Elements of a Robotics Research Roadmap: A Model-Based Design Perspective

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I. Introduction

For the past several decades, the staple application of robots has been in manufacturing where they have been a key technology to improve factory performance, and efficiency [1]. Where in manufacturing robots are often immobile, recently there is a growing interest in mobile robots. For example, the deep space probes of NASA, unmanned autonomous vehicles (UAV) in general, the Aibo robotic toy, the Roomba robot vacuum, and the Toyota partner robots.

At present, most of these robots are of a more or less experimental nature, but they herald an era in which automated physical manipulation will be as ubiquitous as embedded computing has become.

With increasing capabilities of future mobile robots come increasing responsibilities. Three essential criteria for a successful realization of this view can be identified as:

- **Safety**—Clearly when robots become mobile, they should operate in a manner that is safe to humans in every sense.
- **Security—**As potential agents for malicious intent, robots should be secure against hostile take over.
- **Robustness—**There are two forms of required robustness: (i) in mixed-initiative interaction (*robot to robot* as well as *human to robot*) and (ii) in handling of uncertainties.

To produce robots that qualify against these criteria, methodological and technological advances are required that support a successful design. Because of the complexity of the physics

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as well as the control and information technology that is immanent in robotic systems, combined with the need to understand and design the interaction between these elements, a multi-disciplinary approach is a prerequisite for success. The multi-disciplinary character is of a two-dimensional nature:

- **Vertical—**High-level synthesized robust control laws need to be transformed into a representation that ultimately can be implemented in a computer architecture.
- **Horizontal—**Design teams with expertise in the different areas need to collaborate so that, for example, a control law can be designed in conjunction with a physical assembly given the quality-of-service of a sensor network.

Ideally, the separate systems can then be integrated in a predictable and straightforward manner.

This position statement outlines a set of methodologies and technologies that need to be developed and mastered over the next five to ten years in an attempt to address the criteria sketched.

II. A Model-Based Design Roadmap

A Model-Based Design roadmap is outlined by methodological and technological advanced along a number of different dimensions: (i) control engineering, (ii) fault detection and isolation, and (iii) systems engineering. Furthermore, a number of necessary developments in foundational methodologies and technologies are posited. This is not intended to be an exhaustive overview and areas such as signal processing and machine intelligence, albeit critical, are not specifically addressed.

A. System Engineering

Methodologies:

- Standardize on an architecture (e.g., four layers consisting off: a planner, a supervisor, loop control, a plant).
- Develop a platform-based design approach.
- Establish a framework for compositionality.
- Direct reliability approaches towards highly dependable and configurable systems.

Technologies:

- Formally model transformations of models.
- Being able to statically verify dynamic properties of models (as well as transformation models).
- Certify adaptive systems.
- Develop a middleware platform, in particular a platform that fits the compositionality framework.

B. Control Engineering

Methodologies:

- Cultivate robust control approaches to become more accessible.
- Further the state of reconfiguration control at a supervisory level.
- Advance distributed and collaborative control methods.
- Research exploiting nondeterminism in control.

Technologies:

- Automate robust control design methods.

C. Fault Detection and Isolation

Methodologies:

- Adapt health monitoring methodologies to highly dependable systems.

Technologies:

- Employ watchdog prognostic technology for highly dependable systems.
- Establish diagnostic technology, for example to aid in debugging of mixed-initiative systems.
- Develop robotic reconfiguration technology, for example, for plan-driven systems.

D. Foundations

Methodologies:

- Advance and focus nondeterministic as well as probabilistic modeling.
- Solidify approaches to heterogeneous modeling and execution of such models.
- Develop frameworks for efficient and effective model transformation and model (including transformation model) evolution.

- Research approaches to inconsistency management and consistency maintenance.

Technologies:

- Provide automated modeling facilities.
- Support semantic anchoring of domain-specific modeling formalisms.

III. A Tools Perspective

Where much robotics research still relies on physical prototyping, for example, in the study of bipedal motion, production-based robots will put forward a need for extensive use of computational models. Such Model-Based Design has shown to be essential to be competitive in industrial areas such as Automotive, Aerospace, and Consumer Electronics, and it will be critical for a future Robotics Industry as well.

The nature of robotics calls for broad horizontal tool support across many different domains such as control design, signal processing, physics modeling, computer engineering, and artificial intelligence. Specific effort in the different domains needs to be related to each other and vertical traceability from requirements to implementation must be supported. The need for Model-Based Design will, therefore, drive extensive adoption of products that facilitate a comprehensive tool chain to support the approach of using computational models for design.

References

[1] EUROP-The European Robotics Platform. Strategic research agenda. Technical report, European Union, May 2006.

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Pieter J. Mosterman is a senior research scientist at The MathWorks, Inc. in Natick, MA. Before, he held a research position at the German Aerospace Center (DLR) in Oberpfaffenhofen. He has a Ph.D. degree in Electrical and Computer Engineering from Vanderbilt University in Nashville, TN, and a M.Sc. degree in Electrical Engineering from the University of Twente, Netherlands. His primary research interests are in Computer Automated Multiparadigm Modeling (CAMPaM) with principal applications in training systems and fault detection, isolation, and reconfiguration. He designed several modeling and simulation environments such as the Electronics Laboratory Simulator, nominated for The Computerworld Smithsonian Award by Microsoft Corporation, a first version of Transcend for diagnosis of continuous-time system in transient operating regions, and MAsim for simulating differential and algebraic equation based models from Modelica. He was awarded the IMechE Donald Julius Groen Prize for a paper on HyBrSim, a hybrid bond graph modeling and simulation environment. Specific areas of interest are modeling of physical systems, meta-modeling, and model and formalism transformation in computer aided control system design (CACSD) and in Electronics Design Automation (EDA). An important aspect concerns the behavior generation for heterogeneous models, which requires a hybrid dynamic systems approach.

Dr. Mosterman is currently Editor-in-Chief of Simulation: Transactions of The Society for Modeling and Simulation International for the Methodology section, and Associate Editor of IEEE Transactions on Control Systems Technology and of Applied Intelligence. He was Guest Editor of special issues of ACM Transactions on Modeling and Computer Simulation, IEEE Transactions on Control Systems Technology, and Simulation: Transactions of The Society for Modeling and Simulation International on the topic of multiparadigm modeling. He co-organizes the Model-Based Design for Embedded Systems track at the Design Automation and Test in Europe conference and exhibition since 2007, the Computational Modeling and Simulation of Embedded Systems track at the 2007 Summer Computer Simulation Conference, the International Conference on High Level Simulation Languages and Applications in 2007, the annual International Bellairs CAMPaM Workshop since 2004, and the 14th International Workshop on Principles of Diagnosis in 2003.