Journal of Network and Computer Applications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

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

A R T I C L E   I N F O

Article history:
Received 12 June 2015
Received in revised form
17 January 2016
Accepted 21 January 2016

Keywords:
Wireless sensor
Actuator and robot network
Autonomous systems
Distributed control

A B S T R A C T

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.

Contents

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

http://dx.doi.org/10.1016/j.jnca.2016.01.013

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

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

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

Table 1
Classification of WSANs–robots interactions.

Collaboration between WSAN and Robots	Type of interaction	Interaction	Approaches and references
Robot helping WSANs	Unidirectional	Robots performing automatic node deployment	• Node deployment performed by ground mobile robots (Suzuki et al., 2010;Tuna et al., 2014) • Node deployment performed by unmanned aerial vehicles (Corke et al., 2004; Ollero et al., 2007; Tuna et al., 2012)
		Robot-assisted node localization	• GPS-equipped robots used as mobile beacons(Sichitiu and Ramadurai, 2004) • Odometer-equipped robots used as mobile beacons (Zanella et al., 2007) • Robots used as mobile beacons and geometric computations (Ssu et al., 2005) • Robots equipped with directional antennas used as mobile beacons (Guerrero et al., 2009) • GPS-equipped unmanned aerial vehicles (Villas et al., 2015)
		Robots as data carriers	• Underwater data muling system (Dunbabin et al., 2006) • Ground-based data muling system (Tekdas et al., 2009) • Structural health monitoring with unmanned aerial vehicles (Todd et al., 2007)
		WSAN optimization and healing with mobile robots	• Randomized robot-assisted relocation of static nodes (Fletcher et al., 2010) • Restore the connectivity inside a wireless network (Younis et al., 2008; Abbasi et al., 2007; Katsikiotis et al., 2014) • Repaire the connectivity and ensure a given redundancy level (de San Bernabé et al., 2014) • Node replacement (Sheu and Hsieh, 2008) • Recharging or replacing the batteries of static nodes (LaMarca et al., 2002; Rahimi et al., 2003)
WSAN helping robots	Unidirectional	Robots localized by WSANs	• Using Radio Signal Strength (RSS) (Chessa et al., 2014) • Using Radio Signal Strength (RSS) and Time Difference of Arrival (TDOA) (Cheng et al., 2011) • Using Angle of Arrival (AoA) (Eren et al., 2006; Bekris et al., 2004) • Using relative position measurements (Wang et al., 2010) • Using hop counts (Hu and Evans, 2004)
		Robots navigation assisted by WSANs	• Position-aware methods (Li et al., 2003; Kotay et al., 2006; Verma et al., 2006; Corke et al., 2005; Viana and Dias de Amorim, 2008) • Position-unaware methods (Batalin et al., 2004; Jiang et al., 2011)
		Robots recharged with energy by WSAN nodes	• Static nodes viewed as docking stations (Khalid and Sualeh, 2013)
Integrated networks of WSANs and mobile robots	Multifaceted	Self-learning robotic ecology made up of sensor, actuators and mobile robots Deployment and operation of heterogeneous networked cooperating objects	• Project RUBICON (Amato et al., 2012; Dragone et al., 2013; Amato et al., 2015) • Project PLANET (Shih et al. 2014; Martini et al., 2015; Fernández et al., 2015)

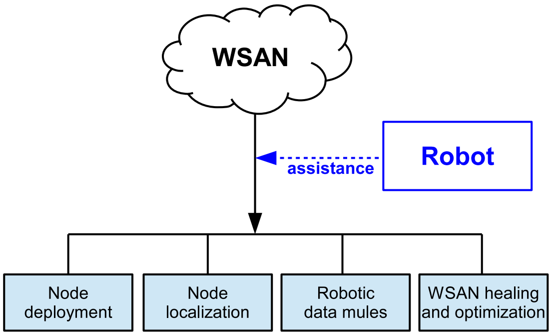

Fig. 1. WSAN operations assisted by mobile robots.

a couple of cooperating Multi-purpose Aerial Robot Vehicle with Intelligent Navigation (MARVIN) node deployment devices are used to transport the sensor/actuator nodes to the desired locations. Tuna et al. (2012) investigated the node deployment procedure in post-disaster environments using a quadrotor, equipped with Inertial Navigation System (INS) and Global Positioning System (GPS) sensors, that drops a couple of nodes in every predetermined locations to mitigate the risks related to node damaging.

