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Review

Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives

Daniel-Ioan Curiac

Automation and Applied Informatics Department, "Politehnica" University of Timisoara, Bd. V. Parvan 2, 300223 Timisoara, Romania

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ABSTRACT

The design of intelligent autonomous systems able to sense, react and control the environment or complex processes has been a long term research desideratum. By integrating the concepts of mobile multi-robot systems and wireless sensor and actuator networks into a single framework, a powerful technology can be obtained, promising to serve as a backbone for complex distributed and mobile control applications. In this context new research challenges and opportunities have opened up. This paper defines the new integrated concept of wireless sensor, actuator and robot networks, surveys the current state-of-art in the field and presents design requirements and open research issues.

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E-mail address: daniel.curiac@aut.upt.ro

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1. Introduction

In the last two decades the tremendous advances in smart micro-devices, wireless communications and mobile robotics offered researchers the opportunity to tackle an important real-world problem: sensing, monitoring and remote control of complex processes distributed within unstructured, dynamic or even hostile environments. As a result, the development of fully-autonomous networks of collaborative devices being able to adapt to complex situations, to effectively react to unpredictable events and to control critical processes within their coverage area is not so far away. The road towards this desideratum is already marked by two important conceptual milestones: Wireless Sensor Networks (WSNs) and Wireless Sensor and Actuator Networks (WSANs).

Wireless Sensor Networks (Akyildiz et al., 2002; Dargie and Poellabauer, 2010) are collections of tiny, low cost and spatially-distributed autonomous devices, called sensor nodes, deployed in a given area of interest for sensing or monitoring purposes. Besides their resource constraints, the sensor nodes are able to sense, process and communicate information about a wide diversity of physical phenomena in a broad spectrum of applications ranging from wildlife and habitat monitoring to health care or battlefield surveillance.

Actuator nodes augment the perceive-and-report capabilities of WSNs to a higher level, transforming them into complex distributed perceive-and-react platforms named Wireless Sensor and Actuator Networks (WSANs) (Nayak and Stojmenovic, 2010; Verdone et al., 2010). This significant enhancement enabled new kinds of applications where coping with events or controlling distributed processes is of major importance. Such applications include traffic control, precision agriculture, home automation, city lighting, etc. In WSANs the sensing and actuating potentials are allocated to sensor or actuator nodes, respectively (Melodia et al., 2007). An improved type of WSAN replaces the stationary actuator nodes with so-called actor nodes (Akyildiz and Kasimoglu, 2004; Melodia et al., 2007), which can be stationary or mobile wireless nodes (e.g. robots) that can act upon environment. Even for these wireless sensor and actor networks, a demarcation line between the functional role of the two types of nodes (sensing or acting, respectively) is drawn, which simplifies the mechanisms and protocols.

This paper introduces the new concept of Wireless Sensor, Actuator and Robot Network (WSARN) which is not a simple theoretical enhancement of the intensively-studied wireless sensor and actor networks, but goes beyond. Inside this concept the robots can accomplish a plethora of tasks besides actuating. We motivate this novel concept by the need to: (i) separate static (sensor and actuator nodes) from mobile nodes (robots); (ii) better classify the roles of the nodes inside the network: sensor nodes are tasked with gathering data from the environment, actuators are used to act upon the environment, while robots are envisioned as a sort of "factotum nodes", addressing a large variety of tasks including sensing, actuation, network healing, nodes deployment or redeployment, batteries recharging, etc.; (iii) enhance the operational synergies between the three categories of nodes by establishing multifaceted bidirectional links among nodes; and (iv) prepare the road to total autonomy of such cyber-physical systems (autonomous deployment, operation and healing, or even autonomous withdrawal from the environment when the WSARN's life-cycle is ended).

The remainder of the paper is organized as follows. The state of the art in integrating WSANs and mobile robots is analyzed in Section 2. Section 3 defines the new conceptual framework of WSARN, the taxonomy of the tasks that can be accomplished by each type of nodes and the main design requirements. Research challenges and open issues are presented in Section 4, while conclusions are drawn in Section 5.

2. State of the art in integrating robots and WSANs

Integrating robotic systems with sensor networks or sensor and actuator networks has been a research topic for more than two decades. This conceptual fusion is two-fold (Gil et al., 2007): firstly, the robots can assist the sensing/actuating nodes (Wichmann et al., 2014) by providing additional resources whenever or wherever needed inside the area under investigation including operations like nodes deployment, localization or healing, improving the wireless connectivity, etc.; and, secondly, the WSAN can extend the sensorial and actuator capabilities of the robots in the surrounding environment. Additionally, the WSARN components can act synergically to accomplish complex missions involving distributed decision making processes, resource allocation and task scheduling, etc.

In the following paragraphs we review the main researches in this field, their taxonomy being presented in Table 1.

2.1. Robots assisting WSANs

Autonomous robots can assist WSANs in a large variety of operations and can even enhance the WSANs' capabilities beyond their initial design goals based on the power of mobility (Fig. 1). Sometimes acting as mobile nodes to improve the network connectivity or to aggregate information, and sometimes acting as mobile service units that perform specialized tasks like node healing or node deployment, the robots help WSANs to progress to a superior level of autonomy and efficiency.

In the following sections some relevant researches involving robots supporting WSANs are categorized and briefly presented.

2.1.1. Robots performing automatic node deployment

Mobile robots can be used for placing sensor and actuator nodes in remote areas during the pre-operational phase of a WSAN (initial deployment) or as a mean to streamline an already operating WSAN. This process is performed in a single stage if a map of the environment a priori exists or in two stages when an exploration and mapping procedure must be previously carried out. Being engaged in such a node deployment mission, the robot faces a specific challenge that has to be addressed and managed: to distribute the sensing, actuating, communication and computational resources represented by network nodes in the area under investigation ensuring the WSAN's required quality of service.

In Suzuki et al. (2010) the authors described the deployment of a wireless sensor network in an underground post-disaster environment. The sensor nodes are carried and deployed by mobile robots which are continuously measuring the Received Signal Strength Indication (RSSI) to ensure radio communication inside the newly formed wireless network. If the communication link is disrupted, it will be restored by placing an additional node in a suitable location. This approach is further developed in Tuna et al. (2014) where mobile robots evolving in a post-disaster environment not only deploy WSN nodes but also use them for communication purposes and simultaneous localization and mapping.

The use of unmanned aerial vehicles (UAVs) in node deployment has been a research topic for more than a decade. In 2004, Corke et al. (2004) presented an experimental autonomous helicopter named Avatar, able to deploy a sensor network with a controlled topology. In order to establish the ground locations that require supplementary nodes, the connectivity map has been used. Another approach was proposed within the AWARE project (Ollero et al., 2007, 2010), where