionality instance and add it to ret_list
22:                         if c.kind == CONSENSUS then             ▷ Handle consensus replication.
23:                             create consensus service functionality instance and add it to ret_list
24:                             add implies (replica functionality instance, consensus service functionality instance) constraint
25:                             add collocate (replica functionality instance, consensus service functionality instance) constraint
26:                     if c.kind == VOTER then                     ▷ Handle voter replication.
27:                         create voter functionality instance and add it to ret_list
28:                     if range_based == True then                 ▷ If replication range is given, add atleast constraints.
29:                         add atleast (c.rangeMinValue, replica functionality instances) constraint
30:                     add distribute (replica functionality instances) constraint
31:         else
32:             create functionality instance and add it to ret_list
33:         add func to computed_functionalities
```

Unlike a per-node replication constraint, the voter, consensus, and cluster replication

constraints depend on exact replication value or replication range to determine the number of replicas (line 13-19). In the case of a range-based replication, CHARIOT tries to maximize the number of replicas by using maximum of the range, which ensures that maximum number of failures are tolerated without having to reconfigure the system. After the number of replicas is determined, CHARIOT computes the replica functionality instances (line 21), as well as special functionality instances that support different kinds of replication constraint. For example, for each replica functionality instance in a consensus replication constraint, CHARIOT generates a consensus service functionality instance (line 23) (a consensus service functionality is provided by a component that implements consensus logic using existing algorithms, such as Paxos [53], Raft [79]). For a voter replication constraint, in contrast, CHARIOT generates a single voter functionality instance for the entire replication group (line 27). In the case of a cluster replication constraint, no special functionality instance is generated as a cluster replication comprises independent functionality instances that do not require any synchronization (see Section VI.3.2.2).

To ensure proper management of instances related to functionalities with voter, consensus, or cluster replication constraints, CHARIOT uses four different constraints: (1) implies, (2) collocate, (3) atleast, and (4) distribute. The *implies* constraint ensures all replica functionality instances associated with a consensus pattern require their corresponding consensus service functionality instances (line 24). Similarly, the *collocate* constraint ensures each replica functionality instance and its corresponding consensus service functionality instance are always collocated on the same node (line 25). The *atleast* constraint ensures the minimum number of replicas are always present in scenarios where a replication range is provided (line 28-29). Finally, the *distribute* constraint ensures that the replica functionalities are distributed across different nodes (line 30). CHARIOT's ability to support multiple instances of functionalities and distribute them across nodes enables failure avoidance.

After functionality instances are created, CHARIOT next creates the component instances corresponding to each functionality instance. In general, it identifies a component

type that provides the functionality associated with each functionality instance and instantiates that component type. As explained in Section VI.3.2.4, component types are modeled as part of the system description. Different component types can provide the same functionality, in which case multiple component types are instantiated, but a constraint is added to ensure only one of those instances is deployed and running at any given time. In addition, all constraints previously created in terms of functionality instances are ultimately applied in terms of corresponding component instances. Detailed description of how these constraints are encoded is provided below.

Phase 2, Constraint Encoding Phase:

The second phase of the CPC algorithm is responsible for constraint encoding and optimization. The goal is to represent the configuration space and current configuration point using a set of constraints, which allows CHARIOT to use solvers to compute a new configuration point by solving these constraints. The CHARIOT management engine uses *Satisfiability Modulo Theories* (SMT) [15] for constraint encoding and optimization; its underlying solver is Z3 [26]. To present a generic solution, we first identify a set of constraints and optimization that are required:

1. Since reconfiguration involves transitioning from one configuration point to another, constraints that represent a configuration point are of utmost importance.
2. Constraints to ensure component instances that must be deployed are always deployed.
3. Constraints to ensure component instances that communicate with each other are either deployed on the same node or on nodes that have network links between them.
4. Constraints to ensure resources provided-required relationships are valid.
5. Constraints encoded in the first phase of the CPC algorithm for proper management of component instances associated with replication constraints.
6. Constraints to represent failures, such as node failure or device failures.

The remainder of this section describes how CHARIOT implements the constraints

listed above as SMT constraints. These constraints are generic constraints (also presented briefly in previous chapter, see Table 6) that apply to extensible CPS in different domains, though more constraints can be added for special needs of specific domains. For example, given the availability of period and deadline of all component instances, an extensible CPS with stringent real-time deadlines might require a specific resource constraint that ensures periodic scheduling of applications, *e.g.*, using Rate Monotonic Scheduling or another real-time scheduling algorithm.

As mentioned in Section VI.3.4.1, a configuration point represents a valid deployed of all component instances. A configuration point in CHARIOT is therefore presented using a component-instance-to-node (C2N) matrix, as shown in the previous chapter (see Section V.2.3.2).

Now we need a constraint to ensure component instances that should be deployed are always deployed. At this point it is important to recall range-based replication described in Section VI.3.2.2, which results in a set of instances where a certain number (at least the minimum) should always be deployed, but the remaining (difference between maximum and minimum) are not always required, even though all of them are deployed initially. At any given time, therefore, a configuration point can comprise of some component instances that must be deployed and others that are not always required be deployed. In CHARIOT we encode the must deploy constraint as follows:

Definition 10 (Must deploy assignment)**.** *The "must deploy assignment" constraint is used to ensure all component instances that should be deployed are in fact deployed. This constraint therefore uses the C2N matrix (Equation V.1) and a set of component instances that must be deployed, as shown in Equation VI.1.*

Let M be a set of all component instances that must be deployed.

$$\forall m \in M : \sum_{n=0}^{\beta} c2n_{mn} == 1 \tag{VI.1}$$

The third set of constraints we need ensure that component instances with inter-dependencies (*i.e.*, that communicate with each other) are either deployed on the same node or on nodes that have network links between them. CHARIOT encodes this constraint as follows:

Definition 11 (Dependency Constraint)**.** *This constraint ensures that interacting component instances are always deployed on resources with appropriate network links to support communication. This constraint is encoded in terms of two matrices: a node-to-node (N2N) matrix and a component-instance-to-component-instance (C2C) matrix. The N2N matrix represents network links between nodes and therefore comprises rows and columns that represent different nodes (Equation VI.2). Each element of the N2N matrix is either 0 or 1, where 0 means there exists no link and 1 means there a link exists between the corresponding nodes. The C2C matrix is the same except it comprises rows and columns that both represent component instances (Equation VI.3). The constraint itself is presented in Equation VI.4.*

$$N2N = \begin{bmatrix} n2n_{00} & n2n_{01} & n2n_{02} & \dots & n2n_{0\beta} \\ n2n_{10} & n2n_{11} & n2n_{12} & \dots & n2n_{1\beta} \\ & & \dots\dots\dots\dots & & \\ n2n_{\beta 0} & n2n_{\beta 1} & n2n_{\beta 2} & \dots & n2n_{\beta\beta} \end{bmatrix} =$$

$$n2n_{n_1 n_2} : (n_1, n_2) \in \{0 \dots \beta\}, \beta \in \mathbb{Z}^+ \tag{VI.2}$$

$$C2C = \begin{bmatrix} c2c_{00} & c2c_{01} & c2c_{02} & \dots & c2c_{0\alpha} \\ c2c_{10} & c2c_{11} & c2c_{12} & \dots & c2c_{1\alpha} \\ & & \dots\dots\dots\dots & & \\ c2c_{\alpha 0} & n2n_{\alpha 1} & n2n_{\alpha 2} & \dots & n2n_{\alpha\alpha} \end{bmatrix} =$$

$$c2c_{c_1 c_2} : (c_1, c_2) \in \{0 \dots \alpha\}, \alpha \in \mathbb{Z}^+ \tag{VI.3}$$

Let c_s and c_d be two component instances that are dependent on each other.

$$\forall n_1, \forall n_2 : ((c2n_{c_s n_1} \times c2n_{c_d n_2}) \wedge (n_1 \neq n_2)) \implies (n2n_{n_1 n_2} == c2c_{c_s c_d}) \tag{VI.4}$$

The fourth set of constraints CHARIOT needs ensure the validity of resources provided-required relationships, such that essential component instances of one or more applications can be provisioned. CHARIOT encodes these constraints in terms of resources provided by nodes and required by component instances. Moreover, resources are classified into two categories: (1) cumulative resources and (2) comparative resources. Cumulative resources have a numerical value that increases or decreases depending on whether a resource is used or freed. Examples of cumulative resources include primary memory and secondary storage. Comparative resources have a boolean value, *i.e.*, they are either available or not available and their value does not change depending on whether a resource is used or freed. Examples of comparative resources include devices and software artifacts. These two constraints can be encoded as follows:

Definition 12 (Cumulative resource constraint)**.** *The "cumulative resource" constraint is encoded using a provided resource-to-node (CuR2N) matrix and a required resource-to-component-instance (CuR2C) matrix. The CuR2N matrix comprises rows that represent different cumulative resources and columns that represent nodes; the size of this matrix is $\gamma \times \beta$, where γ is the number of cumulative resources and β is the number of available nodes (Equation VI.5). The CuR2C matrix comprises rows that represent different cumulative resources and columns that represent component instances; the size of this matrix is $\gamma \times \alpha$, where γ is the number of cumulative resources and α is number of component instances (Equation VI.6). Each element of these matrices are integers. The constraint itself (Equation VI.7) ensures that for each available cumulative resource and node, the sum of*

the amount of the resource required by the component instances deployed on the node is less than or equal to the amount of the resource available on the node.

$$CuR2N = \begin{bmatrix} r2n_{00} & r2n_{01} & r2n_{02} & \dots & r2n_{0\beta} \\ r2n_{10} & r2n_{11} & r2n_{12} & \dots & r2n_{1\beta} \\ & & \dots\dots\dots\dots & & \\ r2n_{\gamma 0} & r2n_{\gamma 1} & r2n_{\gamma 2} & \dots & r2n_{\gamma\beta} \end{bmatrix} =$$

$$r2n_{rn} : r \in \{0 \dots \gamma\}, n \in \{0 \dots \beta\}, (\gamma, \beta) \in \mathbb{Z}^+ \tag{VI.5}$$

$$CuR2C = \begin{bmatrix} r2c_{00} & r2c_{01} & r2c_{02} & \dots & r2c_{0\alpha} \\ r2c_{10} & r2c_{11} & r2c_{12} & \dots & r2c_{1\alpha} \\ & & \dots\dots\dots\dots & & \\ r2c_{\gamma 0} & r2c_{\gamma 1} & r2c_{\gamma 2} & \dots & r2c_{\gamma\alpha} \end{bmatrix} =$$

$$r2c_{rc} : r \in \{0 \dots \gamma\}, c \in \{0 \dots \alpha\}, (\gamma, \alpha) \in \mathbb{Z}^+ \tag{VI.6}$$

$$\forall r, \forall n : \left(\sum_{c=0}^{\alpha} c2n_{cn} \times r2c_{rc} \right) \leq r2n_{rn} \tag{VI.7}$$

Definition 13 (Comparative resource constraint)**.** *The "comparative resource" constraint is encoded using a provided resource-to-node (CoR2N) matrix and a required resource-to-component-instance (CoR2C) matrix. The CoR2N matrix comprises rows that represent different comparative resources and columns that represents nodes; the size of this matrix is $\phi \times \beta$, where ϕ is the number of comparative resources and β is the number of available nodes (Equation VI.8). Similarly, the CoR2C matrix comprises rows that represent different comparative resources and columns that represent component instances; the size of this matrix is $\phi \times \alpha$, where ϕ is the number of comparative resources and α is number of component instances (Equation VI.9). Each element of these matrices are either 0 or 1; 0*

means the corresponding resource is not provided by the corresponding node (for CoR2N matrix) or not required by the corresponding component instance (for CoR2C matrix), whereas, 1 means the opposite. The constraint itself (Equation VI.10) ensures that for each available comparative resource, node, and component instance, if the component instance is deployed on the node and requires the resource, then the resource must also be provided by the node.