2.1.2. Robot-assisted node localization

Localization represents a key prerequisite for diverse WSANs services and applications. The physical coordinates of the nodes are needed not only to report the origin of a sensed event or to activate the optimally placed actuators to change the parameters in a given part of the environment, but also for routing purposes or nodes' sleep/wake-up procedures.

A robot, aware of its location, can assist the node localization process by acting as mobile beacon for neighboring WSAN nodes. The range-based method presented by Sichitiu and Ramadurai (2004) uses a GPS-equipped mobile node for localizing the neighboring static nodes based on RSSI measurements. A similar mechanism was proposed in Zanella et al. (2007) for indoor environments.

The approach described in Ssu et al. (2005) proposes a range-free localization technique that uses the principles of elementary

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

geometry (perpendicular bisector of a chord) in conjunction with location information sent by mobile anchors. Another range-free method is presented in Guerrero et al. (2009) and involves a beacon node endowed with a rotating directional antenna. In this case, the static nodes will execute the azimuthally defined area localization (ADAL) algorithm to obtain their coordinates.

A UAV-assisted localization and clock synchronization method for WSN nodes is presented in Villas et al. (2015). The approach assumes a UAV equipped with GPS sensor that flies over the WSN area, broadcasting its position and clock time. Each node will listen to and utilize the received information to compute its location and to synchronize with the other nodes.

2.1.3. *Robots as data carriers*

In the case of WSANs deployed over vast areas, mobile robots may serve as mechanical carriers of data either to collect measurements from sensor nodes or clusters and transport it to the sink or to transmit the control commands from decisional entities of the network to actuator nodes. These types of services are needed when parts of the WSANs remain isolated due to communication failures or when the energy used for wireless transmission becomes impractical because of the huge number of hops. By this, a part of the energy consumption spent in network communication may be shifted to robots that can be periodically recharged at base stations.

A series of applications using mobile robots as data mules has been reported so far. In Dunbabin et al. (2006) the authors describe an underwater data muling system where an autonomous underwater vehicle named Starbug uses video cameras to locate a static node and establishes an optical communication channel with the node for data download. A ground-based experiment is presented in Tekdas et al. (2009) and uses the Acroname Garcia robot to download the collected measurements from Tmote Sky motes over direct wireless links. An application to structural health monitoring (Todd et al., 2007) uses Unmanned Aerial Vehicles (UAVs) to collect data from completely passively nodes (without batteries), the necessary energy to wake up the nodes and to obtain the measurements being provided via microwave transmission.

In order to schedule the nodes that need to be visited by mobile robots, the classic Traveling Salesman Problem (TSP) (Ekici et al., 2006; Bhadauria et al., 2011; Martinez-de Dios et al., 2013) or derived variants (Yuan et al., 2007; Moazzez-Estanjini and Paschalidis, 2012) are mainly employed.

2.1.4. *WSAN optimization and healing with mobile robots*

Mobile robots can be used in servicing operational WSANs (Li et al., 2012) by accomplishing a large spectrum of tasks including WSAN diagnosis, recharge nodes' batteries or replace broken nodes. Moreover the WSAN functioning may be optimized by robots performing nodes relocation in areas where more resources are needed.

In Fletcher et al. (2010) the authors described an algorithm-Randomized Robot-assisted Relocation of Static Sensors (R3S2), able to identify and collect the redundant sensor nodes and relocate them to cover the sensing holes. Another relevant approach involves mobile robots in sensor node redeployment to improve the coverage ratio of the monitored area and the network connectivity by modeling the WSN as an islets-based topology (Houaidia et al., 2011).

