Value-of-information in spatio-temporal systems: Sensor placement and scheduling

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**ABSTRACT**

The management of infrastructure involves accounting for factors which vary in space over the system domain and in time as the system changes. Effective system management should be guided by models which account for uncertainty in these influencing factors as well as for information gathered to reduce this uncertainty. In this paper, we address the problem of optimal information collection for spatially distributed dynamic infrastructure systems. Based on prior information, a monitoring scheme can be designed, including placement and scheduling of sensors. This scheme can be adapted during the management process, as more information becomes available. Optimality can be defined in terms of the value of information (VoI), which provides a rational metric for quantifying the benefits of data gathering efforts to support system management decision-making. However, the computation of this metric in spatially and temporally extensive systems can present a practical impediment to its implementation. We describe this complexity, and investigate a special case of system topology, termed as a temporally decomposable system with uncontrolled evolution, in which the complexity of assessing VoI grows at a manageable rate with respect to the system management time duration. We demonstrate the evaluation and optimization of the VoI in an example of such a system.

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1. Motivation and background

In this paper, we examine the optimization of sensor placements and scheduling to support the management of infrastructure systems. For the management of large systems with numerous components whose states evolve in time, the determination of optimal policies both for maintaining these systems and for inspecting these systems to determine what management actions are needed are important questions [1–5]. As a motivating example of sensing and decision-making in an evolving system, consider a system whose performance is influenced by a physical quantity which varies in both space and time, such as depicted in Fig. 1; a spatial region, described by horizontal coordinates \( x_1 \) and \( x_2 \), is represented at different time instants \( t = 1 \) and \( t = 2 \). The set of random values for this physical quantity at each coordinate in space and time is described as the random field. For instance, this field might represent the temperature to which a population is subjected, which can cause health difficulties, placing strain on a medical system e.g., [6,7]. An underlying probabilistic model of the random field captures its characteristics, including its expected value, variability, and interdependence relationships in space and time e.g. [8]. In Fig. 1a, a map of the field at one time is depicted, showing its variation in space. Fig. 1c depicts the random field at a subsequent time; note the similarities in the field shape, stemming from the modeled correlation of the field across time. The infrastructure system might then consist of a continuous domain, e.g. in the case of population in a region exposed to extreme temperatures, or of discrete components occupying positions within this domain, e.g. in the case of several critical assets vulnerable to high temperature.

Based on prior knowledge, where the field is predicted to exceed a threshold, an appropriate intervention activity can be carried out to avoid the negative consequences of this exceedance. For example, heat advisories might be issued for specific regions and times, which can mitigate the consequences of the population being exposed to extreme heat. Intervention decisions take into account the consequences of different possible outcomes, the costs of response options, and the inherent uncertainty in the field. Measurements of the field can also be made and used to update the prior model. For example, in Fig. 1a, x’s indicate locations where measurements of random field values are made, and Fig. 1b presents an example of decision-making based on these measurements. The red area denotes where the field exceeds a set threshold (causing a local failure in the system), while the blue area depicts where, based on the updated knowledge of the field obtained by processing the available measures, threshold exceedance is predicted, and therefore an appropriate intervention is taken. Note that there is not perfect overlapping between these regions, since there remains residual uncertainty in the field.

Information can be costly to acquire, and therefore should be prioritized in both time and space to trade off the costs of collecting this information against its potential benefits. In Fig. 1a, measurements at initial time \( t = 1 \) are distributed evenly over the domain of the system, to provide adequate spatial coverage. In Fig. 1c, at a later time, measurements are again distributed evenly, but at different locations; this reflects the temporal correlation of the field, which makes repeated measures at the...
same location somewhat redundant. This represents the related problems of sensor placement, i.e., determining an appropriate spatial arrangement of sensors, and of scheduling, i.e., determining at what times measures should be collected.

Decisions about sensor placement and scheduling take a variety of factors into account. High prior uncertainty in the random field can be reduced through sensing. However, factors relevant to decision-making, such as the likelihood and potential consequences of making an incorrect decision without additional data, should also be accounted for. Furthermore, the interdependence of the random field, in both space and time, should inform the sensing plan. In space, collecting many measures in highly interdependent fields can be redundant, but in fields with weak interdependence, more closely spaced measures may be necessary to avoid missing features of interest. In time, earlier measurements can help to identify trends and support later decision-making, but need also be updated as information becomes out-of-date. Finally, the relative precisions and costs of different sensors, especially costs relating to sensor placement (whether it is cheap or expensive to gather a measurement at a new location) and scheduling (whether it is cheap or expensive to repeatedly collect measurements at the same location) should be taken into account when determining which measures will be cost-effective.

Finally, there is the problem of online or adaptive sensing, where sensor placements and schedules can be changed in light of new information. Fig. 1e depicts such a case, where, because of the high observed random field values in the upper right, at a later time more measurements are allocated for this area to better determine whether or not the field will exceed the threshold. By comparing Fig. 1d and Fig. 1f, the greater number and concentration of measurements in the upper-left allows the intervention zone to more closely match the area of exceedance. This illustrates the potential benefits of adaptive or online sensing, but these benefits should be traded off against the additional costs of evaluating and implementing a revised sensing plan.

In this paper, we examine how to optimally place and schedule measurements to best support decision-making for system management by taking into account the various factors mentioned above. We do this making use of the value of information (VoI) to explicitly trade off the benefits of collected information, in terms of improved decision-making, against the costs of information collection [9]. The VoI metric aligns well with many of the intuitive ideas discussed above of what makes a sensor placement in space informative to system management [10]. Here, we extend these results from static sensor placements to sensor placements and schedules in dynamic systems, and also to adaptive sensing, where sensor placements can change over time. Previous work has made use of VoI to quantify the benefits of structural health monitoring efforts [11–13], optimize the positioning of sensors to support the management of structures under uncertain extreme loading [10,14], and optimize inspection schemes for deteriorating components [15,16]. Other approaches to sensor scheduling, making use of concepts such as observability and state estimation accuracy, have also been applied to this problem e.g., [17,18].

In general, the computational cost of VoI evaluation grows exponentially as the size of the system increases; this can be seen by examining the management decision-making problem via a decision tree and noting that the number of “leaves” will grow exponentially as the number of possible management actions, observations, and system states increases [19]. Previous work in spatial systems identified a special case of system topology, termed as a cumulative system topology, in which this exponential growth can be reduced to a linear growth in the number of system components, provided management activities are conducted locally for each component [14].

In Section 2 of this paper, the assumption that the actions taken to manage an evolving system have temporally local effects is used to identify a corresponding special case in which the computational demand of VoI evaluation is merely linear in the time duration for system management. In Section 3, we give a brief overview of greedy offline and online approaches to efficient sensor placement and scheduling based on VoI which are used in this paper; further information on these methods is available in the companion paper [20]. In Section 4, we introduce a Gaussian random field modeling framework for spatio-temporal systems. This framework is used in Section 5 to demonstrate the application of the VoI metric in two examples: a simulated system modeling differential settlement between structural columns over time and a problem based on measurements taken on structural columns during the construction of the Scott Hall building at Carnegie Mellon University. Finally, some general conclusions are drawn in Section 6.

2. Value of information in spatio-temporal systems

This section begins by outlining a model for the monitoring and management of a system whose behavior is affected by random variables which vary in both time and space in Section 2.1. Within this model, the VoI metric is defined in general in Section 2.2. The metric is also examined under several assumptions on the structure of the system and its management which lead to increasing computational tractability for the.
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