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Smart Cities: A Golden Age for Control Theory?

The recent radical progress in the fields of future Internet and Smart City related technology innovation are transforming society. Zambonelli describes upcoming society as a sociotechnical urban superorganism [1]. One of the main drivers of this transformation is digital technology, whose impact on the structure and on the dynamics of social networks is also explored in [2]. The ubiquitous presence of networked embedded devices is the cornerstone of the Internet of Things (IoT) paradigm [3], which thanks to portable devices (e.g., smartphones), is quickly evolving into a so-called Internet of People (IoP) dimension [4]. The social impacts of future Internet and Smart City related technologies range over very different fields, including health-care [5], [6]; natural disaster prevention [7]; cooperative transportation [8], [9]; as well as enabling the realization of low-carbon societies [10], advanced E-Commerce [11], and real-time human behaviors and activity monitoring [12].

Accordingly, research questions arising in the context of the Smart City are driving exciting new activities in a number of classical disciplines. Among these, control theory has much to offer and much to gain as a discipline, by embracing some of the questions that are of concern as planners and municipalities re-imagine growing cities. Smart City research, at a very high level, is about making best use of existing resources in cities, as we try to manage congestion, pollution, food production, and maintain living standards in the face of ever increasing pressure on natural resources. Managing resources, optimally, is a classical consideration of control theory.

Modern control theory is a rather established discipline, and most electrical and mechanical engineers are now familiar with the basics of this theory. While a classical version of control theory has still much to offer the city, there are new "twists" that arise in the context of Smart City research that offer the opportunity for theorists to explore new boundaries that go beyond classical control. Specific challenges and some examples are now briefly identified and described.

First, classical control is typically concerned with regulating a single system such that the system behavior achieves a desired behavior in an optimal way, given the constraints imposed by the problem and the available resources. Even in areas where large-scale coupled systems are studied, it is the behavior of all components of the system that is analyzed and designed. In contrast, in Smart City applications it is not the behavior of individual agents that is of interest. Rather, the aggregate effect of the actions of a multitude of agents is the variable of interest. For this it is not necessary or maybe it is even harmful to synchronize behaviors, and it is not even necessary that all agents behave in a rational way. Examples of this appraisal can be found in the allocation of parking spaces, in the regulation of demand for shared resources like water and electricity, or in the supply of medical assistance. De-synchronization in fact eases the burden of supplying the resource, and the quality of the supply is measured by aggregate effects. Bounds on the required quality of service for individuals, on the other hand, are more or less stringent depending on the application area, e.g., medical infrastructure vs. parking spaces. A further difference arises when dealing the scale of Smart City applications. Typically, classical control is concerned with the control of systems of fixed dimension. On the other hand, in the Smart City we typically wish to control and influence the behavior of large-scale aggregations of populations. In such situations, even the dimension of the system may be uncertain and varying, and the need for scale-free control of very large-scale systems is pressing. Scale-free control for big systems, except in the case of passive control design, is a

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topic that is relatively unexplored in the classical control community.

Second, in classical control, the system to be controlled does not change its mathematical description in response to control signals. In Smart City applications this fundamental paradigm is hard to realize. In general, models can only provide approximations of the dynamics of real processes. This is not problematic as long as there is an understanding of the possible deviation of reality and model. Models in the area of Smart Cities, however, cannot readily be derived from first principles but are empirical, i.e., based on data obtained through measurements of established processes. In addition, the empirical data cannot be obtained from controlled experiments over a range of operating points but only from the system as is. An attempt to improve the processes in question, e.g., by providing information to the agents involved, creates a feedback loop that was not previously present. This change in the underlying process may invalidate the empirical model; in the derivation of the model there simply was no data available in order to capture the dynamic effect of such a feedback. Very often the proposed solutions do not take this feedback loop into account. This latter consideration gives rise for the need to study prediction and optimization under feedback in a much more detailed manner than has hitherto been the case. In this context, the topic of signaling to alleviate this feedback effect is of considerable current interest and is an interesting evolution of classical pricing theory. The effect of transport delays and the fact that all agents are informed of signals in an instantaneous manner pose further interesting problems in this respect.

Third, data sets in the city are often obtained in "closed loop." That is, decision maker information is often included in available data sets. The need for building models of large-scale systems under feedback is a significant impediment to progress in applying some control techniques in Smart City applications. Here Smart City research may have much to learn from both economic and control theory in dealing with such effects.

Finally, a fundamental difference between classical control and Smart City control is the need to study the effect of the control signals on the statistical properties of the populations being controlled. Since in many cases we are dealing with the delivery of services, these statistical properties should be stationary and predictable – giving rise to the need for "ergodic" control design.

Speaking from a broad perspective, Smart City applications are about inducing behavioral change to make better use of available resources. Control theory has much to offer in this domain. A theory of feedback has been well tuned over the last century and applications of this theory can provide not only valuable insights and tools for the design of Smart City applications, but also inspiration for the next generation of control pioneers to push back the existing boundaries of control. Embracing this vision could indeed open the door to a "Smart City inspired golden age of control," where control theory can inspire and contribute to the growth of smart cities.

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