Mobile robots can restore the connectivity inside a wireless network by substituting a failing node with a similar one (Abbasi et al., 2007; Younis et al., 2008; Katsikiotis et al., 2014). In their work, de San Bernabé et al. (2014) presented a set of three consecutive mechanisms aimed to diagnose, to repair the connectivity and to ensure a specified level of redundancy for a WSN. The approach considers the deployment of new nodes instead of relocating existing ones. Another option for repairing the wireless network connectivity using mobile robots is the deployment of a special type of wireless nodes, endorsed with higher energy backup and longer communication range-relay nodes. Such a deployment procedure can be addressed using methods based on virtual force-based movements or game theory (Senturk et al., 2014), or by employing multi-objective hierarchical algorithms (Truong et al., 2015).

The implementation of a mobile robot for nodes replacement is depicted in Sheu and Hsieh (2008). In this approach, a node having the battery level below a given threshold sends out a "help" message to the base station. As a result, a mobile robot will be guided by the wireless network to the low-energy node location for node replacement.

Robots may also be employed in recharging or replacing the batteries of static nodes. This idea is presented in LaMarca et al. (2002) where a sufficiently agile robot can replace weak batteries or can recharge them using either inductance or a direct electrical connection. An energy management and equalization approach and the related experimental testbed is described in Rahimi et al. (2003) and uses a set of robots acting as energy equalizers in the network. These mobile robots are transferring the energy payloads from plentiful network areas to energy scarcity areas.

2.2. *WSANs assisting robots*

When operating in unstructured, dynamic or hazardous environments, the autonomous mobile robots are confronted with three types of challenges that can be addressed with the help of WSANs deployed in the area: precise localization, efficient navigation and energy recharging (Fig. 2).

2.2.1. *Robots localization by WSANs*

Being aware of their location in global or local coordinates, the sensor/actuator nodes can collaboratively locate mobile robots within WSAN's coverage area. Such methods are especially effective in two cases: when the mobile robots are not equipped with their own localization mechanism; or, when the robot's localization mechanism becomes unusable due to device failures or environmental factors (e.g. a GPS-based localization device cannot be used efficiently inside buildings, under dense foliage, or in urban canyons).

Localization algorithms are basically computing the geographical position of the robots using diverse geometric methods (e.g. triangulation or trilateration) by employing various types of measurements (Liu et al., 2010) like: length measurements using Radio Signal Strength (RSS) or Time Difference of Arrival (TDoA) (Chessa et al., 2014; Cheng et al., 2011), angle measurements based on Angle of Arrival (AoA) (Eren et al., 2006; Bekris et al., 2004; Niculescu and Nath, 2003); relative position measurements (Wang et al., 2010) or hop counts (Bergamo and Mazzini, 2002; Hu and

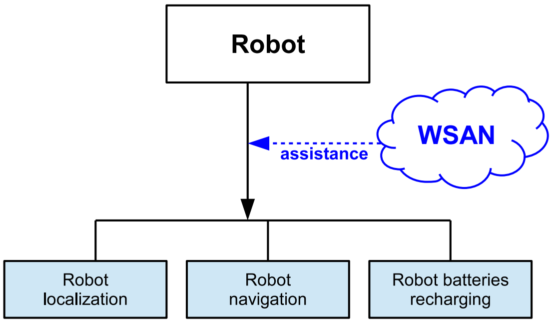

Fig. 2. Robot operations assisted by WSANs.

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

Evans, 2004). Selecting the proper method from the large spectrum of localization algorithms is driven by a broad set of factors that includes: resource availability, environment-related restrictions, deployment constraints or accuracy requirements. Moreover, in the case of static nodes, the localization process is usually done only once, i.e., immediately after deployment, while for robots, the procedure must be repeated to catch the continuous change of their positions.

Another task that can be accomplished by a mobile robot under WSAN assistance is known as Simultaneous Localization and Mapping (SLAM), where a robot starting from an unknown location has to incrementally build or update a map of an unknown environment while simultaneously computing its position inside this map (Torres-González et al., 2014; Menegatti et al., 2009). If this SLAM procedure is done by a team of robots then we speak about Cooperative, Simultaneous Localization and Mapping (CSLAM), a complex process that can be streamlined and accelerated by the stationary wireless nodes (Tuna et al., 2011; Tuna et al., 2015).