$$CoR2N = \begin{bmatrix} r2n_{00} & r2n_{01} & r2n_{02} & \dots & r2n_{0\beta} \\ r2n_{10} & r2n_{11} & r2n_{12} & \dots & r2n_{1\beta} \\ & & \dots\dots\dots\dots & & \\ r2n_{\phi 0} & r2n_{\phi 1} & r2n_{\phi 2} & \dots & r2n_{\phi\beta} \end{bmatrix} =$$

$$r2n_{rn} : r \in \{0 \dots \phi\}, n \in \{0 \dots \beta\}, (\phi, \beta) \in \mathbb{Z}^+ \tag{VI.8}$$

$$CoR2C = \begin{bmatrix} r2c_{00} & r2c_{01} & r2c_{02} & \dots & r2c_{0\alpha} \\ r2c_{10} & r2c_{11} & r2c_{12} & \dots & r2c_{1\alpha} \\ & & \dots\dots\dots\dots & & \\ r2c_{\phi 0} & r2c_{\phi 1} & r2c_{\phi 2} & \dots & r2c_{\phi\alpha} \end{bmatrix} =$$

$$r2c_{rc} : r \in \{0 \dots \phi\}, c \in \{0 \dots \alpha\}, (\phi, \alpha) \in \mathbb{Z}^+ \tag{VI.9}$$

$$\forall r, \forall n, \forall c : Assigned(c, n) \implies (r2n_{rn} == r2c_{rc}) \tag{VI.10}$$

Assigned (c, n) function returns true if component c is deployed on node n, i.e.*, it returns true if* $c2n_{cn} == 1$.

The fifth set of constraints are needed for management of component instances associated with replication constraints. As mentioned previously, *assign*, *implies*, *collocate*,

atleast, and *distribute* are the five different kinds of constraints that must be encoded. Each of these constraints is encoded as follows:

Definition 14 (Assign constraint)**.** *The "assign constraint" is used for component instances corresponding to functionalities associated with per-node replication constraint. It ensures that a component instance is only ever deployed on a given node. In CHARIOT, an assign constraint is encoded as shown in Equation VI.11.*

Let c be a component instance that should be assigned to a node n.

$$Enabled(c) \implies (c2n_{cn} == 1) \tag{VI.11}$$

Enabled(c) function returns true if component instance c is assigned to any node, i.e*, it checks if* $\sum_{n=0}^{\beta} c2n_{cn} == 1$.

Definition 15 (Implies constraint)**.** *The "implies" constraint is used to ensure that if a component depends upon other components then its dependencies are satisfied. It is encoded using the implies construct provided by an SMT solver like Z3.*

Definition 16 (Collocate constraint)**.** *A "collocate" constraint is used to ensure that two collocated component instances are always deployed on the same node. In CHARIOT, as shown in Equation VI.12, this constraint is encoded by ensuring the assignment of the two component instances is same for all nodes.*

Let c_1 *and* c_2 *be two component instances that needs to be collocated.*

$$\begin{aligned}(Enabled(c_1) \wedge Enabled(c_2)) \implies \\ (\forall n : c2n_{c_1 n} == c2n_{c_2 n})\end{aligned} \tag{VI.12}$$

Definition 17 (Atleast constraint)**.** *An "atleast" constraint is used to encode a M out of N semantics to ensure that given a set of components* (i.e. *N), a specified number of those*

*components (*i.e. *M) is always deployed. CHARIOT only uses this constraint for range-based replication constraints and its implementation is two fold. First, during the initial deployment CHARIOT tries to maximize M and deploy as many component instances as possible. Current implementation of CHARIOT uses the maximum value associated with a range and initially deploys* N *component instances, as shown in Equation VI.13. This of course assumes availability of enough resources. A better solution to this would be to use the maximize optimization, as shown in EquationVI.14. However, in Z3 solver, which is the SMT solver used by CHARIOT, this optimization is experimental and does not scale well. Second, for subsequent non-initial deployment CHARIOT relies on the fact that maximum possible deployment was achieved during initial deployment, so it ensures the minimum number required is always met, as shown in Equation VI.15.*

Let $S = \{c_1, c_2 \ldots c_{\alpha'}\}$ *be a set of replica component instances associated with an atleast constraint; N is the size of this set. Also, let min_value be the minimum number of component instances required; this is synonymous to M.*

$$\sum_{c \in S} \sum_{n=0}^{\beta} c2n_{cn} == max\_value \tag{VI.13}$$

$$maximize(\sum_{c \in S} \sum_{n=0}^{\beta} c2n_{cn}) \tag{VI.14}$$

$$\sum_{c \in S} \sum_{n=0}^{\beta} c2n_{cn} >= min\_value \tag{VI.15}$$

Definition 18 (Distribute constraint)**.** *A "distribute" constraint is used to ensure that a set of components are deployed on different nodes. In CHARIOT this constraint is encoded by ensuring at most only one component instance out of the set is deployed on a single node, as shown in Equation VI.16.*

Let $S = \{c_1, c_2 \ldots c_{\alpha'}\}$ *be a set of components that needs to be distributed.*

$$\forall n : \sum_{c \in S} c2n_{cn} \leq 1 \tag{VI.16}$$

The final step (step 8) of the second phase of the CPC algorithm encodes and adds failure constraints. Depending on the kind of failure, there can be different types of failure constraints. We describe how CHARIOT encodes node failures and component failures below.

Finally, the sixth set of constraints handles failure representation. Constraints related to different failures are encoded in CHARIOT as shown below:

Definition 19 (Node failure constraint)**.** *A "node failure" constraint is used to ensure that no components are deployed on a failed node. CHARIOT encodes this constraint as shown in Equation VI.17.*

Let n_f be a failed node.

$$\sum_{c=0}^{\alpha} c2n_{cn_f} == 0 \tag{VI.17}$$

Definition 20 (Component failure constraint)**.** *A component can fail for various reasons, so there can be different ways to resolve a component failure. One approach is to ensure that a component is redeployed on any node other than the node in which it failed (Equation VI.18). If a component keeps failing in multiple different nodes, however, then CHARIOT may need to consider another constraint that ensures the component is not redeployed on any node (Equation VI.19).*

Let us assume component c_1 failed on node n_1.

$$c2n_{c_1 n_1 == 0} \tag{VI.18}$$

$$\sum_{n=0}^{\beta} c2n_{c_1 n} == 0 \tag{VI.19}$$

Phase 3, Solution Computation Phase:

The third and final phase of the CPC algorithm involves computing a "least distance" configuration point, *i.e.*, a configuration point that is the least distance away from current configuration point. To achieve this, we leverage the least distance constraint (see Definition 9) and associated recursion presented as part of the CPC algorithm in the previous chapter (see Section V.3.3.2).

At this point in the CPC algorithm, CHARIOT invokes the Z3 solver to check for a solution. If all constraints are satisfied and a solution is found, the CPC algorithm computes a set of deployment actions. CHARIOT computes deployment actions by comparing each element of the C2N matrix that represents the current configuration point with the corresponding element of the C2N matrix associated with computed solution, *i.e.*, the target configuration point. If the value of an element in the former is 0 and later is 1, CHARIOT adds a *START* action for the corresponding component instance on the corresponding node. Conversely, if the value of an element in the former is 1 and the later is 0, CHARIOT adds a *STOP* action. Applying this operation to each element of the matrix results in a complete set of deployment actions required for successful system transition.

VI.3.4.3 The Look-ahead Reconfiguration Approach

By default, the CPC algorithm yields a reactive self-reconfiguration approach since the algorithm executes once a failure is detected. Runtime reconfiguration will therefore incur the time taken to compute a new configuration point and determine deployment actions required to transition to a new configuration. This approach might be acceptable for extensible CPS consisting of non-real-time applications that can incur considerable downtime. For systems that host real-time, mission-critical applications, however, predictable and timely reconfiguration is essential. Since all dynamic reconfiguration mechanisms rely

on runtime computation to calculate a reconfiguration solution, the time to compute a solution increases with the scale of the system. The CPC algorithm is no different, as shown by experimental results presented in previous chapter (see Section VI.4.).

To address this issue, therefore, we extend the CPC algorithm by adding a configurable capability to use a finite horizon look-ahead strategy that pre-computes solution and thus significantly improves the performance of the management engine. We call this capability the Look-ahead Re-Configuration (LaRC). The general goal of the LaRC approach is to pre-compute and store solutions, so it just finds the appropriate solution and applies it when required. When the CPC algorithm is configured to execute in the “look-ahead" mode, solutions are pre-computed every time the system state (*i.e.*, the current configuration point) changes.

The first pre-computation happens once the system is initially deployed using the default CPC algorithm. Once a system is initially deployed, we pre-compute solutions to handle failure events. It is important to note that pre-computed solutions cannot be used for update events as update events change the system is such a way that the previously pre-computed solutions are rendered invalid. So, once we have a set of pre-computed solutions, failures are handled by finding the appropriate pre-computed solution, applying the found solution, and pre-computing solutions to handle future failure events. Whereas, for update events, the default CPC algorithm is invoked again (same as during initial deployment) to compute a solution. Once a solution for an update event is computed, we again pre-compute solutions to handle failure events.

In order to pre-compute solutions, CHARIOT currently uses Algorithm 6. Since our work presented in this chapter focuses on node failures, this algorithm pre-computes solutions for node failures only. Assuming that a system is in a stable state, this algorithm first removes any existing look-ahead solutions (line 1) since it is either invalid (update event) or already used (failure event). After this the algorithm iterates through each available

Algorithm 6 Solution Pre-computation.

Input: nodes (*nodes_list*)

```
1:  remove existing look-ahead information from the configuration space
2:  for node in node_list do
3:      if node is alive then
4:          tmp_config_space = get configuration space
5:          mark node as failed in tmp_config_space
6:          actions = CPC algorithm on tmp_config_space
7:          if actions != null then
8:              l_ahead = new LookAhead instance
9:              l_ahead.failedEntity = node.name
10:             l_ahead.failureKind = NODE
11:             l_ahead.deploymentActions = actions
12:             store l_ahead in the configuration space
```

node (line 2-3) and for each node, the algorithm creates a temporary copy of the configuration space (line 4), which includes the current (stable) configuration point. All subsequent actions are taken with respect to the temporary configuration space copy, so the original copy is not corrupted during the pre-computation computation process. After a copy of the configuration space is made, the particular node is marked as failed (line 5) and the CPC algorithm is invoked (line 6). In essence, this pre-computation algorithm injects a failure and asks the CPC algorithm for a solution. If a solution is found, the injected failure information and the solution is stored as an instance of the *LookAhead* class presented in Section VI.3.3.2 (line 7-12).

Design Discussion and Rationale:

Above description of the LaRC approach yields interesting observations with regards to the solution pre-computation algorithm. First, the current version of the solution pre-computation algorithm only considers node failures. We will alleviate this limitation in future work by adding system-wide capabilities to monitor, detect, and handle failures involving application processes, components, and network elements.

Second, and the more interesting observation is related to the fact that the solution pre-computation algorithm specifically pre-computes solution only for the next step,*i.e.*, the algorithm only looks one step ahead. We believe that *the number of steps to look-ahead*

should be a configurable parameter as different classes of system might benefit from different setting of this parameter. For example, consider systems that are highly dynamic and therefore subject to frequent failures resulting in bursts of failure events. For such systems, it would be important to look-ahead more than one step at a time otherwise we won't be able to handle multiple failures happening in short timespan. However, if we consider systems that are comparatively more static, like the smart parking system presented earlier in this chapter (Section VI.1), we expect a higher Mean Time To Failure (MTTF) and therefore do not require to pre-compute solutions by looking ahead more than one step at a time.

