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Wireless Sensor Networks and Their Applications: Where Do We Stand? And Where Do We Go?

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***Abstract*—Research on wireless sensor networks has been ongoing for more than 15 years. As a result, an enormous number of novel ideas have been proposed in academic and industrial research since then. These comprise the design of new hardware components, novel communication and processing regimes, and the realization of systems that would have been unimaginable before wireless sensor networks came into existence. The resulting application areas are broad, ranging from deployments of a few low-cost sensor nodes to the installation of large numbers of highly specialized sensing systems. In this paper, we summarize wireless sensor network application trends and point out future directions and emerging novel application domains that bear high research potential.**

I. Introduction

In 1999, the notion of *mote*s has been introduced in [1]. This visionary idea of combining sensing, computation, and communication capabilities into minuscule systems that can easily be deployed to sense environmental parameters has since been taken up by innumerable researchers around the world. Consequently, many facets of the resulting wireless sensor networks (*WSN*s) have been investigated to date, ranging from designs for hard- and software to novel application scenarios. In fact, virtually no part of motes and their applications has been left untouched by researchers in search for optimization potential, new research directions, and beyond.

Strong ongoing research activities confirm the topicality of WSN research. However, at the same time the ubiquity of research in this domain naturally elicits the question whether new research is still possible and meaningful. In this paper, we thus present our vision of future research directions in wireless sensor networks. Although a large spectrum of potential open challenges still exists, we specifically focus on application scenarios for WSN technology. Novel applications directly implicate the need for research on many underlying aspects, e.g., hardware platforms, processing algorithms and communication protocols as well as sensor data collection and interpretation.

In this paper, we first survey existing WSN applications in Sec. II, in order to delineate emerging trends in sensor networks from the state-of-the-art. Subsequently, we highlight our visions for sensor network applications in Sec. III and outline selected required research contributions. Finally, we summarize the core findings of this paper in Sec. IV.

II. Applications of Wireless Sensor Networks

In an approach to highlight the breadth of WSN application areas, we categorize the deployments presented in twelve survey publications (cf. [2–13]) in Table I. We discuss the characteristics of the nine resulting categories and summarize representative deployments for each category as follows.

A. Environmental monitoring

Environmental monitoring is one of the oldest application areas for WSN technology. WSNs provide the opportunity for the unobtrusive monitoring of areas that are difficult to access for humans, e.g., natural animal habitats. One of the earliest WSN deployments has been the deployment within the Great Duck Island project [14], where the natural habitat of Leach's Storm Petrels was monitored. Another prominent environmental monitoring deployment is the PermaSense project [15], in which WSN technology is applied to monitor a hard-to-reach permafrost area in the Swiss Alps.

B. Disaster control

The prevention of disasters and proper reactions to disasters where prevention is not possible is a second application area for WSNs. An application example is the usage of motes on chemical drums [16, 17] to monitor that a maximum quantity of chemicals allowed to be stored together in a certain area is not exceeded. Structural health monitoring, e.g., of bridges, constitutes another example for applying WSNs in the field of disaster control. It serves the purpose to estimate the current state of a structure and detect relevant state changes so that critical states can be identified and countermeasures taken in time to prevent disasters. One such WSN has, e.g., been deployed on the Golden Gate Bridge in San Francisco [18].

C. Smart spaces

Ambient intelligence, or *smart spaces*, can be realized by continually monitoring the environment and taking actuation decisions to improve the users' comfort and safety. Currently, many applications focus on the user-oriented control of heating, ventilation, and air conditioning systems [19]. Another application example for WSN technology in the context of smart space realizations is the usage of motes for monitoring electrical energy consumption [20], targeting building energy efficiency by reducing energy consumption.

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D. Object tracking and monitoring

Thanks to their small size and unobtrusive wireless operation capabilities, motes can easily be attached to everyday objects. This allows these objects to be monitored, e.g., with regard to their location and environment. A prominent application area for the resulting tracking capabilities is the use of WSN technology in logistics. The enablement of tracking assets, in particular high-valued goods, in transport processes where defined transportation routes and object integrity need to be continually ensured is presented in [21, 22].

E. Human-centric WSNs

Similar in their nature to the aforementioned smart spaces, human-centric WSNs comprise unobtrusive sensors collecting a huge range of parameters about humans. The collected data are subsequently being evaluated and combined to serve humans and their wellbeing and learning. In this context, applications in the medical and healthcare domains are prominent examples for the beneficial application of WSN technology. Example applications range from monitoring and supporting hospitalized patients to enabling new possibilities for extensive medical field studies [23].

F. Traffic control

Intelligent parking management systems constitute one prominent example for the beneficial application of WSN technology in the domain of traffic control [24, 25]. In this context, WSN technology can be employed to detect and identify vehicles with the goal to monitor vehicles in a parking lot and thus being able to provide information for example on the number and location of free sparking spaces. Similar concepts can also be applied to freeways, intersections, and many other traffic entities within the scope of realizing smart cities. WSN technology can substantially support traffic surveillance systems in this context as well (cf. [26]).

G. Security

In particular in military sensing, security applications constitute another one of the oldest application domains for WSN technology. The detection of snipers on a battlefield with the help of WSN technology has, e.g., been presented in [27]. Furthermore, WSN technology can be beneficially employed in the context of surveillance systems with the goal to autonomously detect intruders, track their movements, and classify them [28].

H. Industrial process monitoring and control

WSNs can also be employed to monitor the correct execution of process steps in industrial deployments by providing the operator with means to adapt process parameters on demand [29]. Machine surveillance and maintenance is another huge application field in this context. Here, WSNs can be employed for condition-based maintenance of machines exploiting the capability of local data processing and providing monitoring data in real time in order to enhance the utilization and lifetime of the monitored equipment [30].