2.2.2. Robots navigation assisted by WSANs

Mobile robots equipped with fewer on-board resources or evolving in constrained environments can be efficiently guided using the distributed sensing and computing capabilities of static sensor/actuator nodes. A common situation is depicted in Fig. 3, where the mobile robot's optimal path is jointly calculated by neighboring WSAN nodes.

Previous researches in this field provided navigation mechanisms that can be grouped into two categories (Deshpande et al., 2014) as follows: (i) position-aware methods that require a previously ran nodes localization process in global coordinates for all WSAN components; and (ii) position-unaware methods that rely only on the topology of the WSAN focusing on immediate neighborhood of nodes to build the navigation strategies.

From the first category of methods, some approaches are worth mentioning. In Li et al. (2003) the authors used a sensor network for guiding a robot across an area with dangerous zones that must be avoided. Their protocol employs artificial potential fields built upon distributed sensing information to find the robot's path to a given goal location. The research was later extended, implemented and tested in real scenarios using a network of Mica motes and an ATRV-mini robot (Kotay et al., 2006). Henderson and Grant (2004) propose and analyze four types of gradient-following algorithms that based on the sensor nodes measurements are generating the optimal trajectories to reach an identified target. Verma et al. (2006) tackled the path planning process using the concept of credit field to increase the trajectories' reliability. The method relies on the group of sensor nodes placed in the proximity of the robot, to compute virtual navigational forces which will guide the robot to a given location. Corke et al. (2005) proposed a navigation protocol derived from the concept of geographic routing, the path optimization being done following the sensor value gradient, while Viana and Dias de Amorim (2008) suggested the use of predefined trajectories.

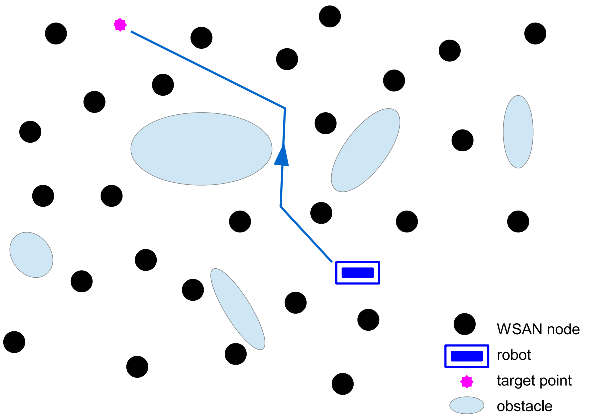

Fig. 3. WSAN nodes guiding a robot to a target point.

In the case of position-unaware methods two papers attracted our attention. Batalin et al. (2004) employed the transition probabilities computed by the sensor nodes situated in the proximity of the mobile robot to select the optimal moving direction. Accordingly, the robot is guided from node to node until it reaches the goal node. The set of neighboring nodes are automatically selected using an ingenious scheme named Adaptive Delta Percent. Jiang et al. (2011) propose a method for robots equipped with directional antennas in an area with a sensor network deployment. When a sensor node detects an event, it broadcasts a notification message throughout the entire network and a navigation tree rooted at that sensor node is constructed. The robot will follow his path on the navigation tree from node to node until it reaches the tree root.

2.2.3. Robots recharged with energy by WSAN nodes

Mobile robots are mainly operated on batteries. To extend their operational autonomy, the robots may follow an automatically recharging process using specialized docking stations. In the case of a WSAN, two types of nodes are endowed with long lasting energy and may act also as stationary docking stations: base stations and actuator nodes. For this, a recharge docking station module must be incorporated in these nodes to exploit nodes' energy and communication resources. Moreover, in exceptional circumstances, even sensor nodes (equipped with energy harvesting devices (Akhtar and Rehmani, 2015)) can help robots to recharge their batteries.