Overall, there is clearly a trade-off between time, space, and number of failures tolerated when considering the number of pre-computation steps. Multi-step pre-computation takes more time as well as space to store large number of solutions based on various permutation and combination of possible failures, but can handle bursts of failures. Whereas, a single-step pre-computation will be much faster and occupy less space but it will be non-trivial to handle bursts of failures.

We believe that an ideal solution would be to achieve a dynamic solution pre-computation algorithm. The dynamism is with respect to the configuration of the pre-computation steps parameter. For any given system, we assume that there is an initial value, however, during runtime, this value can change depending on the system behavior. Further investigating and implementing such a solution is part of our future work.

VI.4 Implementation and Evaluation

This section presents a detailed description of CHARIOT's implementation and empirically evaluates its implementation using the smart parking system use-case scenario previously described in Section VI.1.

VI.4.1 CHARIOT Runtime Implementation

This section presents an overview of the CHARIOT runtime implementation and evaluates its performance. Figure 39 depicts CHARIOT's implementation architecture, which consists of compute nodes comprising the layered stack described in figure 3.

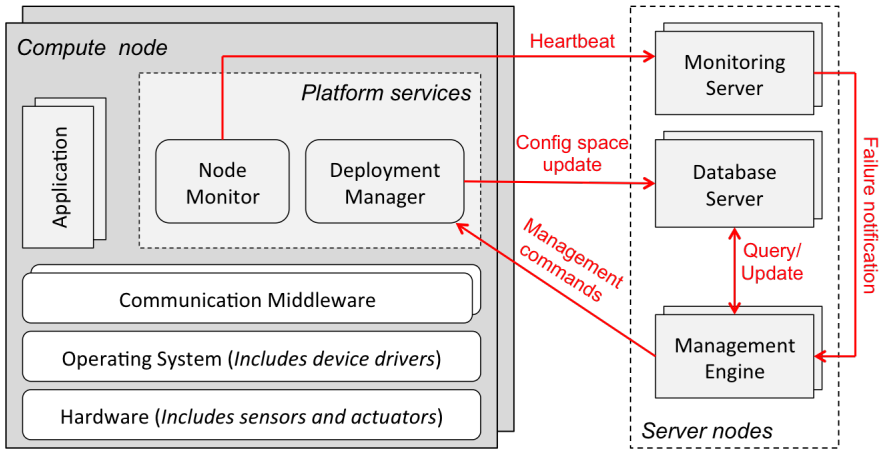


Figure 39: The Implementation Design of the CHARIOT Runtime.

Each CHARIOT-enabled compute node hosts two platform services: a Node Monitor and a Deployment Manager. The Node Monitor assesses the liveliness of its specific node, whereas the Deployment Manager manages the lifecycle of applications deployed on a node. In addition to compute nodes, CHARIOT's runtime also comprises one or more instances of three different types of server nodes: (1) Database Servers that store system information, (2) Management Engines that facilitate failure avoidance, failure management, and operation management, and (3) Monitoring Servers that monitor for failures.[2]

CHARIOT's Node Monitor is implemented as a ZooKeeper [46] client that registers itself with a Monitoring Server, which is in turn implemented as a ZooKeeper server and uses ZooKeeper's group membership functionality to detect member (node) additions and removals (*i.e.*, failure detection). This design supports dynamic resources, *i.e.*, nodes that

[2]Since failure detection and diagnosis is not the primary focus of this chapter, our current implementation focuses on resolving node failures, though CHARIOT can be easily extended to support mechanism to detect component, process, and network failures.

can join or leave a cluster at any time. A group of Node Monitors (each residing on a node of a cluster) and one or more instances of Monitoring Servers define the monitoring infrastructure described in Section VI.3.1.

The Deployment Manager is implemented as a ZeroMQ [45] subscriber that receives management commands from a Management Engine, which is in turn implemented as a ZeroMQ publisher. The Management Engine computes the initial configuration point for application deployment, as well as subsequent configuration points for the system to recover from failures. After a Deployment Manager receives management commands from the Management Engine, it executes those commands locally to control the lifecycle of application components. Application components managed by CHARIOT can be in one of two states: active or inactive. A group of Deployment Managers—each residing on a node of a cluster—represents the deployment infrastructure described in Section VI.3.1.

A Database Server is an instance of a MongoDB server. For the experiments presented in Section VI.4.2, we only consider compute node failures, so deploying single instances of Monitoring Servers, Database Servers, and Management Engines fulfills our need. To avoid single points of failure, however, CHARIOT can deploy each of these servers in a replicated scenario. In the case of Monitoring Servers and Database Servers, replication is supported by existing ZooKeeper and MongoDB mechanisms. Likewise, replication is trivial for Management Engines since they are stateless. A Management Engine executes the CPC algorithm (see Section VI.3.4.2), with or without the LaRC configuration (see Section VI.3.4.3), using relevant information from a Database Server. CHARIOT can therefore have multiple replicas of Management Engines running, but only one performs reconfiguration algorithms. This constraint is achieved by implementing a rank-based leader election among different Management Engines. Since a Management Engine implements a ZeroMQ server—and since ZeroMQ does not provide a service discovery capability by

default—CHARIOT needs some mechanism to handle publisher discovery when a Management Engine fails. This capability is achieved by using ZooKeeper as a coordination service for ZeroMQ publishers and subscribers.

VI.4.1.1 Application Deployment Mechanism

For initial application deployment, CHARIOT ML (see Section VI.3.2) is used to model the corresponding system that comprises the application, as well as resources on which the application will be deployed. This design-time model is then interpreted to generate a configuration space (see Section VI.3.4.1) and store it in the Database Server, after which point a Managment Engine is invoked to initiate the deployment. When the Management Engine is requested to perform initial deployment, it retrieves the configuration space from the Database Server and compute a set of deployment commands. These commands are then stored in the Database Server and sent to relevant Deployment Managers, which take local actions to achieve a distributed application deployment. After a Deployment Manager executes an action, it updates the configuration space accordingly.

VI.4.1.2 Group Membership Mechanism for Failure and Update Detection

CHARIOT leverages capabilities provided by ZooKeeper to implement a node failure detection mechanism, which performs the following steps: (1) each computing node runs a Node Monitor after it boots up to ensure that each node registers itself with a Monitoring Server, (2) when a node registers with a Monitoring Server, the latter creates a corresponding ephemeral node.[3], and (3) since node membership information is stored as ephemeral nodes in the Monitoring Server, it can detect failures of these nodes.

[3]ZooKeeper stores information in a tree like structure comprising simple nodes, sequential nodes, or ephemeral nodes.

VI.4.1.3 Reconfiguration Mechanism

After a failure is detected a Monitoring Server notifies the Management Engine, as shown in Figure 39. This figure also shows that the Management Engine then queries the Database Server to obtain the configuration space and reconfigure the system using relevant information from the configuration space and the detected failure.

VI.4.2 Experimental Evaluation

Although we have previously used CHARIOT to deploy and manage applications on an embedded system comprising Intel Edison nodes (see `http://chariot.isis.vanderbilt.edu/tutorial.html`), this chapter uses a cloud-based setup to evaluate CHARIOT at a larger scale. Below we first describe our experiment test-bed. We then describe the application and the set of events used for our evaluation. We next present evaluation of the default CPC algorithm and evaluate the CPC algorithm with the LaRC algorithm. Finally, we present CHARIOT resource consumption metrics.

VI.4.2.1 Test-bed

Our test-bed comprises 44 virtual machines (VMs) each with 1GB RAM, 1VCPU and 10GB disk in our private OpenStack cloud. We treat these 44 VMs as embedded compute nodes. In addition to these 44 VMs, three additional VMs with 2 VCPUs, 4 GB memory, and 40GB disk is used as server nodes to host Monitoring Server, Database Server, and Management Engine (see Figure 39). All these VMs ran Ubuntu 14.04 and were placed in the same virtual LAN.

VI.4.2.2 Application and Event Sequence

To evaluate CHARIOT, we use the smart parking system described in Section VI.1. We divide the 44 compute nodes into 20 processing nodes (corresponding to the *edison* node template in Figure 33), 21 camera nodes (corresponding to the *wifi_cam* node template

Table 7: Sequence of Events used for evaluation of CPC algorithm.

Event	Description
1	Initial deployment over 21 nodes (10 processing nodes, 10 camera nodes, and 1 terminal node) resulting in 23 component instances; 10 different component instances related to the *occupancy_detector* functionality due to its corresponding cluster replication constraint, 10 different component instances related to the *image_capture* functionality due to its corresponding per-node replication constraint associated with camera nodes (we have 10 camera nodes), a component instance related to the *client* functionality due to its corresponding per-node replication constraint associated with terminal nodes (we have 1 terminal node), and a component instance each related to the *load_balancer*, and *parking_manager* functionalities.
2	Failure of a camera node. No reconfiguration is required for this failure as a camera node hosts only a node-specific component that provides the *image_capture* functionality.
3	Failure of the processing node that hosts a component instance each related to the *load_balancer* and *parking_manager* functionalities. This results in reconfiguration of the aforementioned two component instances. Furthermore, since the processing node hosts an instance of the *occupancy_detection* functionality, the number of component instances related to this funcitonality decreases from 10 to 9. However since 9 is still within the provided redundancy range (min = 7, max = 10), this component instance does not get reconfigured.
4	Failure of the processing node on which the component instance related to the *parking_manager* functionality was reconfigured to as the result of the previous event. This event results in the *parking_manager* functionality related component instance to again be reconfigured to a different node. Furthermore, the number of component instances related to the *occupancy_detector* functionality decreases to 8, which is still within the provided redundancy range; as such, reconfiguration of that component instance is not required.
5	Failure of the processing node on which the component instance related to the *load_balancer* functionality was reconfigured to as result of event 3. This event results in the component instance being reconfigured again to a different node. Also, the number of component instances related to the *occupancy_detector* functionality decreases to 7, which is still within the provided redundancy range so no reconfiguration is required.
6	Failure of another processing node. This node only hosts a component instance related to the *occupancy_detector* functionality. Therefore, as a result of this failure event, the provided redundancy range associated with the *occupancy_detector* functionality is violated as the number of corresponding component instances decreases to 6. So, this component instance is reconfigured to a different node in order to maintain at least 7 instances of the *occupancy_detector* functionality.
7	Failure of the single available terminal node on which the component instance related to the *client* functionality was deployed as part of the initial deployment (event 1). This event results in an invalid system state as there are no other terminal nodes and therefore instances of *client* functionality available.
8-31	Hardware updates associated with addition of 2 terminal nodes, 11 processing nodes, and 11 camera nodes. These nodes are added one at a time. Due to associated per-node replication constraints, addition of a terminal node results in deployment of a component instance associated with the *client* functionality. Similarly, addition of a camera node results in deployment of a component instance associated with the *image_capture* functionality. However, addition of a processing node does not result in any new deployment as it is not associated with a per-node replication constraint.
32	Failure of a processing node that hosts a component instance related to the *occupancy_detector* functionality. This results in reconfiguration of the component instance to a different node.
33	Failure of another processing node, which hosts no applications. Therefore, no reconfiguration is required.
34	Failure of a camera node. Again, no reconfiguration is required (see event 2 above).

in Figure 33), and 3 terminal nodes (corresponding to the *entry_terminal* node template in Figure 33). The goal description we used is the same shown in Figure 34, except we increase the replication range of the *occupancy_detector* functionality to minimum 7 and maximum 10.

To evaluate the default CPC algorithm we use 33 different events presented in Table 7. As shown in the table, the first event is the initial deployment of the smart parking system over 21 nodes (10 processing nodes, 10 camera nodes, and 1 terminal node). This initial deployment results in a total of 23 component instances. After initial deployment, we

introduce 6 different node failure events, one at a time. We then update the system by adding 2 terminal nodes, 10 processing nodes, and 11 camera nodes. These nodes are added one at a time, resulting in a total of 44 nodes (including the 6 failed nodes). These updates are examples of intended updates and show CHARIOT's operations management capabilities. After updating the system, we introduce three more node failures.

