Automata Based Interfaces for Dynamic Resource Scheduling in Control Systems

Summary Description of the Project

The project addressed the need for efficient resource utilization in embedded control software. The main objective was to combine control theory and scheduling theory in such a way as to remove the need for strict requirements on hard deadlines for control software components without compromising the ability to use them in safety-critical applications. Toward this goal, we conducted research on interfaces for components of software control systems that streamline the integration of dynamic scheduling mechanisms in safety critical systems while providing formal performance and stability guarantees. The main benefit that we expect the outcome of the research to give to the society is in allowing efficient resource allocation in critical control systems such as robots, airplanes, and industruial machines by feeding information from the control loop back to the scheduling algorithm and thereby allowing adjustments to resource allocation in response to time varying needs.

The specific achievements of the project were:

- Expansion of the scope of automata-based interfaces: We developed ways for using automata as a practical interface between scheduling and control that allows dynamic scheduling, formal performance guarantees, and separation of concerns between software and control engineers.
- We developed practical mechanisms for dynamic resource allocation in control systems: We propose a lightweight decision-making and scheduling mechanisms that allow control strategies that dynamically change their resource demands based on time-varying conditions.
- An experimental tools for demonstrating the advantages of the new approach: We developed a tool called GameComposer that proves the applicability our vision in some initial case-studies.
- Contribution to formal-methods and hybrids systems theories: We worked in the application domain of Quadrotor control and developed some new control and design techniques. We also produced some new results in formal methods and in automata theory.

The project integrates research in dynamical systems, control theory, computer aided verification, automata theory and other fields toward more flexible interfaces of control and scheduling. It aims at bridging the gap between the traditionally disjoint disciplines of control and real time theories by proposing interfaces that can capture the complexities of both worlds. Because complete co-design of control and scheduling may become prohibitively complex for most systems, we develop engineering methodologies that take into account the artifacts of the interaction of scheduling and control without breaking the separation of concerns between control and software engineers.

A more detailed description of specific results

In this project we examined different application domains and techniques. The team included the PI, Dr. Gera Weiss two master students at the Ben Gurion University: Merav Bukra and Amir Menzel and two Ph.D. students: Hanoch Efraim and Gal Amram. We also collaborated on issues related to the project with Dr. Assaf Marron from the Weizmann Institute and with Dr. Shai Arogeti from the department of Mechanical Engineering at the Ben-Gurion University. The following list summarizes the work done in all this collaborations that relevant to the RSCS project.

With Merav Bukra: We were looking for ways to use automata based scheduling with guards. Specifically, we looked into real-time distributed control systems in which measurement and actuation data is sent via a bus shared with other applications. Using observations from sensors, we direct the CPU and network so that so that all controlled processes are stabilized. Existing approaches to bus scheduling in control applications rely on static (periodic) schedules designed to assure performance in worst-case conditions. The main disadvantage of static schedules, in our context, is that they lack a mechanism to adapt to changing conditions. This often leads to trading off average for worst-case performance. Therefore, our research focused on specification and analysis of dynamic network resource scheduling techniques. We were working on an approach and a tool for specifying and implementing dynamic scheduling policies that are both flexible and allow for performance guarantees. Specifically, we proposed an automata based scheduler which we automatically generate from a model of the controlled plant and the controller. In addition to ensuring performance, our approach allows adjustments to dynamic conditions such as varying disturbances and network load and to dynamic component addition and removal. The schedules for shared CPU and network buses guarantee stability. We use guarded automata as a tool for formalizing the effect of resource scheduling on performance and as a mechanism for scheduling the resources such that stability is guaranteed. A scheduling approach is proposed that provides good performance both in average and worst-case conditions. We can show, with our tool, that automata based scheduling allows the schedule to react to dynamic conditions such as the output of the plant or the load on the network and still guarantee high-level requirements such as stability. In particular, we can demonstrate how, with our approach, resources are only used when needed and, by that, good average performance can be obtained together with worst-case guarantees.