When its energy dives below a given threshold, the robot will move towards the nearby docking station to recharge its batteries (Khalid and Sualeh, 2013). Identifying the closest recharging point and the optimal path toward it can be accomplished either by the robot itself when it possesses a map of docking stations or by the neighboring WSAN's nodes which will guide the robot to that recharging point.

2.3. Cooperative robots and sensor–actuator networks

Being considered as a new research area, the scientific literature presents only a few real collaborative applications involving mobile robots and WSNs/WSANs. Furthermore, these approaches reveal only some facets of the complex and synergic robots–WSANs interactions.

In Batalin (2005) the author describes a symbiotic system, comprising mobile robots and a wireless sensor network, designed for high-fidelity monitoring of spatio-temporal phenomena in dynamic and unknown environments. In this mutualism, the robots are performing sensor deployment and WSN servicing while the WSN assists the robot navigation.

The Robotic UBIquitous COgnitive Network (Rubicon) project (Amato et al., 2012, 2015; Dragone et al., 2013) was aimed to develop a self-learning robotic ecology made up of sensor, actuators and mobile robots integrated in a wireless network. These nodes are collaboratively working in identifying, assigning and fulfilling complex tasks.

Another research project that tackles the interactions between mobile robots and wireless sensor and actuator networks is PLAtform for the deployment and operation of heterogeneous NETworked cooperating objects (PLANET) (Shih et al. 2014; Martini et al., 2015; Fernández et al., 2015). Its primary goal is to design and implement an integrated framework for enabling the remote deployment, configuration, operation and maintenance of complex large-scale systems comprising heterogeneous networked cooperating objects. Two different scenarios, one related to wildlife monitoring of the Donyana Biological Reserve and a highly automated airfield scenario, are proposed for platform validation.

3. Wireless sensor, actuator and robot networks – a new conceptual framework

In the attempt to deal with complex and sometimes hostile or unstructured environments (e.g. industrial facilities (Kumar Somappa et al., 2014), military battlefields, etc.) extended over a geographical area, the researchers proposed efficient solutions using state-of-the-art technologies.

The wireless sensor networks technology was a first step in this direction, assuring the need for distributed sensing based on tiny autonomous devices equipped with restricted computational sensing or wireless communication power. In order to enhance the effectiveness of sensor networks by adding capabilities to manipulate the environment, the WSNs were supplemented with wireless actuator nodes, giving birth to WSANs. In order to advance to a higher level of autonomy, flexibility and functionality, another type of wireless nodes, this time having mobility capabilities to act in any point of interest, had to be included – robots. This way, a new class of wireless networks having enormous capabilities to sense, analyze and control complex environments can be developed.

We define a wireless sensor, actuator and robot network as a collection of intelligent sensor, actuator and robot nodes acting synergically within a wireless network to autonomously accomplish a given set of tasks including distributed sensing and decision making, taking appropriate actions to control the environment whenever and wherever necessary.

The types of network nodes and their updated role in WSARNs are as follows:

a) ***Sensor nodes*** – generally low-cost tiny battery-operated devices having the ability to sense, process and communicate data. After deployment, their location is known. They offer an efficient coverage of a given area from the sensing and communication point of view. In the WSARN paradigm this type of nodes are considered to be stationary. If this assumption is not met, the nodes having sensing capabilities will be included in the robot nodes category.

b) ***Actuator nodes*** – commonly long lasting energy devices with computing and communication abilities, which are able to influence the environment. Depending on the type of actuation mechanism their size may vary considerably. Their location, like in the case of sensor nodes, is also known. Besides of this, actuator nodes offer a possible energy source for recharging robots batteries, and, by this, a possible solution to recharging the sensor nodes. In the WSARN paradigm, actuator nodes are considered to be stationary. If this assumption is not met, the nodes having actuating capabilities will be included in the robot nodes category.

c) ***Robot nodes*** – basically these nodes are represented by mobile 2D (e.g. unmanned ground vehicles, unmanned surface vehicles, etc.) or 3D (e.g. unmanned aerial vehicle, unmanned underwater vehicles, etc.) autonomous robots that can accomplish a large set of tasks. Their main capability is that they can intervene to solve problems in any location of the map. They can act either as mobile sensor or mobile actuator nodes. Moreover they can be used for other types of tasks related to network's security, enhancing the wireless coverage, recharging or healing other nodes, etc.

d) ***Base stations and gateways*** – special types of network nodes endowed with more computational, energy and communication resources with a relevant role in routing, processing and decision making tasks.