VI.4.2.3 Evaluation of the Default CPC Algorithm

Figure 40 presents evaluation of the default CPC algorithm using application and event sequence described above. To evaluate the default CPC algorithm we use the total solution computation time, which is measured in seconds. The total solution computation time can be decomposed into two parts: (1) problem setup time and (2) Z3 solver time. The problem setup time corresponds to the first two phases of the CPC algorithm (see Section VI.3.4.2), whereas the Z3 solver time corresponds to the third phase of the CPC algorithm.

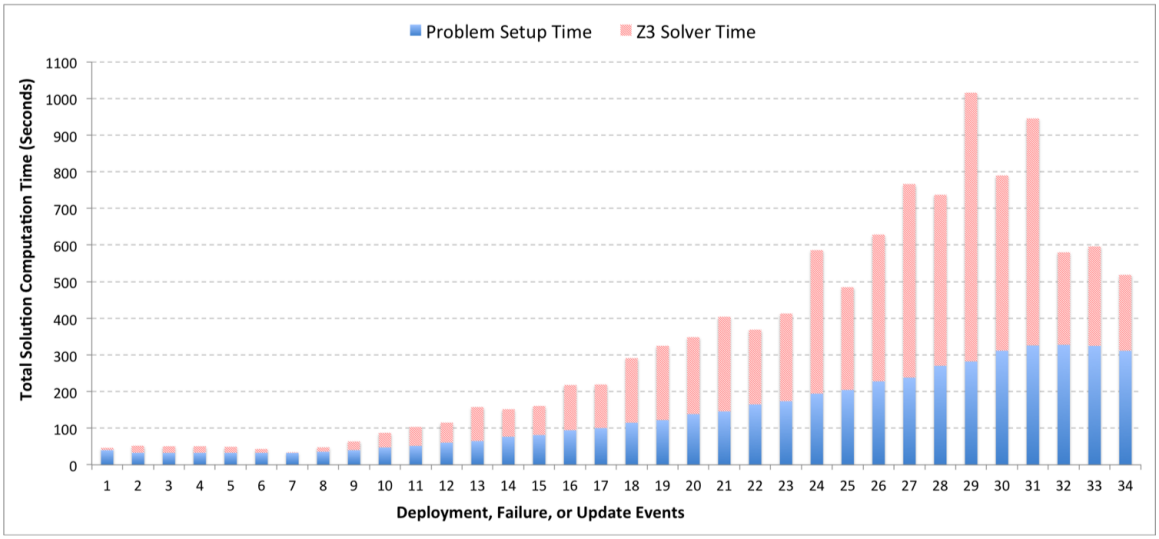


Figure 40: Default CPC Algorithm Performance. (Please refer to Table 7 for details about each event shown in this graph.)

Figure 40 shows that for initial deployment and the first 5 failure events, the total solution computation time is similar (average = 48 seconds) because the size of the C2N matrix

and associated constraints created during the problem setup time are roughly the same. The 6th failure (7th event in Figure 40), is associated with the one and only terminal node in the system. The Z3 solver therefore quickly determines there is no solution, so the Z3 solver time for the 7th event is the minimal 1.74 seconds.

Events 8 through 31 are associated with a system update via the addition of a single node per event. These events show that for most cases the total solution computation time increases with each addition of node. The problem setup time increases consistently with increase in the number of nodes because the size of the C2N matrix, as well as the number of constraints, increases with an increase in the number of nodes. The Z3 solver time also increases with increase in number of nodes in the system, however, it does not increase as consistently as the problem setup time due to the least distance configuration computation presented in Section VI.3.4.2. The amount of iterations (and therefore time) it takes the Z3 solver to find a solution with least distance is non-deterministic. If a good solution (with respect to distance) is found in the first iteration, it takes less number of iterations to find the optimal solution. This is verified by analysis results in Section VI.4.2.6.

Finally, events 33 through 34 are associated with more node failures. The total solution computation time therefore decreases due to the decrease in number of nodes and component instances, which results in a smaller C2N matrix and a fewer number of constraints.

VI.4.2.4 Evaluation of the CPC algorithm with LaRC

For the purpose of this evaluation we use the first 5 events since this is enough to showcase the tradeoff between the default CPC algorithm and the CPC algorithm with LaRC. In this approach, the total solution computation time (apart from the initial deployment) is the time taken to query the database for pre-computed solution. This time is significantly lower (average = 0.0085 seconds) than that for the default CPC algorithm (average = 48 seconds).

To demonstrate the tradeoff between the two versions of the CPC algorithm, we present

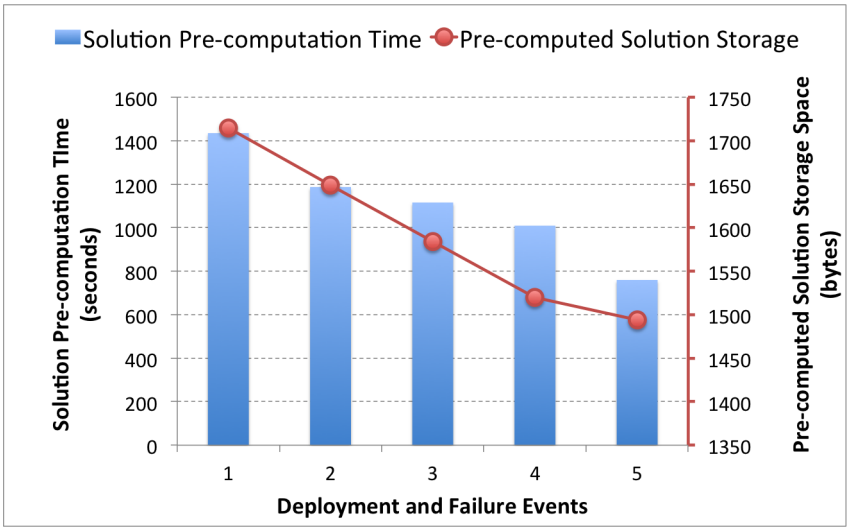


Figure 41: Solution Pre-computation Time for CPC with LaRC. (The solution for failure event i+1 is computed when the reconfiguration action for the failure event i is being applied.)

the time taken for solution pre-computation and space required to store pre-computed solution in Figure 41. As shown in the figure, the time taken to pre-compute solution after initial deployment is 1,400 seconds, which is the time needed to pre-compute solution for 21 node failures (initial configuration). To store this pre-computed solution 1,715 bytes of storage space is used. Events 2 through 5 represent node failures and as we can clearly see, the solution pre-computation time and storage used to store the pre-computed solution decreases with each failure because failures result in less number of scenarios for which we need to pre-compute a solution.

VI.4.2.5 Resource Consumption

To demonstrate the usability of CHARIOT in extensible CPS, we present various resource consumption of CHARIOT entities (Deployment Manager and Node Monitor, see Figure 39) that run on each compute node. The resource consumption number only consider the chariot management entities and not the actual application being managed. Moreover, for the purpose of this evaluation we categorize the compute nodes based on their

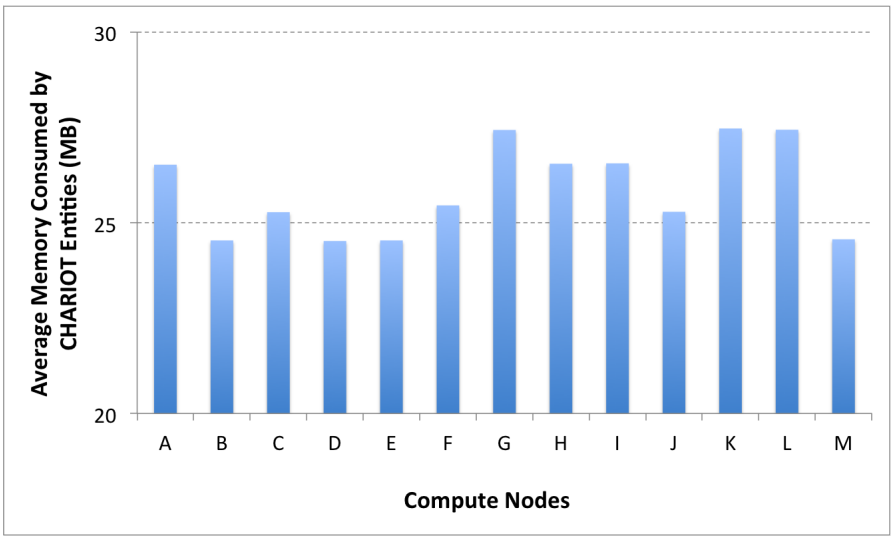


Figure 42: Average Memory Consumption.

lifetime (short, medium, long) and randomly pick 4-5 nodes form each category. Nodes *A*, *B*, *C*, *D*, and *E* are nodes with short lifetime (less than 15 minutes); nodes *F*, *G*, *H*, and *I* are nodes with medium lifetime (between 110 and 154 minutes); nodes *J*, *K*, *L*, and *M* are nodes with long lifetime (between 200 and 235 minutes).

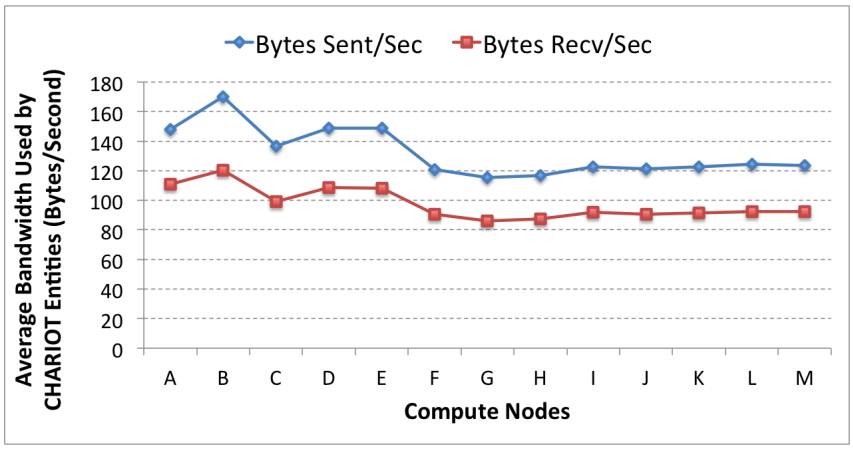


Figure 43: Average Network Bandwidth Consumption.

Figure 42 presents the average memory consumed by CHARIOT entities running on 13 nodes above mentioned throughout their lifetime. This figure shows that the average

memory consumption is close to slightly above or below 25 MB in each node. Similarly, Figure 43 presents the average network bandwidth consumed by CHARIOT entities running on the aforementioned 13 nodes throughout their lifetime. This figure shows that the network bandwidth used to send and receive information is minimal and predictable. We do not show the CPU utilization since it was mostly 0%, sometimes rising to less than 0.5%.

From above results presented above we conclude that the CHARIOT infrastructure is not resource intensive and therefore can be used for resource-constrained extensible CPS devices. CHARIOT is currently written using Python[4], though we intend to convert most of our code to C++ to further improve CHARIOT's performance.

