Design Suite for Deeply Embedded Cyber Physical Systems

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***Abstract*— Many emerging applications are deployed in harsh environments and must operate dependably, efficiently and in real-time. This makes it essential to develop robust system designs before deployment. Thus, there is a tremendous need for a complete design suite for deeply embedded cyber physical systems that will enable the designers to model these systems to the desired level of abstraction, analyze the models and validate them. The main challenges involved in the design process are due to the complex interactions between communication, computing and the physical components in cyber physical systems. We discuss the problems faced in developing such a design suite and possible solutions to overcome them.**

Deeply embedded cyber physical systems are complex system of systems which are deployed in real-world environments. Advances in this area have enabled a variety of new application domains to be identified and applications in a wide range of fields have become a reality using this technology. Many emerging applications such as those concerned with military surveillance, rescue squads, fire alarm systems or other safety-critical systems must operate dependably, efficiently and in real-time in harsh environments. Therefore, properly designing these systems before deployment is crucial. Since cyber physical systems (CPSs) consist of complex interactions between communication, computing and the physical components, the design process involves resolving trade-offs between many competing objectives.

Currently, there are few tools for modeling and analyzing large-scale deeply embedded systems to guide the designers. However, these tools are isolated efforts which cater to specific problems in designing the system or are geared for certain applications. Therefore, there is a tremendous need for a complete design suite for deeply embedded CPSs, which will be used for modeling, analysis and validation throughout the lifecycle of the system. This suite will provide facilities to model any application for deeply embedded systems and estimate the system performance using mathematical analyses. Moreover, it will address all the major issues that are crucial for the designers, such as lifetime, real-time, security, coverage and reliability.

We envision the following issues that need to be addressed to develop a complete design suite for deeply embedded CPSs.

1) *Modeling the system:* One of the major challenges in modeling and analyzing deeply embedded systems is that there is a close interaction between the communication and the computation component. Hence, modeling deeply embedded CPSs can be viewed as a two-level process: modeling the network and modeling the sensor nodes.
    - *Network/Communication Level Modeling:* The concept of radio range and communication range in wireless networks, which is an integral part of the communication component in deeply embedded systems, does not go well with the idea of a bus, which is widely used in wired systems and is supported by many modeling languages. The design suite must provide support to model wireless links using the radio range and explicitly represent the effects of interference in the system model.
    - *Modeling Radio Irregularity:* In most of the analyses and simulation tools, the radio range and the interference range of sensor nodes are assumed to be circular and symmetric. However, it has been shown that this is not true in reality [4]. Since these deeply embedded systems will be deployed in the real world, radio irregularity models should be integrated in the design suite to provide the designers with a close approximation of the real world scenario.
    - *Node Level Modeling:* Modeling a sensor node involves complex interactions between the hardware (sensors, actuators, processor, battery, memory and radio), computation (operating system and application processes) and networking components (protocol stack and connections). Node level modeling is aimed at building a convenient and easy-to-use mechanism for the designers to specify the sensor node system.
    - *Modeling Sensing Irregularity:* Similar to the radio model, a circular sensing model is used for sensor nodes. However, support for modeling sensing irregularities [2] is needed to implement a realistic system model that reflects the real world scenario.

2) *Analyzing the system:* High level analyses, with minimum assumptions about the underlying system, can be used to evaluate trade-offs such as the number of nodes needed to meet certain tracking performance or provide a certain degree of coverage. As the model is refined iteratively, the analyses have access to more detailed knowledge about the system and can deliver more accurate results. Consequently, the designers may evaluate trade-offs which involve detailed system information, e.g. with respect to lifetime, reliability, security.
   We present various types of analyses that need to be

added to the system, as well as analyses that need to be developed for a complete design suite as follows.

- *Topology Control:* As the designers start the design process, it is useful to get an estimate of the number of nodes needed and the possible location of these nodes before getting started. Such an analysis for topology design will be invaluable for the design suite, where the designers can evaluate the cost of the system vs. the coverage provided by the system and evaluate various topologies for the intended deeply embedded system.
- *Communication Reliability Analysis:* The system infrastructure, namely the sensor capabilities, the large scale of the system, the external environment, sensing and radio irregularities, and the deployment strategies, all play a significant role in the communication reliability. The design suite will include analyses to evaluate the communication reliability of various system designs by estimating performance metrics such as end-to-end delay and expected delivery ratio.
- *QoS-centric/Real-time Services Analysis:* Specifying real-time and quality of service (QoS) requirements such as end-to-end deadlines and real-time capacity is crucial for the designers. Such analyses will be an integral part of the design suite and will enable the designers to estimate various QoS metrics and evaluate trade-offs among different types of QoS metrics.
- *Lifetime Analysis:* Lifetime analysis attempts to estimate the length of time for which the system is functional before running out of power. Since deeply embedded systems are severely constrained in terms of battery power, lifetime analysis can be used by the designers to evaluate various protocols. Existing analyses estimate the lifetime of the network for specific scenarios. A generic energy model, integrated with the design suite, will be suitable for estimating the lifetime of different applications and evaluating various system designs.
- *Security Analysis:* Deeply embedded systems have limited node and bandwidth capacity, which makes it challenging to adapt existing internet security solutions to these systems. Moreover, different type of attacks need different defense mechanism. The design suite needs a mechanism to specify different types and levels of security and analyze the trade-off between the level of security and the performance of the system.

3) *Mobility:* Mobile sensor networks add a new dimension to the capability of deeply embedded systems. At the same time, they present additional challenges in modeling, analyzing and designing the system, that have not been studied extensively. As a first step in this direction, the design suite should provide facilities to model mobile deeply embedded CPSs and represent the dynamism of mobile nodes in the system model.

As a first step towards this design suite, we have developed an analysis-based design tool, ANDES [3], which is based on the AADL/OSATE framework [1]. ANDES uses theoretical analysis techniques to resolve key design decisions. Theoretical analysis techniques are used to estimate key performance metrics (such as lifetime, sensing coverage, real-time capacity and reliability) of the system model based on a set of system parameters (such as the number of nodes, duty cycle, sensing range of nodes, and the available bandwidth). These analyses are considerably inexpensive in terms of time and resources as compared to using simulators and developing system prototypes. Currently ANDES supports three analyses: target tracking analysis, real-time capacity analysis and communication schedulability analysis. Working on ANDES helped us identify the major issues involved in developing a complete design suite for deeply embedded CPSs.

We chose the AADL/OSATE framework, which has been widely used for real-time and embedded systems, for ANDES. We believe that AADL/OSATE is an ideal platform for deeply embedded systems, which involve a very close interaction between the hardware and software components, and can benefit from the existing support offered by AADL/OSATE. Moreover, using AADL, which is used in the industry extensively, promotes good software engineering practices and has the potential of developing into a standard for deeply embedded systems as well.

In conclusion, deeply embedded CPSs have a wide range of applications which exert a significant influence on our daily lives. Properly designing these systems is of utmost importance to ensure that the systems are dependable. The strong connection between the communication, computation and the physical components in deeply embedded CPSs poses new challenges for the system designers. Therefore, a complete design suite is needed to develop robust system designs for deeply embedded systems. This design suite will include facilities to model any application for deeply embedded systems and provide a repository of analyses to estimate the system performance and evaluate various system designs. Realistic models of the system will be integrated to obtain better accuracy in guiding the designers. Instead of targeting a specific application, our vision consists of a generic design suite for deeply embedded systems that will be used during all stages of system development.

References

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