Three important remarks concerning the WSARN nodes must be made at this stage:

Remark 1. Robot nodes may substitute sensor nodes or actuator nodes, or even both.

Remark 2. Actuator nodes, base stations and gateways, having enough energy potential, can be the energy source to sensor nodes and robot nodes. Moreover, robot nodes may recharge sensor nodes with energy when needed.

Remark 3. The node taxonomy allows a clearer classification between stationary (actuators, sensors, base stations) and mobile nodes (robot nodes). In the WSARN paradigm any type of non-stationary nodes are considered to be robot nodes.

Practically speaking a WSARN can be envisioned as a complex heterogeneous network containing four types of nodes interconnected by permanent or temporary (only when implying robot nodes) wireless communication links (Fig. 4). Based on the type of messages that particular nodes have to send, one-to-one, many-to-one or many-to-many communication models can be adopted. For example, a wireless message sent by a decision-making node may be intended for a single actuator node (one-to-one) or for several actuator nodes executing the same actuating task (one-to-many). If the decision-making process is done by a couple of nodes which are controlling a group of actuators a many-to-many model will be used.

The WSARN's mission goes beyond standard sensing/monitoring tasks of WSNs, taking the control of environment. Consequently, controlling complex physical systems distributed over a given area is viewed as the fundamental and dominant task of WSARNs. The different types of nodes are fully involved in accomplishing the distributed controller task (all types of WSARN's nodes), the distributed actuation (actuator and robot nodes) and the distributed sensing (sensor and robot nodes), as presented in Fig. 5. Furthermore, all the nodes are employed in communicating sensing data and control decisions throughout the wireless network.

The list of possible tasks that can be accomplished by each type of nodes is presented in Table 2.

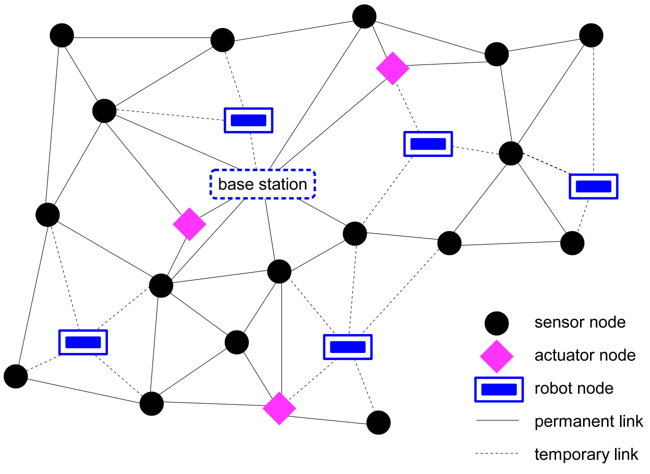

Fig. 4. Wireless sensor, actuator and robot network.

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

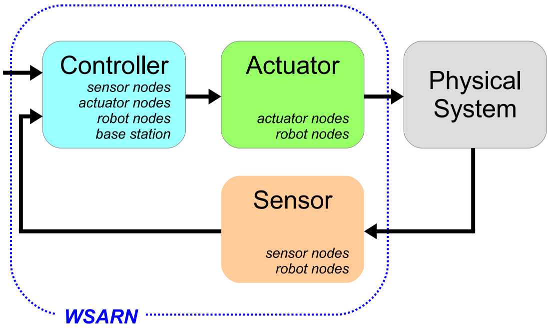

Fig. 5. WSARN as a complex distributed control architecture.

Table 2
The role of individual nodes in accomplishing the various tasks.