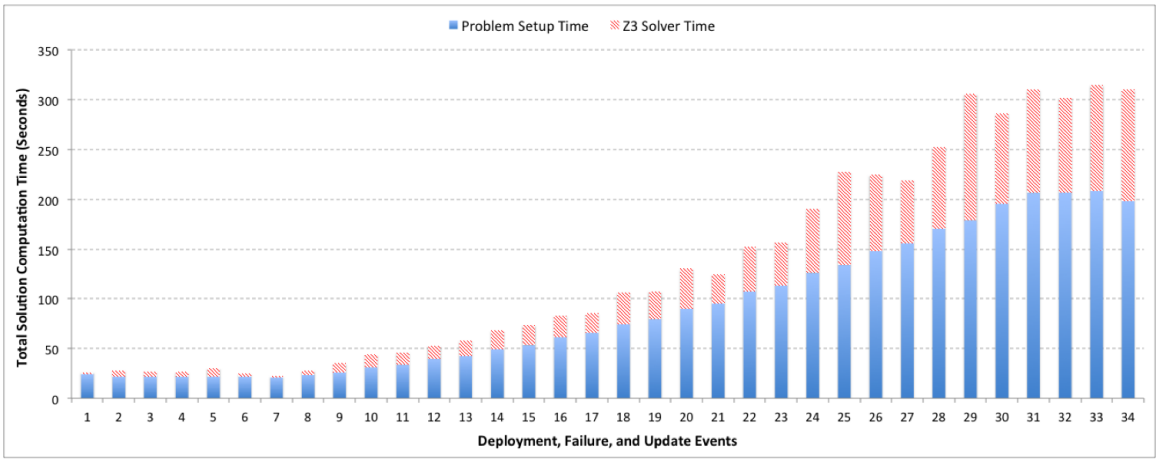


Figure 44: Default CPC Algorithm Performance in Simulated Environment. (Please refer to Table 7 for details about each event shown in this graph.)

VI.4.2.6 Analyzing Performance of the CPC algorithm

To further analyze the CPC algorithm's performance in detail, the experiment presented in Section VI.4.2.3 was replicated in a single machine simulation environment. This was done in a Windows 7 based 64 bit machine with 8 GB memory and 8 cores resulting in 4 GB of additional memory and 6 additional cores compared to the distributed testbed used

[4] https://github.com/visor-vu/chariot

for experiment presented in Section VI.4.2.3. Figure 44 presents the overall performance of the CPC algorithm using application and event sequence described in Section VI.4.2.2. Figure 45 compares the performance of CPC algorithms in simulated and non-simulated environment; from this figure we can clearly see the performance improvement facilitated by the more resourceful hardware used in the simulated environment.

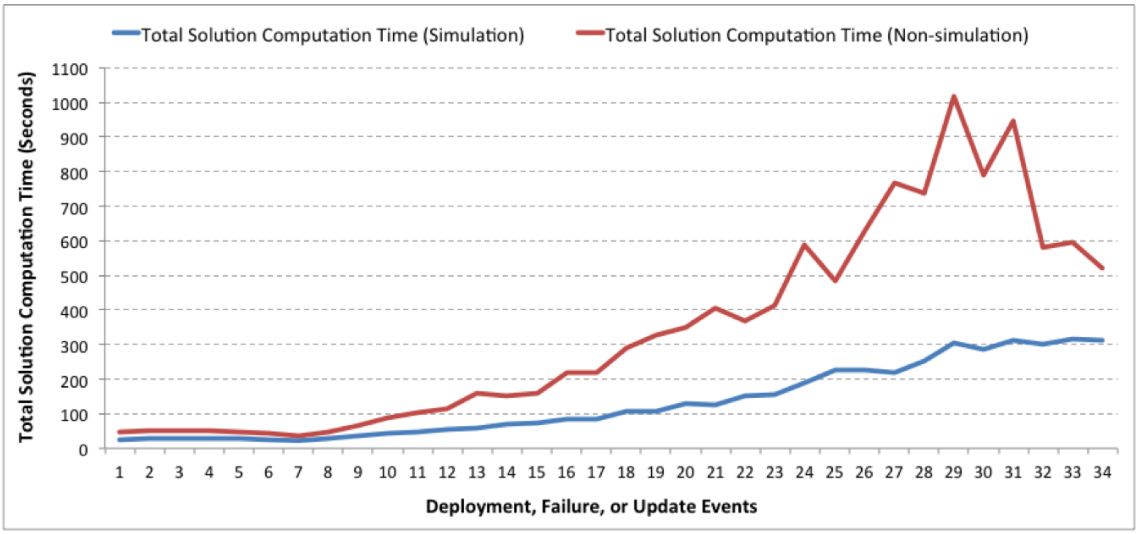


Figure 45: Default CPC Algorithm Performance Comparison between Non-simulated and Simulated Environments. (Please refer to Table 7 for details about each event shown in this graph.)

Figure 46 analyzes the Z3 solver time jitter by comparing the Z3 solver time portion of the graph shown in Figure 44 with the corresponding Z3 problem complexity. Here, the Z3 problem complexity is a metric defined as the product of (1) total number of solver assertions, which indicates the size of the problem being solved by the Z3 solver, and (2) total number of least-distance iterations, which indicates the number of times a problem is solved by the Z3 solver. As shown in the figure, barring few anomalies, the Z3 solver time depends on the Z3 problem complexity.

Finally, in order to determine any possible performance bottleneck, the default CPC algorithm was further analyzed using different initial deployment scenarios (based on varying

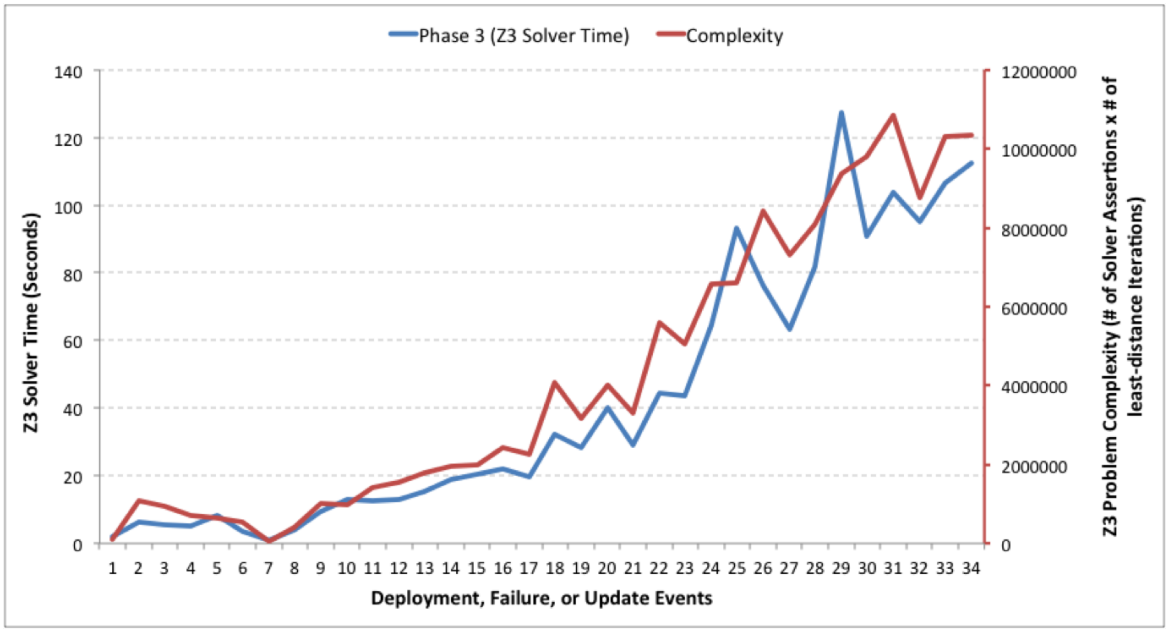


Figure 46: The Z3 Solver Time Jitter versus the corresponding Problem Complexity. (Please refer to Table 7 for details about each event shown in this graph.)

scale) of the application presented in Section VI.4.2.2. Figure 47 presents the total solution computation time, divided into three different phases of the CPC algorithm, for six different initial deployment scenarios. The first deployment scenario comprises 11 nodes and 10 components; the second deployment scenario comprises 22 nodes and 18 components; the third deployment scenario comprises 33 nodes and 26 components; the fourth deployment scenario comprises 44 nodes and 34 components; the fifth deployment scenario comprises 55 nodes and 42 components; and the sixth deployment scenario comprises 66 nodes and 50 components.

Figure 47 clearly shows that the second phase of the CPC algorithm, which corresponds to the constraint encoding phase, contributes to majority of the total solution computation time. Further analysis of the constraint encoding phase of the CPC algorithm (shown in Figure 48) clearly shows that the dependency constraint encoding (see Definition 11) is the main bottleneck as it accounts for more than 90% of the constraint encoding time. This is because for every dependency, the current encoding mechanism incurs $O(n^2)$ time

complexity. Any improvement to the way in which this constraint is encoded will result in significant reduction of the total solution computation time.

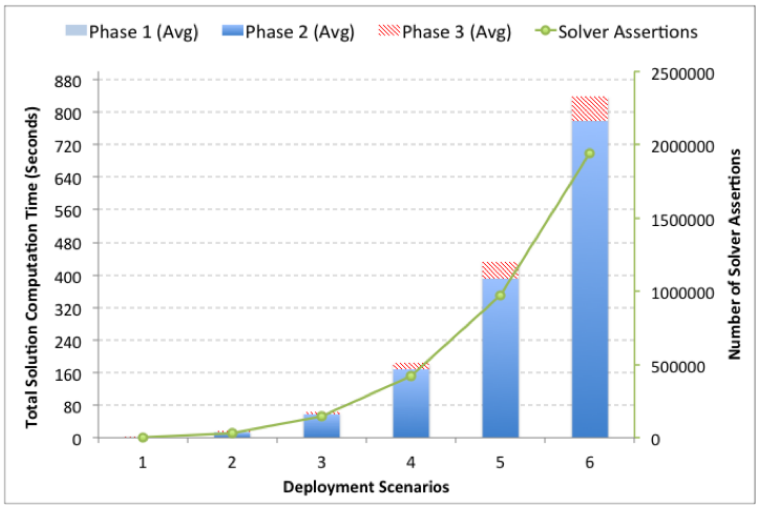


Figure 47: Solution Computation Time for different Initial Deployment Scenarios.

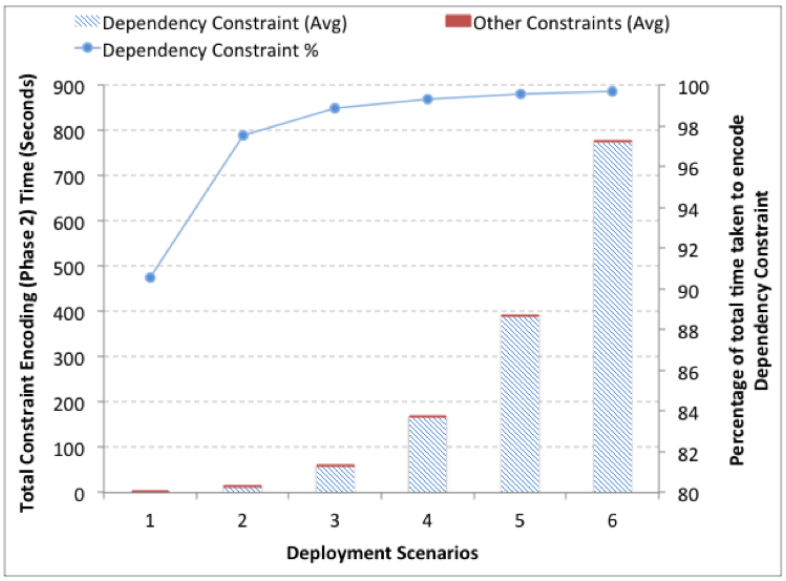


Figure 48: Breakdown of Total Constraint Encoding Time into Different Constraints.

VI.5 Related Work

This section describes related research to distinguish it from our work on CHARIOT presented in the remainder of this chapter.

VI.5.1 Redundancy-based Strategies

Fault tolerance in computing has a long history, but resilience [54][5] is beyond the capabilities of conventional fault-tolerant approaches since resilience means "adapting to change." Conventional fault tolerance techniques are based on redundancy together with comparison or acceptance-based testing, especially for mission-critical systems with extremely high availability requirements. Redundancy-based techniques mask certain classes of persistent and transient faults that may develop in one or more (but not in all) redundant components at the same time, thereby ensuring that faults do not lead to eventual system or subsystem failures. These techniques rely on the assumption that failure of a component is an independent event. Hence, the failure probability of the overall system or subsystem is lower since it is a product of the failure probabilities of the individual components.

