Manfred Morari
Lothar Thiele (Eds.)

Hybrid Systems: Computation and Control

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Preface

This volume contains the proceedings of the 8th Workshop on *Hybrid Systems: Computation and Control* (HSCC 2005) held in Zurich, Switzerland during March 9–11, 2005. The annual workshop on hybrid systems attracts researchers from academia and industry interested in modeling, analysis, and implementation of dynamic and reactive systems involving both discrete and continuous behaviors. The previous workshops in the HSCC series were held in Berkeley, USA (1998), Nijmegen, The Netherlands (1999), Pittsburgh, USA (2000), Rome, Italy (2001), Palo Alto, USA (2002), Prague, Czech Republic (2003), and Philadelphia, USA (2004). This year's HSCC was technically co-sponsored by the IEEE Control Systems Society.

The program consisted of 3 invited talks and 40 regular papers selected from 91 regular submissions. The program covered topics such as tools for analysis and verification, control and optimization, modeling, engineering applications, and emerging directions in programming language support and implementation.

We would like to thank the Program Committee members and reviewers for an excellent job of evaluating the submissions and participating in the online Program Committee discussions. Special thanks go to Markus P.J. Fromherz (Palo Alto Research Center, USA), Edward A. Lee (University of California, Berkeley, USA), and Pablo A. Parrilo (Massachusetts Institute of Technology, USA) for their participation as invited speakers. We are also grateful to the Steering Committee for helpful guidance and support. Many other people worked hard to make the HSCC 2005 a success. We would like to thank Frank J. Christophersen and Ernesto Wandeler, the Publicity Chairs (with the help of Urban Mäder); Martine D'Emma and Monica Fricker for local arrangements; and Frank J. Christophersen for putting together the proceedings. We would like to express our gratitude to HYCON and ARTIST, Networks of Excellence of the Sixth Framework Programme of the European Commission, for their financial support.

January 2005 Manfred Morari and Lothar Thiele

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Coordinated Control for Highly Reconfigurable Systems

(Invited Paper)

Markus P.J. Fromherz, Lara S. Crawford, and Haitham A. Hindi

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Abstract. The remarkable drop in the cost of embedded computing, sensing, and actuation is creating an explosion in applications for embedded software. As manufacturers make use of these technologies, they attempt to reduce complexity and contain cost by modularizing their systems and building reconfigurable products from simpler but smarter components. Of particular interest have recently been highly reconfigurable systems, i.e., systems that can be customized, repaired, and upgraded at a fine level of granularity throughout their lifetime.

High reconfigurability is putting new demands on the software that is dynamically calibrating, controlling, and coordinating the operations of the system's modules. There is much promise in existing software approaches, in particular in model-based approaches; however, current techniques face a number of new challenges before they can be embedded in the kind of real-time, distributed, and dynamic environment found in highly reconfigurable systems. Here, we discuss challenges, solutions, and lessons learned in the context of a long-term project at PARC to bring such techniques to a highly reconfigurable paper path system.

1 Introduction

The remarkable drop in the cost of embedded computing as well as sensing and actuation hardware is creating an explosion in applications for embedded software. Yet while manufacturers are able to add ever more functionality and safety features to their products, they also struggle with the resulting complexity. Increasingly, companies attempt to reduce this complexity, decrease development time, and contain cost by modularizing their systems and building *reconfigurable products* from simpler but smarter networked components. This in turn requires new capabilities from the software that is controlling and coordinating these modules in order to provide an integrated system that is flexible, effective, robust, and safe.

As an example, consider modern high-end printers. One such product comes with about one hundred embedded processors, controlling everything from individual motors in the paper transport to image processing functions to high-level

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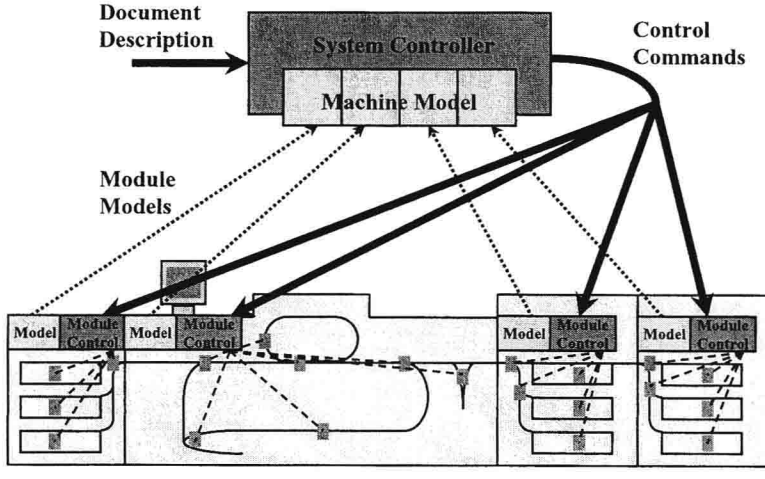

Fig. 1. A modular printing system (feeder, marking engine, and finishers) with model-based auto-configuration and control at three levels

coordination of the entire system to the interaction with the operator. Figure 1 sketches such a system, together with controllers at three different levels (system, module, and component). In this prototypical system, each of the four modules comes with a model, a declarative description of its capabilities, which is passed to the system controller at boot time. This system controller accepts a stream of document descriptions (print jobs) and, using the models, plans and schedules the necessary operations. This results in a stream of control commands to the modules, which in turn control their individual components, many of which have their own low-level controllers. The many controllers in such a system together enable the totally automated operation of a highly complex system that can be considered one of the most sophisticated robots today. These distributed controllers monitor, coordinate, calibrate, optimize, and compensate hundreds of processes with virtually no human involvement.