With Amir Menzel: We were studying approaches for self-configuring wireless control networks. Typical industrial facilities such as chemical or manufacturing factories consist of thousands of processes regulated by programmable controllers at a control room. The control room is usually equipped with panels that depict the state of the controlled processes as captured by sensors and input devices that control the actuators, affecting the state of the plant. It turns out, in practice, that the actuators and sensors are often relatively inexpensive when compared with the cost of the cable that needs to be used to connect them. The difference becomes even greater when considering the high installation and maintenance costs, the high failure rate of connectors and the difficulty of troubleshooting them. This is leading to a technology shift in industrial control application where wired communication is replaced with wireless technologies. In addition to lowering installation and maintenance costs, wireless systems can also offer ease of equipment upgrading and practical deployment of new systems. The shift in the industry toward the use of wireless technologies in industrial control raises many interesting research problems. Specifically, adding a mesh network of sensors, actuator, and wireless transmitters to a control system yields a hybrid system where problems from networking theory and from control theory mix together. Our research provides a unified approach for designing and maintaining such systems. Moreover, a common goal in both wireless networking and industrial control is to provide engineers with systems that configure themselves automatically with minimum need for manual plant-specific configuration. We have initial results that show that this goal is achievable also for systems that involve both control and wireless networking. In particular, we developed a combined algorithm for the network and for the controller. The property that we proved for the algorithm is completeness, i.e., that it stabilizes any network that can be stabilized.

With Hanoch Efraim: We started to look into novel methods for data fusion on board a micro hovercraft using inertial sensors, vision from an on board camera, and dynamic system model. Specifically, we aim to incorporate data from cameras, sensors, and mathematical models toward control at all levels, from speed, location, and accurate pose estimation to navigation and autonomous decision making. We, of course, seek sound techniques based on mathematical and experimental analysis. Whenever possible, our objective is to prove mathematically that the methods we use are optimal. We also aim at algorithms that can be implemented with (relatively low) computational and time resources that are commonly available on board typical micro hovercraft. Our contributions include: (1) In the field of vision - developing algorithms for fast point matching, dynamic environment mapping and pose estimation. We will focus our efforts on higher level data processing and are not expected to develop new image processing techniques. We will, however, survey the existing techniques choosing the most appropriate to our specific control and estimation oriented tasks; (2) In the field of data fusion - developing a complete solution that uses all the information available combined to produce an optimal estimation of the essential parameter needed for guidance and control - Pose, velocity, sensor offsets. We will also expand the state vector of the hovercraft to include external variables such as wind to be estimated; (3) In the field of navigation - dynamic mapping that uses the hovercraft dynamic model to update and refine Its data base while operating. A side effect of this research was a proposal of a new structure for Quadrotors (small hovercrafts that have four statically positioned rotors) that allows for less reliance on accurate velocity measurements.

With Assaf Marron and Amir Nissim: We combined the work on the topics that the RSCS project is focused on with our recently published approach to incremental and modular development of discrete systems, called behavioral programming, in which simultaneous aspects of system behavior are coded as independent behavior threads to be interwoven at runtime. We show that this approach is useful as a tool for the natural development of control systems. Specifically, fuzzy set theory, which uses natural language quantifications like ”hot” or ”dangerous” in programming, has been successfully applied to a wide range of control applications. We combine the fuzzy and behavioral approaches to programming with two goals in mind. First, we make it possible to program discrete multi-step scenarios using fuzzy quantification or classification for inputs and outputs. Second, we simplify the development of switched fuzzy systems when the switching logic can be structured as a composition of multiple independent scenarios.

With Shai Arogeti: We have started to look into quadrotor control. Specifically we are interested in developing new hybrid control techniques, in integrating control and scheduling, and in failure identification techniques. Up to now, we only started to establish the tools toward a long term research in this domain. We installed several models of quadrotors and tested their suitability for different aspects of the research; we developed tools for automatic translation of Simulink models to quadrotor code, and we are in the process of installing a laboratory with cameras that will allow us to follow the exact path of the quadrotor and compare the exact data to the data coming from different estimation techniques. We also have some examples of different techniques for programming quadrotors.

With Gal Amram and Lior Mizrahi: We focused on Automata Theory**.** We developed algorithm and verification techniques for distributed algorithms. Specifically, we proposed new algorithms to solve fundamental problems in distributed computings and proposed new automata-based approaches to verify such algorithms.

List of the main results

With Merav Bukra: We have a prototype implementation and formal analysis of a new algorithm for automata based scheduling.

With Amir Menzel: We have a draft of a complete (works whenever possible) self-configuring scheduling algorithm for wireless control networks.

With Hanoch Efraim: We have initial proposals for mathematical models and algorithms for fusing sensor and camera data onboard a micro hovercraft.

With Assaf Marron and Amir Nissim: We have a prototype implementation of a controller that combines both behavioural-programming and fuzzy logic towards efficient and natural control devices.

With Shai Arogeti: We have an initial setting that will allow us, in the future, to carry practical research on quadrotor control.

With Gal Amram and Lior Mizrahi: We have a new algorithms and verification techniques for distributed computing.