Redundancy-based resilience techniques use comparison (*e.g.*, a voter) or acceptance check (*e.g.*, an acceptance test) schemes to decide if a component is working correctly or not, as well as pass on the 'correct' output to the downstream subsystem. Other well-known redundancy techniques include recovery blocks and self-check programming [105]. None of these methods are sufficient, however, for extensible CPS where both software and hardware topologies can change dynamically.

[5] Resilience [54] is a system level property—by definition any part of the system can fail, yet the system should be able to keep providing the services it supports.

VI.5.2 Reconfiguration-based Strategies

Reconfiguration-based resilience techniques provide an alternative to the redundancy-based strategies described above. The goal of reconfiguration is to detect anomalous behavior, perform diagnosis to identify the fault cause(s) responsible for the detected anomalies, and apply remedies to restore the functionalities affected by anomalies. These techniques can be configured to account for anomalous behavior and their cascading effects due to faults identified at design time, as well as latent bugs, common mode failures, or other unforeseen events or attacks that disrupt the nominal operation. Moreover, these approaches can be applied to augment system resilience when redundancy-based fault tolerance strategies are already in place.

There are two types of reconfiguration-based techniques: offline strategies using prespecified reconfiguration rules and dynamic online reconfiguration. Statically-specified reconfiguration techniques require explicit and declarative modeling of how a system should be reconfigured before it is deployed. Conversely, dynamic reconfiguration techniques require implicit and symbolic capturing of system behavior as a mathematical model that is dynamically searched at runtime to find solutions used to repair and restore a system.

VI.5.2.1 Offline Strategies

In [40, 65] the authors present two solutions for synthesizing an optimal assembly for component-based systems, given a set of constraints. Both solutions perform automatic static assembly at design-time. The key difference between these solutions is that [65] does not consider timing constraints, whereas the solution in [40] targets scheduling constraints in cyber-physical systems. Neither of these solutions meet the needs of extensible CPS, however, since they do not consider dynamic reconfiguration and focus solely on automatically synthesizing optimal system assemblies at design-time. Similarly, there are significant amount of other related work that use different kinds of offline strategies; details of some of these existing work is presented in the previous chapter (see Section V.5).

VI.5.2.2 Online Strategies

The CHARIOT solution described in this chapter uses online dynamically computed strategy for reconfiguration. It requires runtime computation to search for a solution. Reducing this search time and ensuring its predictability is of utmost importance for extensible CPS that host mission-critical, cyber-physical applications. In [61] the authors focused on dynamic reconfiguration using boolean encoding of systems. This work has some limitations, however, since it was (1) based on a SAT solver and therefore could not accommodate complex constraints over integer variables, (2) not flexible enough to consider runtime modification of a system's encoding, and (3) unable to take timing requirements into account.

Dynamic Software Product Lines (DSPLs) have also been suggested for dynamic reconfiguration. In [22], the authors present a survey of state-of-the-art techniques that attempt to address many challenges of runtime variability mechanisms in the context of DSPLs. The authors also provide a potential solution for runtime checking of feature models for variability management, which motivates the concept of *configuration models*. A configuration model acts as a database that stores a feature model along with all possible valid states of the feature model. Although this work is conceptually similar to ours, it does not take timing requirements into account.

Ontology-based reconfiguration work has been presented in [44, 100], where the analytical redundancy of computational components is made explicit. On the basis of this ontology, the system can be reconfigured by identifying suitable substitutes for the failed services. Significant amount of other related work has also been discussed in the previous chapter (see Section V.5).

VI.6 Concluding Remarks

This chapter described the structure and functionality of CHARIOT, which is an orchestration middleware designed to meet the resilience requirements of extensible CPS.

The following is a summary of our lessons learned from developing CHARIOT and applying it in the context of a smart parking system case study:

- **Lesson 1: Design-time system description should be generic.** If the objectives of an application and the different functionality that it requires can be specified in a generic manner, CHARIOT can create an online mechanism that maps the system objectives to required resources based on functionality decomposition and functionality-component association. It is important, however, to extend this concept to support the idea of graceful degradation. As part of future work, we are modeling quality of service functions that provide mechanisms for evaluating the performance of a component's functionality based on available resources. This mechanism can help in cases where we need to arbitrate between different system objectives.
- **Lesson 2: Design-time and runtime system information can be used to encode constraints at runtime.** Using design-time system description and runtime system representation, constraints can be dynamically encoded to represent various system requirements. These constraints can aid online reconfiguration via the use of state-of-the-art solvers such as Z3, which is a SMT solver. To minimize downtime, however, efficient pre-computation of reconfiguration steps is necessary. CHARIOT's look-ahead approach described in this chapter is a step in this direction.
- **Lesson 3: Dynamic online reconfiguration is time consuming.** Online reconfiguration is time consuming and is thus not suitable for low latency real-time extensible CPS. For those types of systems, it is important to include redundancy in the deployment logic. The CHARIOT modeling language and reconfiguration logic provides support for such redundancy concepts.
- **Lesson 4: Failure reconfiguration approach can be extended to support system updates as well.** CHARIOT's reconfiguration framework can be extended to address system evolution, which corresponds to the addition of computational capabilities or

new software applications. By generalizing and automating reconfiguration steps CHARIOT can be adopted to application in many domains.

VI.7 Related Publications

1. Subhav Pradhan, Abhishek Dubey, Shweta Khare, Saideep Nannapaneni, Aniruddha Gokhale, Sankaran Mahadevan, Douglas C Schmidt, and Martin Lehofer. CHARIOT: A Holistic, Goal Driven Orchestration Solution for Resilient IoT Applications. *Transactions on Cyber-Physical Systems*. (Under review)

2. Subhav Pradhan, Abhishek Dubey, Aniruddha Gokhale, and Martin Lehofer. CHARIOT: A Domain Specific Language for Extensible Cyber-Physical Systems. *The 15th Workshop on Domain-Specific Modeling (DSM 2015)*, pages 9 - 16, Pittsburgh, Pennsylvania, USA.

CHAPTER VII

CONCLUDING REMARKS AND FUTURE WORK

Over the past decades, distributed computing paradigm has evolved from smaller and mostly homogeneous clusters to the current notion of ubiquitous computing, which consists of dynamic and heterogeneous resources in large scale. Recent advancement of edge computing devices has resulted in sophisticated and resourceful devices that are equipped with variety of sensors and actuators. These devices can be used to connect physical world with the cyber world. As such, the future of ubiquitous computing is cyber-physical in nature, and therefore, Cyber-Physical Systems (CPS) will play a crucial role in the future of ubiquitous computing.

CPS are engineered systems that integrate cyber and physical components, where cyber components include computation and communication resources and physical components represent physical systems. However, in order to realize this future of ubiquitous computing, we need to investigate and understand limitations of traditional CPS that were not meant for large-scale dynamic environment comprising resources with distributed ownership and requirement to support continuous evolution and operation. Hence, the goal is to transition from traditional CPS to the next-generation CPS that supports extensibility by allowing us to view CPS as a collection of heterogeneous subsystems with distributed ownership and capability to dynamically and continuously evolve throughout their lifetime while supporting continuous operation.

This dissertation first identified the four key properties of next generation, extensible CPS: (1) resource dynamism, (2) resource heterogeneity, (3) multi-tenancy with respect to hosted applications, and (4) possible remote deployment of resources. These properties result in various challenges; this dissertation primarily focused on challenges arising from

dynamic, multi-tenant, and remotely deployed nature of extensible CPS. Summary of the contributions made in this dissertation to resolve these challenges are listed below.

VII.1 Summary of Research Contributions

- Contribution 1: A resilient management infrastructure for distributed component-based applications
  1. Identified key considerations and challenges for realizing a resilient Deployment and Configuration (D&C) infrastructure (management infrastructure).
  2. Designed and implemented a resilient management infrastructure using an open source Data Distributed Service (DDS) middleware implementation.
  3. Provided empirical evidence to demonstrate the autonomous resilience capabilities of the management infrastructure under node failures.

- Contribution 2: A mechanism to establish secure interaction between distributed component-based applications
  1. Designed a mechanism to establish secure interactions between applications with varying security requirements. The core of this contribution was a novel discovery mechanism that took into account application security requirements.
  2. Implemented the secure discovery mechanism as an extension of the DDS specification provided by the Objected Management Group (OMG).
  3. Provided empirical evidence to demonstrate secure interactions between distributed component-based applications.

- Contribution 3: A self-reconfiguration mechanism to achieve autonomous resilience
  1. Helped prototype a design-time modeling language and corresponding resilience analysis tool to compute best and worst case resilience metrics.
  2. Designed and implemented CHARIOT, a holistic solution for managing extensible CPS. CHARIOT comprises of design-time modeling language, a distributed

database to store system information, and a runtime self-reconfiguration mechanism that implements a *sense-plan-act* closed loop.

3. Provided empirical evidence to demonstrate overall autonomous management capabilities of CHARIOT. Thorough analysis was also performed to isolate and identify characteristics and performance bottlenecks.

VII.2 Future Work: Towards a Generic Computation Model

Smart cities are example of extensible CPS that promise to enrich the lives of residents by providing better services while also empowering them to make efficient and informed decisions. Implementing smart cities requires large-scale platforms that facilitate collaboration between multi-domain systems, such as Electric Grid, Water Supply, Transportation Networks, Emergency Services, etc. In general, smart city systems are designed to collect data, process collected data, transmit data, and analyze data. In the context of smart city systems, data collection usually happens at the edge because that is where edge devices with sensors are deployed to monitor surrounding environments.

Unlike data collection, processing and analyzing data are resource intensive tasks that usually cannot be executed on resource-constrained edge nodes. In traditional large-scale CPS, this problem was solved using backend resources owned and maintained in-house [99]. This results in isolated islands of domain-specific platforms that incur significant construction and maintenance costs. Furthermore, integration across platforms becomes a very challenging task. Another approach to solving this issue is to take advantage of cloud computing technology resulting in a complex computing paradigm that involves deploying different kinds of applications on different kinds of resources. Resources can be provided by edge nodes, cloudlets and mobile clouds, private clouds, or public clouds. Applications deployed on edge nodes incur minimal, if any, network latency since they are close to the source of data. Whereas, applications deployed on public cloud resources incur significant network latency as they use remote computational resources that can be located far from

their corresponding sources (e.g.,edge nodes with related sensors) and they require sensor data to be transmitted from different sources.

The possibility of different application types is a source of software heterogeneity in smart city platforms. Applications can be of different types due to varying (1) timing requirements, as they might need real-time, near real-time, or non real-time responsiveness, (2) rate and volume of data they interact with, and (3) behavior, as they can be stateful or stateless (*i.e.,* functional). Different application types can result in different computation patterns. For example, a cyber-physical application that interacts with a physical environment via sensors and actuators requires as close to real-time responsiveness. This kind of application is usually implemented as a closed loop control application and deployed as close as possible to the target environment. In comparison, a long running, computation heavy, big-data application is usually implemented using some notion of a computation graph supported by existing dataflow engines such as Storm [9], Spark [8], or TensorFlow [2]. Above described software heterogeneity is further exacerbated by the availability of various middleware solutions targeted for different domains and therefore applications.

Given that there can be applications that rely on varying computation patterns and communication middleware, realizing smart city platforms requires us to devise solutions that facilitate integration of and interaction between these heterogeneous application. This section proposes a generic computation model to address this problem by facilitating (1) interaction between heterogeneous applications while remaining agnostic to the underlying middleware, and (2) *write once, run anywhere* model for heterogeneous applications. This section also describes how the aforementioned generic computation model fits within the holistic management infrastructure previously presented in Chapter VI.

VII.2.1 Background and Problem Description

To describe the problem at hand, this section first presents a resource model. Second, different types of applications and corresponding computation patterns are identified.

