Research Directions for the Internet of Things

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***Abstract*—Many technical communities are vigorously pursuing research topics that contribute to the Internet of Things (IoT). Today, as sensing, actuation, communication, and control become ever more sophisticated and ubiquitous, there is significant overlap in these communities, sometimes from slightly different perspectives. More cooperation between communities is encouraged. To provide a basis for discussing open research problems in IoT, a vision for how IoT could change the world in the distant future is first presented. Then, eight key research topics are enumerated and research problems within those topics are discussed.**

***Index Terms*—Cyber Physical Systems, Internet of Things, Mobile Computing, Pervasive Computing, Wireless Sensor Networks.**

I. Introduction

Smart devices. Smartphones. Smart cars. Smart homes. Smart cities. A smart world. These notions have been espoused for many years. Achieving these goals has been investigated, to date, by many diverse and often disjoint research communities. Five such prominent research communities are: Internet of Things (IoT), Mobile Computing (MC), Pervasive Computing (PC), Wireless Sensor Networks (WSN), and most recently, Cyber Physical Systems (CPS). However, as technology and solutions progress in each of these fields there is an increasing overlap and merger of principles and research questions. Narrow definitions of each of these fields are no longer appropriate. Further, research in IoT, PC, MC, WSN and CPS often relies on underlying technologies such as real-time computing, machine learning, security, privacy, signal processing, big data, and others. Consequently, the *smart vision of the world* involves much of computer science, computer engineering, and electrical engineering. Greater interactions among these communities will speed progress.

In this paper, as a backdrop to identifying research questions, I briefly highlight a vision for a smart world (Section II). I then discuss open research questions categorized into 8 topics (Section III). The research discussed is representative rather than complete. Two goals of the paper are: (i) to highlight a number of significant research needs for future IoT systems, and (ii) to raise awareness of work being performed across various research communities.

This work was supported in part by the National Science Foundation under grants CNS-1239483, CNS-1017363, and CNS-1319302.

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II. Vision and IoT Scope

Many people [8], including myself [28][29], hold the view that cities and the world itself will be overlaid with sensing and actuation, many embedded in "things" creating what is referred to as a *smart world*. But it is important to note that one key issue is the degree of the density of sensing and actuation coverage. I believe that there will be a transition point when the degree of coverage triples or quadruples from what we have today. At that time there will be a *qualitative* change. For example, today many buildings already have sensors for attempting to save energy [7][38]; home automation is occurring [3]; cars, taxis, and traffic lights have devices to try and improve safety and transportation [9]; people have smartphones with sensors for running many useful apps [2]; industrial plants are connecting to the Internet [1]; and healthcare services are relying on increased home sensing to support remote medicine and wellness [11]. However, all of these are just the tip of the iceberg. They are all still at early stages of development. The steady increasing density of sensing and the sophistication of the associated processing will make for a significant *qualitative change* in how we work and live. We will truly have systems-of-systems that synergistically interact to form totally new and unpredictable services.

What will be the platform or platforms that support such a vision? One possibility is a global sensing and actuation utility connected to the Internet. Electricity and water are two utilities that can be used for a myriad of purposes. Sensing and actuation in the form of an IoT platform will become a utility. IoT will not be seen as individual systems, but as a critical, integrated infrastructure upon which many applications and services can run. Some applications will be personalized such as digitizing daily life activities, others will be city-wide such as efficient, delay-free transportation, and others will be worldwide such as global delivery systems. In cities perhaps there will be no traffic lights and even 3D transportation vehicles. Smart buildings will not only control energy or security, but integrate personal comfort, energy savings, security and health and wellness aspects into convenient and effective spaces. Individuals may have patches of bionic skin with sensing of physiological parameters being transmitted to the cloud which houses his digital health, and to the