I. Diverse other application areas

Manifold other application domains exist that cannot be unambiguously assigned to one of the application areas. For example, enhancing the efficiency of aircrafts during their flights constitutes a general engineering task, which can as well benefit from the application of WSN technology [31].

III. Future Research Directions

After having highlighted the broad range of existing domains, the identification of novel fields appears challenging. While most of the previously introduced solutions, however, solve well-defined problems by applying WSN technology, we highlight future research directions at a more generic scale. As follows, we list selected research challenges which we expect to play a vital and integral role in future WSN deployments.

A. Enabling the Internet of Things

The emerging vision of the Internet of Things (*IoT*) entails many research challenges to ensure its success. While today's WSN deployments are commonly designed and operated by a single stakeholder and rely on hardware of one particular type only, the billions of networked devices envisioned in the IoT cannot be assumed to follow this tradition. Novel means for cross-platform address allocation, device addressing, unicast and multicast routing, energy efficiency, and interoperability between applications are essential for the successful realization of the IoT. Besides these more technical challenges, novel applications and business models are also strongly required to make the IoT a success and cater to the creation of smart buildings, smart cities, and beyond.

B. Component re-use and smart data processing

The prevalent majority of existing WSNs have been tailored to application-specific use cases. While component modularization plays a crucial role in other software engineering-related disciplines, WSN applications are still often developed from scratch. The definition of re-usable components and corresponding interfaces to simplify and streamline application development is still an open issue. This especially applies to data processing components, which are generally developed from the ground up for each new application scenario despite their potential re-usability in other areas.

C. Validation of results through practical experimentation

Newly proposed algorithms and protocols for WSNs are often only validated by means of analytical and/or simulation studies. While this allows for the simple evaluation of the devised algorithms at scale, real-world effects are implicitly not considered. The widely observed discrepancies between simulations and real-world experiments, however, strongly motivate more practical experimentation in WSN research. Due to the availability of embedded sensing system hardware in many varieties and the large number of publicly accessible testbed sites, practical research is easily possible and essential to demonstrate the viability of any newly proposed solution.

IV. Conclusions

In this paper, we have briefly summarized the broad range of current application domains for wireless sensor networks. We have compiled a short list of representative applications for each category and thus highlighted the versatility of WSN technology. From the broad range of existing applications, however, the question emerges whether further research is still necessary and worthwhile. We agree that indeed many WSN implementations have been presented in the last 15 years to solve existing real-world challenges in unprecedented novel ways. However, following our overview of the state-of-the-art, we have also identified several future research directions and methodologies that we expect to bear significant potential. Besides continuing to deploy WSNs and gain more practical experiences, most identified challenges are of a more generic nature. Once viable solutions to these challenges have been found, we strongly expect them to be enabling technologies for the widespread use of WSNs in the future. Especially as WSNs play an integral role for the emerging Internet of Things, their *raison d'être* will be given for many years to come.

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TABLE I
OVERVIEW OF APPLICATION AREAS FOR WSN TECHNOLOGY AS IDENTIFIED IN RESPECTIVE LITERATURE.

		Arampatzis et al. [2]	Callaway Jr. [3]	Chong and Kumar [4]	Culler et al. [5]	Haenggi [6]	Karl and Willig [7]	Khemapech et al. [8]	Oliveira and Rodrigues [9]	Sohraby et al. [10]	Verdone et al. [11]	Wang et al. [12]	Zhao and Guibas [13]
Environmental Monitoring	Environment Detection and Monitoring									x		x	
	Environment Control and Biodiversity Mapping						x						
	Agriculture and Environmental Monitoring		x			x							
	Environmental Monitoring	x						x			x		x
	Soil Moisture and Temperature Monitoring								x				
	Environmental and Habitat Monitoring			x	x								
	Habitat Monitoring				x			x	x				
	Ecophysiology				x								
	Weather Forecasting								x				
	Scientific Exploration											x	
	Urban Terrain Mapping				x								
Disaster Control	Disaster Prevention and Relief				x		x					x	
	Emergency Response				x								
	Chemical Hazardous Detection								x				
	Fire and Civil Structures Deformations Detection								x				
	Flooding Detection								x				
	Earthquake Detection								x				
	Volcano Eruption								x				
	Structural Monitoring				x								
Smart Spaces	Building and Office Control								x				x
	Intelligent Buildings / Home Intelligence		x				x	x		x	x	x	
	Industrial Applications (e.g., Smart Store)										x		
	Industrial Control and Monitoring		x										
	Facility Management						x						
	Indoor Climate Control				x								
Monitoring	Logistics						x				x		
	Telematics						x						
	Tracking (Inventory System)							x					
	Asset and Warehouse Management												x
	Asset Tracking and Supply Chain Management		x		x								
Human	Medicine and Health Care	x	x		x	x	x	x		x	x	x	x
	Mood-Based Services										x		
	Entertainment										x		
	Interactive Surroundings											x	
Traffic	Transportation										x		
	Automotive												x
	Traffic Monitoring			x					x				
	Vehicle Tracking							x					
Security	Military Sensing	x	x	x		x		x		x		x	x
	Surveillance			x	x								x
	Intelligent Alarms				x								
	Treaty Verification				x								
Process	Industrial Process Control												x
	Manufacturing Process Control				x								
	Machine Surveillance and Maintenance			x	x		x				x		
Others	General Engineering					x							
	Civil Engineering					x							
	Ubiquitous Computing Environments				x								
	Precision Agriculture				x		x						
	Positioning and Animals Tracking										x		
	Robotics	x											