Networks of Sensors

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SUMMARY

Networks of Sensors – Operation and Control

Over the past few years, the use of sensors has been growing at an unprecedented rate. Smartphones, intelligent washing machines, smart energy meters, and cars all work with a wide variety of sensors. On a larger scale, sensors are used for, e.g., patient observation in health care, smart building management, monitoring of infrastructural performance, and tracking wildlife. Further evidence of the popularity of sensors can be found on Gartner's 2015 Hype Cycle, which features 'The Internet of Things' – in which sensors play an important role – as one of the emerging technologies. With modern-day technology it is possible to make cheap 'mini-computers' that sensors can be attached to, yielding devices smaller than a credit card capable of monitoring of and interaction with the environment. In this thesis we refer to these devices as *sensor nodes*. Typically, besides sensors and basic processing capabilities, a node is also equipped with a radio that allows it to communicate wirelessly over short distances. Multiple nodes can form a network to jointly cover large geographical distances, i.e., form a *sensor network*.

Applications working with sensors and sensor networks face a number of challenges that are unique to sensor technology. Measurements from sensors are, for instance, subject to a certain amount of noise and can thus be unreliable. Also, sensor nodes are often battery-powered, and a nearly depleted battery might cause parts of a sensor network to be unreachable, or increase unreliability of measurements. Challenges such as these will become more relevant as the use of sensor technology gains in popularity in the near future. This raises the need for a deeper understanding of the challenges, for practical methods to deal with them, and for innovative solutions. This is the main motivation for the research in this thesis.

The chapters in thesis are grouped in two parts, with Part I consisting of three chapters on topics related to sensor networks and their challenges. Part II, also containing three chapters, deals with Markov Decision Processes (MDPs), a popular framework for controlling systems under uncertainty.

The first chapter in Part I is Chapter 2, and reviews middleware components for sensor networks. Typically, sensor technology uses a wide range of data formats and access protocols, and applications relying on sensor technology are forced to deal with this diversity. A middleware component forms a bridge between sensor applications and sensor technology, and hides the technological diversities from applications by offering a unified access point to the sensor technology. In Chapter 2 we review several types of component available in the literature, and then focus on a specific type that has gained in popularity recently. We call this a *centralized middleware component*, describe its general architectural form, and discuss four well-known centralized components. We finish with an outlook to future developments in the area of centralized middleware components.

In Chapter 3 we consider outliers (abnormal measurements) in sensor data, and how well dimensionality reduction techniques preserve these outliers. Dimensionality reduction is a family of techniques that aims to remove redundancy from data and create a shorter summary. Applying a dimensionality reduction technique to sensor data might reduce an outlier to a summary that is normal (compared to other summaries), thus losing the outlier and preventing applications relying on outliers to work with the short summaries. In Chapter 3 we describe three popular dimensionality reduction techniques, and experimentally determine how well they preserve outliers on a number of sensor data sets. The experiments identify one of the techniques as best able to preserve outliers, and we discuss the intuitions behind this result.

Chapter 4 deals with an important performance indicator of sensor networks: the *saturation throughput*. This property reflects how fast a sensor network can transmit measurements when many sensor nodes have a measurement to transmit. The network can only transmit one measurement at a time, so each node follows a set of rules to determine when it is allowed to transmit a measurement. This set of rules is described in the 'Media Access Control' protocol of IEEE 802.15.4, and instructs nodes to alternate a random waiting time with transmission attempts. Although the random waiting time allows multiple nodes to transmit measurements, it also causes the channel to be idle for short periods of time and thus to decrease throughput. In this chapter we provide a model for analyzing the saturation throughput of the IEEE 802.15.4 MAC protocol. Central to the model is the concept of a *natural layer*, which reflects the time that a sensor node typically has to wait before sending a packet (as instructed by the MAC protocol). The key feature of the model is its simplicity compared to existing models in the literature. Also, it provides insight how the throughput depends on the protocol parameters and the number of nodes in the network. Validation experiments with simulations demonstrate that the model is highly accurate for a wide range of parameter settings of the MAC protocol, and applicable to both large and small networks.

The first chapter in Part II is Chapter 5, in which we consider the control of a queueing system. The controller of the system has to answer incoming queries with a response, which it can do by either forwarding incoming queries to the system (where it needs time for processing), or by responding with a previously generated response (incurring a penalty for not providing a fresh value). Hence, the controller faces a trade-off between data freshness and response times. Addressing the trade-off is traditionally done using a threshold policy. When the age of the database value exceeds a certain given threshold, fresh data is retrieved, and otherwise the latest database value is used. Although such policies are commonly used, there is room for improvement by setting a dynamic threshold: in cases where the information retrieval is time-consuming (as it is in wireless sensor networks), using a database value that is slightly above the threshold value might be acceptable. In Chapter 5 we model the system as an MDP, which turns out to be complex. In order to circumvent the complexities, we simplify the model and use this model to construct a control policy for the full, complex, model. Experiments with value iteration show that applying this policy leads to near-optimal performance and, in particular, that it performs significantly better than a traditional threshold policy.

In Chapter 6 we introduce *Value Function Discovery* (VFD), a novel method for discovery of relative value functions for MDPs. This method learns algebraic descriptions of relative value function by applying an Evolutionary Algorithm to sample points of the relative value function of an MDP. VFD's key feature is that the model parameters of the MDP are included in the discovered algebraic descriptions. The relative value function discovered by VFD can be used to, e.g., construct a policy for controlling a system with time-varying parameters. In Chapter 6, we describe VFD and apply it to an example MDP. We demonstrate that the discovered relative value function closely resembles the relative value function of the MDP. Additionally, we convert the discovered function to a policy, and demonstrate numerically that the resulting policy has excellent performance on a wide range of model parameters.

Finally, in Chapter 7 we continue work on VFD and again apply it to the example MDP of Chapter 6. This time, we include prior knowledge that the optimal policy of the MDP is of threshold type. Instead of using MDP to discover a relative value function, we apply VFD to sample points of the threshold policy so that VFD discovers an algebraic expression for the threshold in terms of the model parameters. We demonstrate that this alternative use of VFD also yields near-optimal policies, illustrating that VFD is not restricted to learning relative value functions and can be applied more generally.