VII.2.1.1 Resource Model

The physical computing infrastructure available to smart parking systems comprises *computation* and *communication* resources. Computation resources include hardware facilities required to execute computation tasks, wheres, communication resources represent facilitates required for interaction between tasks executing on different computation nodes. This includes communication bandwidth, latency, network topology, and available security measures.

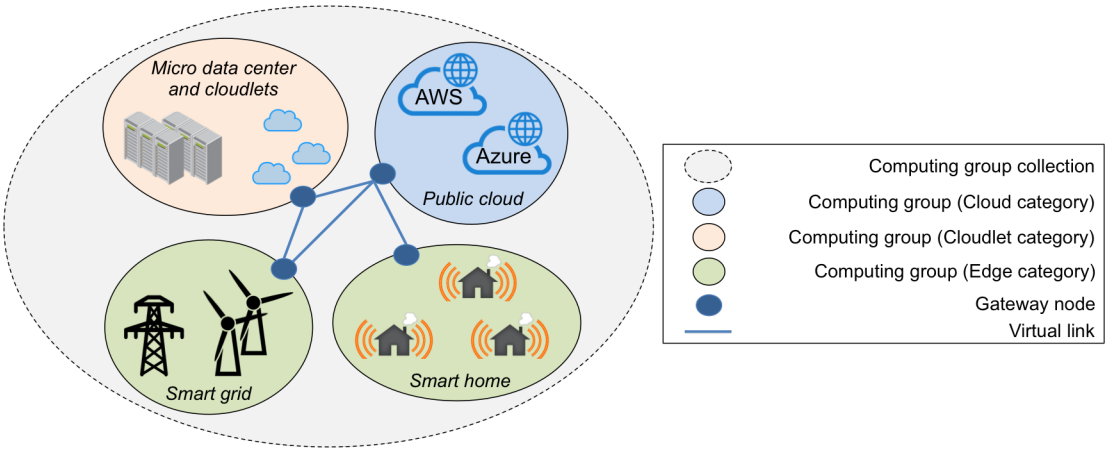


Figure 49: A Smart City Platform comprising a single Computing Group Collection composed of four different Computing Groups of three different categories.

In order to represent collection of above described resources, the concepts of *computing groups* (CG) and *computing group collections* (CGC) is used. A CG is a collection of physical computing nodes that share a common communication network that can be thought of as a *subnet*. Similarly, a CGC is a collection of one or more computing groups. Any two CGs of a CGC can have a virtual link between them. Presence of a virtual link indicates that entities of the associated CGs can communicate with each other via their corresponding gateway nodes. Different CGs of a CGC can be classified into categories, such that each CG belongs to a category and multiple CGs can belong to the same category.

Given these abstract notions of resource collection, we can easily represent resources

Table 8: Different Categories of Resources in a Smart City Platform.

Category	Description
Edge	In this category nodes are resource-constraint and they are usually deployed in or close to the target physical environment. Further, edge nodes are generally equipped with sensors and actuators to monitor and control their physical environment. As such, edge nodes are ideal for deploying cyber-physical applications that need to interact with the physical environment in real-time using available sensors and/or actuators. Smart home and smart grid are examples of this category.
Cloudlets	This category comprises nodes with more computing and storage resources than edge nodes. Unlike public clouds with data centers located in different geographic regions, cloudlets comprise of resources located in specific regions of interest resulting in less communication latency between these resources and edge nodes [96]. Connectivity between edge nodes and cloudlets can span from best-effort, internet-type connectivity over low-latency Local Area Networks (LANs) to real-time industrial Ethernet or field busses. As such, these resources can be used to host (soft) real-time applications.
Cloud	In this category nodes are highly resourceful and resources can be scaled up or down as modern cloud infrastructures support on-demand elasticity. Data centers that provide these resources are usually located far from edge nodes, as such, the communication latency between these resources and edge nodes are comparatively higher than that between cloudlets and edge nodes. Therefore, this category is well-suited to host long-running computation intensive tasks that do not require real-time responsiveness. Example of this category are various public cloud service providers.

provided by a smart city platform as CGCs. To better describe these concepts, Figure 49 presents a smart city platform that consists of a single CGC comprising four different CGs (1) smart home, (2) smart grid, (3) micro data center and cloudlets, and (4) public cloud. These CGs are divided into three categories described in Table 8.

VII.2.1.2 Application Types and Existing Computation Patterns

Smart city platforms can hosts different applications. In some cases, these applications are deployed on resources of same computing group, while in other cases, applications are deployed on resources of different computing groups. For the former, consider a smart home application that uses temperature monitors to check indoor temperature and control available thermostats accordingly. For the latter, consider a smart grid application, where different sensor applications are deployed on resources of edge category and short-term analysis and planning applications are deployed on resources of cloudlet category. Finally,

a long running evaluation and design application can also be part of the smart grid application; this application will be resource intensive, and therefore, is well-suited to run on resources of cloud category.

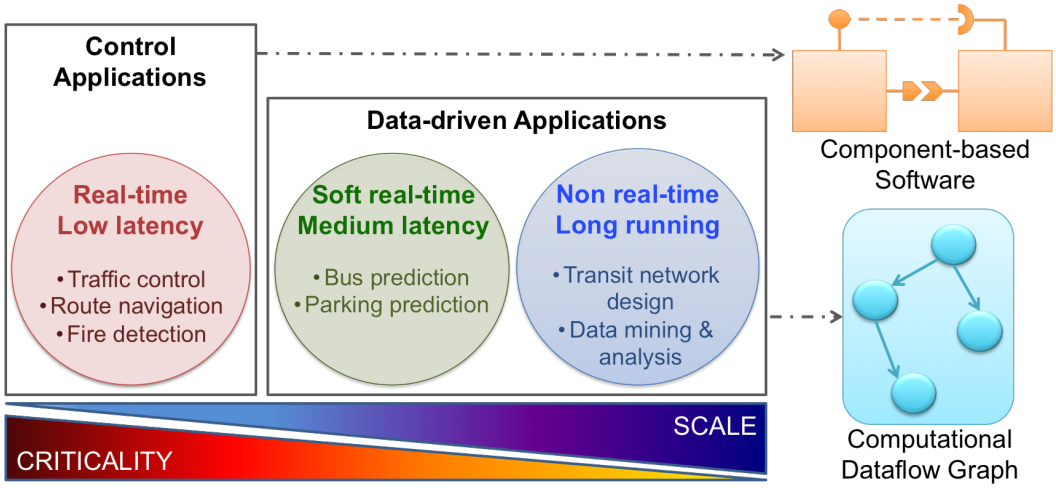


Figure 50: Different Types of Applications based on Resource requirement, Timing requirement, Criticality, and Scale.

Applications can be of different kinds. One way of differentiating applications is by determining their properties using key characteristics such as resource requirement, timing requirement, criticality, and scale. As shown in Figure 50, these characteristics are used to introduce two different application types (1) control applications, and (2) data-driven applications. Control applications are those applications that are cyber-physical in nature and by default are critical and require real-time responsiveness. These are low latency applications. Fire detection application in smart homes, and traffic control application in smart transportation are some examples of control applications.

Data-driven applications are soft or non real-time applications that rely on best-effort responsiveness. Short-term traffic, parking, home energy consumption analysis and prediction applications are some example of soft real-time applications. Whereas, a long running transit network design application is an example of a non real-time application. Since data-driven applications are computation heavy, they are usually deployed as large-scale

Table 9: Different Computing Patterns for a Smart City Platform.

Computing Patterns	Description
Time-driven component assembly	This pattern involves designing applications as composition of interacting components [41] based on an underlying component model that focuses on assuring domain requirements, which includes non-functional properties such as timeliness. Examples of such component models have been presented in [81]. In this pattern, the computation logic itself is executed either periodically, depending on available timers, or reactively depending on external events, such as message arrival at a component's port. This pattern can be used by control applications.
Stream processing	This pattern involves processing data in near real-time. Real-time stream of data is continually fed as input, which is then processed to generate output. What this means is that computations always happen on real-time data as it flows through a system. Storm [9] is an example of a popular stream processing framework. The Spark framework [8] can also be used for stream processing. S4 [67] is another solution that can be used for stream processing. This pattern can be used by soft real-time, as well as non real-time, data-driven applications.
Batch processing	In this pattern, computations are performed in *batches*, *i.e.*, a collection of non-interactive jobs are executed all at once. This pattern becomes useful in scenarios where high volume data acquisition happens over a period of time. Once data is acquired and stored, it can be processed in batches to obtain computation results. MapReduce [27] is a popular batch processing paradigm. Spark [8] framework, at its core, also supports batch processing. This pattern can be used by non real-time applications as it is not designed to support real-time data processing.

applications. Depending on these application types, corresponding applications can have varying computation patterns; Table 9 identifies relevant exiting computation patterns for smart city platforms.

VII.2.1.3 Problem Statement

An extensible CPS such as a smart city platform requires some mechanism that facilitates collaboration between applications of different types. In order to devise any such mechanism, we need to be able to design and develop applications without having to worry about differences in their type. To resolve this challenge we need an abstraction that allows us to view all applications as the same so that we can model their compositions and

interactions. This also allows us to better reason about a system as a whole. This chapter proposes a solution for this challenge by presenting a generic computation model that facilitates middleware heterogeneity.

VII.2.2 Proposed Solution: A Generic Computation Model

To generalize the different computation patterns, this section proposes a generic computation model that represents distributed computations as a computation graph resulting in a dataflow network. This approach aligns well with existing data processing engines – such as Storm, Spark, S4, and TensorFlow – as these technologies also rely on some form of computation graph. For example, in the case of Storm, *topologies* are used to define computation graphs that comprise *spouts*, which represent streams of data sources, and *bolts*, which represents data processing. Edges between nodes of a topology represent data flow. Similarly, in the case of Spark, an application is first divided into jobs, which are then broken down to computation graphs composed of *task stages*. Edges between task stages represents a data flow. S4's computation graphs are composed of nodes called *Processing Elements* and edges called *Streams*. Finally, TensorFlow's computation graphs are composed of nodes, which can be *ops* (operational) or *source ops*, and edges between these nodes are represented by the concept of *tensors*, which are typed multi-dimensional arrays.

For the above described computation pattern to work, we must ensure that it can be used for component-based control applications as well. Traditionally, these applications have been designed using time-driven component assembly VII.2.1.2, but they can be designed using a dataflow graph approach as well; nodes can represent computations, whereas, edges can represent events or dataflow. An added advantage of this approach is that the computation model can easily support a generic reactive model whereby events can be separated from related computations. This is not necessarily the case with existing component models that have tight coupling between events (specially external message related event) and

corresponding computation logic. This is mainly because existing computation models are designed to work with a specific communication middleware.

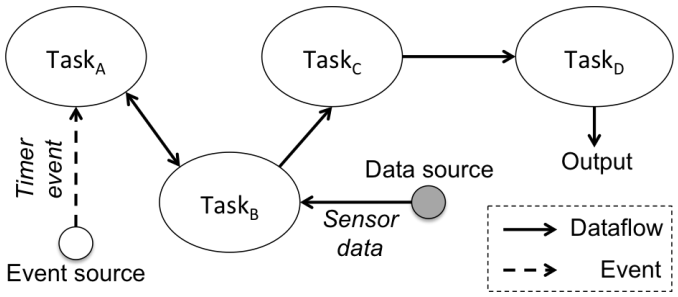


Figure 51: A Computation Graph comprising Computation Tasks, Dataflows between Tasks, an Event Source and a Data Source.

Figure 51 presents the proposed computation model represented as a computation graph comprising multiple computation tasks, edges between these tasks to denote dataflow dependencies, and event and data sources. Each task is a unit of computation which can consume data and/or produce data. Each task can also be connected to one or more event sources and data sources. An example of an event source is a timer, which periodically fires a timer event, or an application lifecycle manager, which fires lifecycle events (application start, pause, etc.). Sensors are an example of data source. Data files stored in a filesystem can be another data source.

