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When sensing goes pervasive

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ABSTRACT

In line with the pervasive vision, pervasive sensing allows the provision of ubiquitous and pervasive monitoring and heterogeneous data collection. In the past decade, two dominant pervasive sensing paradigms have emerged: a mostly *human-free* paradigm centered around wireless sensor networks and a *human-centric* paradigm fueled by the rise of personal smart devices (smartphones and wearables). In this paper, we review the key advances in these areas and outline our vision for future directions and developments.

1. Introduction

In the pervasive vision, processing and communication capabilities are ubiquitously embedded in our world so that information can be produced and consumed anywhere. Back in 1991 [1], Mark Weiser's dream of a ubiquitous technology that would permeate everyday life and become transparent to human users was visionary, but only five years later Mark Weiser predicted that the cross-over point of ubiquitous computing and PC would occur between 2005 and 2020 [2]. We are now past that cross-point due to the phenomenal uptake of personal smart devices. In August 2013, Lenovo, at the time the world's top PC vendor, announced that its combined smartphone and tablet sales had just overtaken PC sales [3].

In line with the pervasive vision, pervasive sensing allows the provision of ubiquitous and pervasive monitoring and heterogeneous data collection. In the past decade, two dominant pervasive sensing paradigms have emerged: a *human-free* paradigm centered around wireless sensor networks and a *human-centric* paradigm fueled by the rise of personal smart devices.

The human-free paradigm dates back to the late 90s and Kris Pister's smart dust vision [4]. The basic idea was to deploy and forget: unobtrusively sense the phenomena of interest with no human intervention. Later, the focus shifted toward the more down-to-earth form factor of the various iterations of Berkeley motes. Over a decade of efforts in wireless sensor networks has taught us how to efficiently collect sensory data in an untethered and fully autonomous fashion in a wide array of applications. Recently, advances [5,6] are reviving the smart dust vision [7], which in future will likely be fueled by the progress of nanotechnologies [8].

The rise of the human-centric paradigm is more recent and has been fueled by the unprecedented success of mobile personal devices, particularly smartphones [9]. Current smartphones contain a variety of sensors that can be used for the continuous real-time location-aware monitoring of human activities as well as environmental conditions. Going forward, it seems likely that the human-centric paradigm of pervasive sensing will be further promoted by the uptake of wearable computing, which at the time of writing is the object of an increasing level of consumer interest.

In this paper, we look back at the quest for pervasiveness in both the human-free and the human-centric dimension. We recognize that there is a definite overlap between the two dimensions, as many sensor networking applications (such as

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healthcare monitoring) can hardly be viewed as human-free, but we maintain that only technologies that pervade virtually aspects of human lives, such as smartphones and, to a growing extent, wearables, can be said to be truly human-centric. At the same time, we also observe that, as the number of smart devices continues to grow, the line between human-free and human-centric sensing is likely to get increasingly blurred.

We begin with wireless sensor networks and outline the latest developments in the human-free paradigm. We then turn our attention to the human-centric paradigm and its applications to smartphone-based sensing and wearable sensing. We review the key advances in these domains and outline our vision for future directions and developments.

2. Wireless sensor networks

2.1. Unobtrusive, untethered monitoring

Originally viewed as a spinoff of MANETs [10], wireless sensor networks used a radically different line of attack that was mostly platform- and application-driven [11]. Initially spearheaded by the smart dust vision [4,12] and fueled by a great deal of military interest in the United States, the sensor network community went on to produce a decade's worth of rich and innovative research largely centered around the resource-constrained yet versatile Berkeley mote platform [13]. Although, in principle, sensor networks are very close to the pervasive vision, their pervasiveness has always remained confined to specific scenarios.

Generally speaking, a wireless sensor network is designed to monitor a well-defined scenario, be it a volcano [14], a bridge [15], a smart building [16], or a person's body [17]. A sensor network can therefore be considered pervasive, but only with respect to the specific scenario it monitors.

In spite of an extremely rich application spectrum, wireless sensor networks of mote-class devices never caught the attention of mainstream users because they never offered a killer application or service that would appeal to a large number of consumers. On the contrary, mote-based sensor networks are generally designed to keep people out of the loop and to pursue their monitoring tasks unobtrusively. At the same time, in spite of many attempts to boost their developer-friendliness [18,19], wireless sensor network programming never really caught the interest of developers outside academia and specific niches within industry, never achieving anything remotely comparable to the massive uptake of smartphone programming. Chatschik Bisdikian underscored a key point: the overall Quality of Information (QoI) that is presented to the end-user by a sensor network significantly impacts the ability of the user to take appropriate action in response to the information. In [20], Bisdikian et al. proposed a split of the traditional notion of QoI into an application-dependent component, the value of information (VoI), and an application-independent one, the QoI proper, which serves to characterize the inherent properties of information. It can be argued that wireless sensor networking has so far failed to tackle QoI and VoI to the extent that its potential human users expect, while human-centric pervasive sensing has fully understood the importance of both QoI and VoI.

2.2. Platforms and hardware trends

Though the smart dust vision was the starting point for wireless sensor networks, the research community moved away from it after Jason Hill's Spec mote [12] in 2003 and converged toward a mote design based on the Telos platform [21] that was built around an 802.15.4-compliant radio transceiver. Telos-like motes are used in remote-access testbeds such as TU Berlin's Twist [22] and National University of Singapore's Indriya [23] and are still very popular for academic research. In recent years, Libelium's Waspmote [24] has become a very popular platform among developers thanks to its user-friendliness and modular design.

After over a decade of work around Telos-like mote platforms, recent trends in miniaturization seem to be enabling a renaissance of the original smart dust vision. A notable case in point is the Michigan Micro Mote project [5], whose ambitious goal is the design of a novel cubic-mm sensor node with a power draw in the order of tens of nW capable of periodic data delivery on a timescale of a few minutes over a multihop network. Nanotechnologies are also poised to contribute to the smart dust vision [8]. Nanosensors have been used for several years in bio and chemical sensing applications, and recent advances are paving the way to nanoscale sensor networks [25].

The miniaturization of all components and their operation in close quarters are a huge challenge, particularly with respect to power consumption. As length shrinks, volume drops cubically, thus leading to a dramatic reduction of battery capacity [7]. On top of that, the reliance on batteries is a serious drawback for systems that are supposed to operate without human supervision. Aside from energy harvesting, which has been the subject of a significant number of studies and was recently surveyed in [26], a promising effort in battery-free communication is ambient backscatter communication [6]. With traditional backscatter communication (used, for instance, in RFID), a device modulates its reflected radio waves as opposed to generating new ones. While traditional backscatter communication requires the use of a dedicated power infrastructure, such as an RFID reader that energizes an RFID tag, ambient backscatter uses energy that is already in the air and enables device-to-device communication. Ambient backscatter may become a key communication technology for small-scale human-free pervasive sensing over the next decade.