Preface

Cyber-physical systems (CPSs) are emerging as an integrative research field aimed towards a new generation of engineered systems. From a dynamic systems and control point of view, CPS can be defined in the following way: “computational thinking and integration of computation around the physical dynamic systems form CPSs where sensing, decision, actuation, computation, networking, and physical processes are mixed.” CPS applications can be found in medical devices and systems, patient monitoring devices, automotive and air traffic control, advanced automotive systems, process control, environmental monitoring, avionics, instrumentation, oil refineries, water usage control, cooperative robotics, manufacturing control, smart greener buildings, etc.

CPSs are mostly distributed parameter systems (DPSs) and dynamic evolutions happen not only along the time axis but also along spatial axes. Within the spatial domain of interest, due to the infinite-dimensional nature, it is natural and fundamental to consider the optimal observation or optimal measurement problems in CPSs.

Recently, wireless sensor networks (WSNs) have attracted many researchers from both industry and academia and it is widely believed that the technology will bring important changes to our society in this century. An important class of application for the WSN is to observe physical systems, where the sensor networks together with the physical processes are considered as part of CPSs. The research and development of WSNs incorporate knowledge from many disciplines, such as communications, computer engineering and computer science, electronic engineering and mathematics, to name a few.

The authors of this book come from both academia and industry and bring expertise from both sides. Overall, we intend to make this book practical since the authors were motivated by real engineering challenges. In the past 6 years, based on our award-winning hardware experiment systems, we have attempted to solve challenging problems and to generalize the results to address a large class of WSN design issues. Two hardware platforms have been described in this book. The MAS-net (mobile actuator and sensor networks) project won 2nd place on the 2005 Cross-bow’s Smart Dust Challenge and was demonstrated on the TinyOS Technical Exchange at UC Berkeley. Our sensor selection testbed was demonstrated at the 2006

DSN Symposium (International Symposium on Innovations and Real Time Applications of Distributed Sensor Networks). Later, some preliminary results of our sensor selection method were presented at the 2007 IEEE Sarnoff Symposium at Princeton University and we won 3rd Best Paper Prize in the student paper/poster competition session. Some theoretical analysis results are presented in the book with clear practical motivations to address some important design questions. Therefore, this book is not intended to be a pure theoretical research monograph.

Based on our hands-on experiences, we think that the fundamental challenge in the area of WSN is to design and implement systems that are robust and reliable for real-world safety-critical applications. In practice, the design frequently involves delicate tradeoffs between precise estimates and physical system constraints. In addition, the disturbances should be quantitatively analyzed in order to ensure the quality of the sensor network service. Due to the complexity of the problems, it is usually very difficult to balance the tradeoffs by heuristic or ad hoc methods. For example, energy costs and estimation precision are counteractive under certain cases, in terms that putting too many sensors in the dormant mode may save precious onboard energy but also nullify the observation. In light of this challenge, this book presents a unified theoretical framework, which is based on the well-established theory of optimal experiment design (OED), to solve a large class of optimal observation problems involving WSNs. The Fisher information matrix (FIM), which has been studied for decades, plays a key role in the theoretical framework. We would like to demonstrate in this book that, the FIM framework is fundamental in solving a wide spectrum of design problems for WSNs in CPSs.

We addressed three major problems in the book.

The first addressed problem is the trajectory optimization for observation of DPSs, where wireless sensors were mounted on mobile robots. In this example, the cost function in the problem was constructed based on the FIM. The problem was formulated as an optimal control problem. It is demonstrated that FIM is applicable to mobile sensor networks for CPSs modeled by partial differential equations (PDEs).

The second problem is the optimal sensor selection problem (SSP) illustrated in a target tracking scenario. In this case, the positions of the sensors are fixed. Instead of driving the sensors along certain trajectories like the first problem, we activate or scan “just enough” sensors in order to save the precious on-board energy. Thanks to FIM, we proved that the observation based on a small number of sensors could be as precise as the observation based on the whole network. We proposed a convex optimal sensor selection (COSS) framework to select the proper sensors for generic parameters identification problems. We also discussed how to place sensors to ensure that the network is optimal sensor selection feasible.

Finally, we discussed the optimal beacon placement problem, where the balance between the positioning error and beacon placement is discussed. Since the positioning errors of many localization systems are affected by the placement of the beacon nodes, it is desirable to place the beacons properly, such that the maximum positioning error is minimized. To solve the problem, we formulate a semi-infinite programming (SIP) problem, where the cost function is again based on FIM.

In summary, the optimal observation problems of WSNs considered in this book share the same theoretical framework in terms of OED that are formulated as an optimization problem with a cost function in terms of FIM.

The topic of CPS is fantastic as well as challenging. Due to the multidisciplinary nature of the topic, we frequently come across problems that are out of our expertise. We are lucky that we can always gain valuable knowledge from our colleagues and friends. We are grateful to all the people helped us and supported our research. Some of them shared their valuable knowledge and experiences with us. Many of them spent their valuable time to review our work and provided faithful and insightful feedback.

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