The proposed computation model comprises of components; they are the unit of computation. As such, a component is equivalent to a task in Figure 51. The concept of component assemblies is also introduced; a component assembly is nothing but a collection of components. The components themselves can be of different kinds: (1) external components, and (2) CHARIOT components. A component that represents a Storm *bolt*, a Storm *spout*, or a Spark *job* is considered external component because these dataflow engines have their own computation model. However, for component-based control applications, a new computation model is required. This computation model should be part of a solution

that facilitates a clean separation-of-concerns between computation and communication aspects. The section below proposes one such solution – the CHARIOT component model.

VII.2.2.1 The CHARIOT Component Model

Figure 52 presents an overview of the CHARIOT component model. A CHARIOT component is hosted in a container, which represents the process boundary. Furthermore, a CHARIOT component comprises (1) state variables, (2) input ports, each with a message queue and a trigger, (3) output ports, each with a message queue, (4) timers with triggers, and (5) an execution logic with trigger callbacks and a business logic.

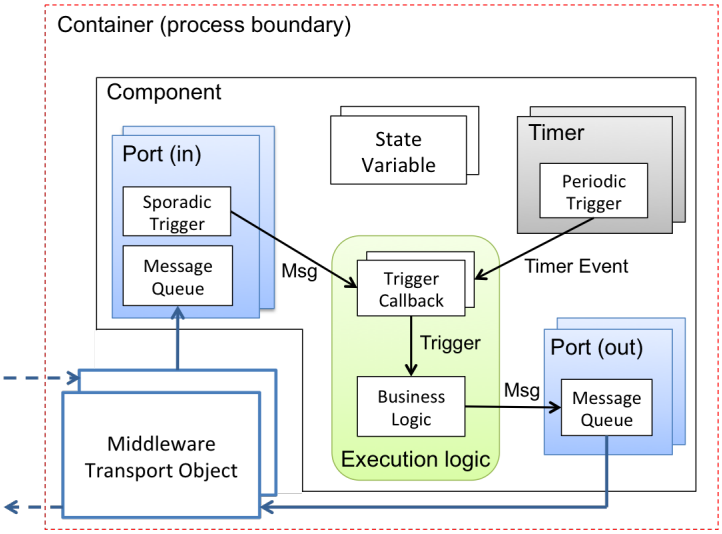


Figure 52: Overview of the CHARIOT Component Model.

A component can have multiple input and output ports which can follow *pull* or *push* semantics. Each port also has its own message queue. The size of this queue is 1 for ports with pull semantics, i.e., these ports are *sampling ports*. Whereas the ports with push semantics can have size greater than or equal to 1; if the size is 1, it is a sampling port and if the size is greater than 1 then it is a *buffered port*. Furthermore, input ports, regardless of type, can contain a trigger. These port-associated sporadic triggers are registered by

the execution logic; during this registration process, appropriate trigger callback is also created in the execution logic. It is important to note that a component can have multiple input ports and therefore can define sporadic triggers that depends on messages arriving at different ports. In this scenario, each sporadic trigger will be associated with a unique trigger callback in the execution logic.

Similar to sporadic triggers, an execution logic can also be associated with periodic triggers. These periodic triggers are registered with timers and each periodic trigger has a corresponding trigger callback in the execution logic. As the name suggests, a periodic trigger gets fired periodically resulting in invocation of the corresponding trigger callback.

The ports and the timers run on their own thread, whereas the execution logic runs on the component's main thread of execution. By default, when a trigger callback is invoked, the execution logic executes the associated business logic in the same thread. This implies that there should exist a queue to keep track of trigger callback invocation. However, another approach could be a multi-threaded approach, where we use a thread pool and every invocation of the trigger callback will result in creation of a new thread in which the business logic will be executed.

A component uses middleware transport object(s) to communicate with other component(s). Each transport object is associated with a middleware and helps expose standard APIs that can be used by component ports to send and receive messages. This approach is middleware agnostic and at its core relies on generic data types [87].

VII.2.2.2 Component Assembly

A component assembly is a collection of components that have inter-dependencies (*i.e.*, connections). In addition to components and connections, a component assembly can also have one or more ports and associated transport objects to communicate with a different

component assembly or a component. To better describe the concept of component assemblies, Figure 53 presents a component assembly, called *StormAssembly*, which interacts with a CHARIOT component, called *SensorComponent*.

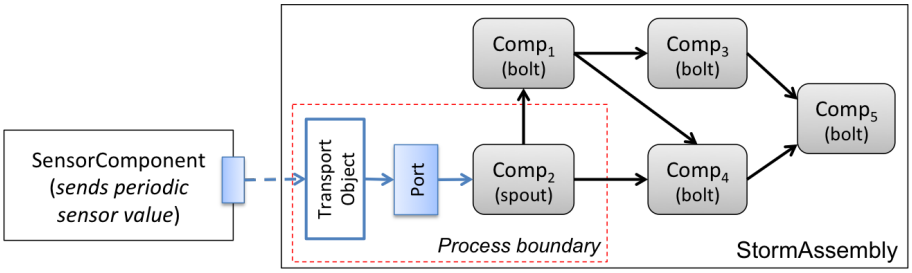


Figure 53: An Example Demonstrating interaction between a Component Assembly that maps to a Storm Topology and a CHARIOT component.

The aforementioned component assembly (*StormAssembly*) consists of five different external components; these components and their inter-dependencies can be mapped to a Storm topology where four of the components are mapped to bolts and the remaining component is mapped to a spout. The spout component ($Comp_2$) is the data source for the topology, and therefore, consists of a collocated (same process) port and a transport object[1] to receive messages from the *SensorComponent*. This example assumes the *SensorComponent* to periodically send some sensor data to the *StormAssembly* for analysis.

Above proposed solution of a generic computation model, that comprises of a novel component model for component-based control applications and component assemblies that represent computation dataflow graph for data-driven applications, can facilitate interaction and collaboration between heterogeneous applications.

VII.3 Summary of Publications

Journal and Book Chapter Publications:

1. Subhav Pradhan, Abhishek Dubey, Shweta Khare, Saideep Nannapaneni, Aniruddha

[1] A transport object for a Storm topology can be based on Kafka [50]

Gokhale, Sankaran Mahadevan, Douglas C Schmidt, and Martin Lehofer. "CHARIOT: A Holistic, Goal Driven Orchestration Solution for Resilient IoT Applications". ACM Transactions on Cyber-Physical Systems. (Under review)

2. Subhav Pradhan, Abhishek Dubey, Tihamer Levendovszky, Pranav Kumar, William Emfinger, Daniel Balasubramanian, William Otte, and Gabor Karsai. "Achieving Resilience in Distributed Software Systems via Self-Reconfiguration". The Elsevier Journal of Systems and Software (JSS 2016), vol. 122, pp. 344-363.

3. Subhav Pradhan, Abhishek Dubey, and Aniruddha Gokhale. "Designing a Resilient Deployment and Reconfiguration Infrastructure for Remotely Managed Cyber-Physical Systems". Book chapter in Software Engineering for Resilient Systems (SERENE 2016), vol. LNCS 9823, pp. 88-104.

Conference and Symposium Publications:

1. Subhav Pradhan, William Emfinger, Abhishek Dubey, William Otte, Daniel Balasubramanian, Aniruddha Gokhale, Gabor Karsai, and Alessandro Coglio. "Establishing Secure Interactions Across Distributed Applications in Satellite Clusters". Proc. of the 5th IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT 2014), pp. 67 - 74, Laurel, Maryland, USA.

2. William Otte, Abhishek Dubey, Subhav Pradhan, Prithviraj Patil, Aniruddha Gokhale, and Gabor Karsai. "F6COM: A Component Model for Resource-Constrained and Dynamic Space-Based Computing Environment". Proc. of the 16th IEEE Computer Society symposium on object/component/service-oriented realtime distributed computing (ISORC 2013), pp. 1-8, Paderborn, Germany.

Workshop Publications:

1. Abhishek Dubey, Subhav Pradhan, Douglas C. Schmidt, Sebnem Rusitschka, and Monika Sturm. "The Role of Context and Resilient Middleware in Next Generation Smart

Grids". The 3rd Workshop on Middleware for Context-Aware Applications in the IoT (M4IOT 2016). (To be published)

2. Saideep Nannapaneni, Sankaran Mahadevan, Subhav Pradhan, Abhishek Dubey. "Towards Reliability-based Decision Making in Cyber-Physical Systems". Presented at the 1st IEEE Workshop on Smart Service Systems (SmartSys 2016), St. Louis, Missouri, USA.

3. Subhav Pradhan, Abhishek Dubey, Sandeep Neema, and Aniruddha Gokhale. "Towards a Generic Computation Model for Smart City Platforms". Proc. of the 1st International Workshop on Science of Smart City Operations and Platforms Engineering (SCOPE 2016), pp. 1- 6, Vienna, Austria.

4. Subhav Pradhan, Abhishek Dubey, Aniruddha Gokhale, and Martin Lehofer. "CHARIOT: A Domain Specific Language for Extensible Cyber-Physical Systems". Proc. of the 15th Workshop on Domain-Specific Modeling (DSM 2015), pp. 9 - 16, Pittsburgh, Pennsylvania, USA.

5. Subhav Pradhan, William Otte, Abhishek Dubey, Aniruddha Gokhale, and Gabor Karsai. "Towards a Resilient Deployment and Configuration Infrastructure for Fractionated Spacecraft". Proc. of the 5th Workshop on Adaptive and Reconfigurable Embedded Systems (APRES 2013), pp. 29 - 32, Philadelphia, PA, USA.

6. Kyoungho An, Subhav Pradhan, Faruk Caglar, and Aniruddha Gokhale. "A Publish/-Subscribe Middleware for Dependable and Real-time Resource Monitoring in the Cloud". Proc. of the MIDDLEWARE 2012 workshop on Secure and Dependable Middleware for Cloud Monitoring and Management (SDMCMM 2012), article no. 3, Montreal, QC, Canada.

Poster and Work-in-Progress Publications:

1. Subhav Pradhan, Abhishek Dubey, Shweta Khare, Fangzhou Sun, Janos Sallai, Aniruddha Gokhale, Douglas Schmidt, Martin Lehofer, and Monika Sturm. "Poster Abstract: A Distributed and Resilient Platform for City-scale Smart Systems". The 1st IEEE/ACM Symposium on Edge Computing (SEC 2016), Washington DC, USA. (To be published)

2. Subhav Pradhan, Abhishek Dubey, Aniruddha Gokhale, and Martin Lehofer. "WiP Abstract: Platform for Designing and Managing Resilient and Extensible CPS". Proc. of the 7th International Conference on Cyber-Physical Systems (ICCPS 2016), article no. 39, pp. 1 - 1, Vienna, Austria.

3. Subhav Pradhan, Aniruddha Gokhale, William R. Otte, and Gabor Karsai. "Real-time Fault Tolerant Deployment and Configuration Framework for Cyber Physical Systems". Proc. of the RTSS-WiP Session (RTSS-WiP 2012), pp. 32 - 32, San Juan, Puerto Rico.

Technical Reports:

1. Subhav Pradhan, William Otte, Abhishek Dubey, Csanad Szabo, Aniruddha Gokhale, and Gabor Karsai. "Towards a Self-adaptive Deployment and Configuration Infrastructure for Cyber-Physical Systems". Institute for Software Integrated Systems (ISIS) Technical Report, ISIS-14-102, 2014, Nashville, TN, USA.

2. Subhav Pradhan, Abhishek Dubey, William Otte, Gabor Karsai, and Aniruddha Gokhale. "Towards a Product Line of Heterogeneous Distributed Applications". Institute for Software Integrated Systems (ISIS) Technical Report, ISIS-15-117, 2015, Nashville, TN, USA.

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