Today, such high-end print systems are put together from about ten to twenty feeder, marking, and finishing modules. Given the trends and motivations indicated above, it is conceivable that these numbers will increase by an order of magnitude with a corresponding reduction in module size, leading to highly reconfigurable (or hyper-modular) systems. We define a highly reconfigurable system as a modular system that can be reconfigured both in the factory and in the field, often dynamically and at a fine level of granularity. Consequently, there is no final configuration, and both hardware and software modules have to be designed without knowledge of future configurations and other modules that form the context in which a module will operate. Where so far most of a system's behaviors were confined to individual modules, with little regard to concurrent activities in other modules, now most of the behavior comes from the interaction and collaboration of networked, tightly coupled modules.

We believe that highly reconfigurable systems with coordinated control will appear in a number of domains. In some high-end cars, for example, a braking operation already involves the coordinated execution of subsystems such as engine and suspension control, in addition to the coordinated control of the brakes in all four wheels. Today, though, these controllers require careful tuning, and subsystems cannot be upgraded easily. Similarly, in the domain of assembly lines and production systems, retooling and reprogramming the robot stations for new product models sometimes takes days, if not weeks or even months, as much of the equipment works without awareness of the environment. Adding coordinating controllers that can reasons about the capabilities and coupled actions of multiple robots will allow the overall system to adapt automatically when robots are added, upgraded, or replaced over time. In other domains, there are strong incentives to modularize systems from current monolithic designs. In the space exploration domain, for example, weight is a dominant cost factor in the deployment of robots and material. Sustainable planetary missions will only be possible with modular robots and reconfigurable structures that allow for local reuse and reduced material transport across space. Overall, modular architectures promise to lower production, deployment, and maintenance costs and at the same time improve flexibility, performance, and safety. As a consequence, more emphasis will be on the coordinated control of the diverse functions of modular systems.

There is much promise in existing software approaches to address the challenges of highly reconfigurable systems. In particular, *reasoning techniques* such as model-predictive control, model-based planning and scheduling, knowledge-based diagnosis, and intelligent configuration [21] promise powerful solutions to the problems of embedded control and coordination. However, current techniques face a number of challenges that revolve around the *location and communication of knowledge* in a distributed control system, namely knowledge about the system's capabilities, its states, and its goals. In designing architectures and algorithms for such systems, we have to consider where this knowledge is generated, where it will be applied, how it is to be communicated, and how it has to be transformed in order to provide fully integrated system behavior without losing the advantages of high reconfigurability. This leads to the fundamental tension between *module autonomy* and *integrated behavior*: module controllers need to be able to make valid and efficient local decisions that are consistent and even optimal with respect to decisions of other relevant controllers.

This paper discusses challenges, solutions, and lessons learned in the context of a long-term project to embed reasoning techniques in a highly reconfigurable system. We provide a first description of our domain in Section 2. In Sections 3 and 4, we describe the top control design challenges we experienced so far, and we present a set of principles for compositional control that we found useful in addressing these challenges. In Section 5, the approach to our concrete control coordination problem is presented and discussed. We note that the discussion of design challenges and principles will necessarily be somewhat abstract. We invite the reader to jump from Section 2 to Section 5 for a concrete embodiment. We end with conclusions and thoughts about future work.

2 A Simple Domain Example

As a simple model domain, consider a linear sequence of rollers that together are transporting an object, such as a sheet of paper (Figure 2). Each roller is powered by its own independent motor, and each motor is controlled by its dedicated controller. The rollers are spaced such that a typical object will be moved by several rollers at a time, e.g., between two and six consecutive rollers depending on the object's size. For our purposes, we treat each roller with associated motor and controller as a separate transport module. We assume exactly one roller per module and call its controller the module controller. Each module further has associated sensors to detect the presence of the object. In general, all modules do not have to be identical, but instead may differ in their elements (e.g., the number of sensors) and in their behavior characteristics (e.g., velocity and acceleration limits). When used in a production line, there will be multiple parallel and interconnected material paths, with special branching modules for splitting and merging these material paths. We disregard these capabilities in this paper.

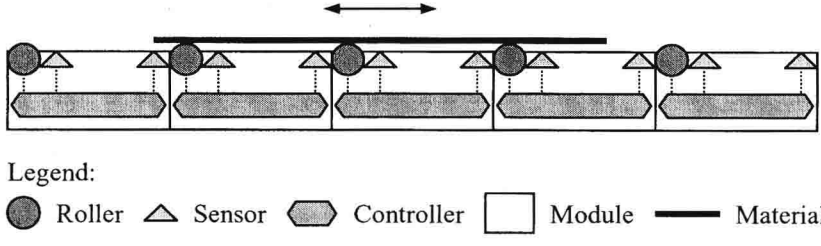

Fig. 2. Modular material path

At the top level of this system, a centralized planner (and scheduler) receives a series of job requests and determines the overall flow of material to produce these jobs [6, 20]. In the following, we provide a short overview of the planning level. The remainder of this paper will focus on the problem of implementing the planner's output, in particular on controlling the transport of objects along modular reconfigurable material paths.

A typical job description is a set of literals that describe an initial state and a desired output, as in the following example.

Job-23	
initial:	goal:
Location(Job-23, Source)	Location(Job-23, Destination)
Blank(Job-23)	Image(Job-23, Black)
Color(Job-23, White)	Color(Job-23, White)
Size(Job-23, A4)	Size(Job-23, A4)
¬Aligned(Job-23)	

In this example, `Source` and `Destination` are virtual locations where all sources or destinations are placed. All other literals describe initial or desired attributes of the job.

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