Task description	Sensor node	Actuator node	Robot node	Base station
Network communication	x	x	x	x
Sensing and monitoring	x		x	
Information processing and decision making	x	x	x	x
Actuating		x	x	
Node healing			x	
Energy source		x		x
Security	x	x	x	x
Beacon/landmark in localization process		x		x
Automated node deployment			x	
Robot guiding	x	x	x	x

Considering the capabilities of each node type, WSARNs can achieve a very high degree of autonomy, a possible scenario being the following: (a) in the pre-deployment phase a robotic swarm (part of the WSARN) knowing the WSARN's mission and future location can explore, map and understand the environment, and moreover identify the needs for sensor or actuator nodes; (b) in the deployment phase the robots will deploy the WSARN's static nodes; (c) in the operational phase the nodes will be able to cooperatively solve all the problems related to an autonomous functioning, from addressing the energy needs of each node to self-healing or node reprogramming; and (d) after the operational phase is completed, the WSARN can be withdrawn from the environment by one of its components-robotic swarm.

3.1. WSARN requirements

In the design of a wireless sensor, actuator and robot network, a general set of requirements must be carefully taken into account. From this perspective, the current section is devoted to the discussion of the most important WSARN features.

3.1.1. Autonomy

Being designed to operate in unknown or remote environments, this type of ad-hoc networks must possess the ability to control their own internal states and their own actions without depending on anything else. This autonomous behavior presumes a variety of issues, the most important being the understanding of the environment and the WSARN missions inside this environment, self-configuration intelligent decision making and task allocation, energy harvesting, power consumption optimization and self-healing. Although a very long-term absolute autonomy is almost unattainable, a high level of autonomy can be maintained over a significant time interval.

3.1.2. Adaptability

A WSARN must efficiently react to a dynamic and stochastic environment by automatically adjusting its settings and behavior. Additionally, events occurring inside the network like node failures or malicious security attacks must be accurately identified and treated. A special focus must be directed to control- and actuation-related aspects, mainly when this type of collaborative networks is employed in real-time or time-critical control applications. The spectrum of operations that can be taken into account is extremely vast. Examples include the use of mobile robots to redeploy nodes or to collect measurement data to cope with connection failures, adaptive sleep/wakeup procedures for energy optimization, etc. In order to achieve a high degree of adaptability the WSARN redundancy, in all its aspects, plays a crucial role.

3.1.3. Scalability

In many applications, the network must be expanded with new sensor, actuator or robot nodes either to enhance its capabilities or to cover a larger geographic area. WSARN algorithms and protocols have to be designed in such a way that any number of additional nodes may operate together with negligible network performance degradation.

3.1.4. Heterogeneity

The nodes comprised in a WSARN have different abilities (mobility, sensing, actuating, data processing and storage, communication) and different energy levels. Moreover, these characteristics are changing over time, further complicating the design of protocols and algorithms. Especially affected are the decision making, task allocation and distributed control system mechanisms which have to carefully consider the heterogeneity as a mandatory factor.

3.1.5. Real-time requirement

Being envisioned as possible solutions for complex and distributed control applications, wireless sensor, actuator and robot networks must conform to specific control-related requirements such as real-time constraints and reliable data transmission. Moreover, some Quality of Service (QoS) requirements are also applied for the wireless network including guaranteed delivery of packets and minimum delay. Another facet of this WSARN characteristic is related to the necessity of immediate responses to unpredictable events raised in their coverage area.

3.1.6. Energy efficiency

Prolonging the lifetime of the nodes and of the entire network represents a key desideratum. Operating sometimes in remote environments, the nodes rely on batteries that are prone to energy depletion. In order to attenuate this process, or even to countermeasure it, the network will utilize a mixture of methods: energy harvesting, sleep/wakeup procedures, static nodes' batteries recharging using robots, etc.

3.1.7. Fault tolerance

We can define the WSARN's fault tolerance as the capability to maintain the network functionalities in the case of nodes failures, without any interruption. WSARN nodes may fail or their functioning may be blocked due to energy depletion, physical damage or malicious security attacks. In such circumstances, other adjacent static nodes or mobile robots sent in that area must take over their roles. This way, the failure nodes will not affect the overall mission of the network.

3.1.8. Coordination

Sensor, actuator and robot nodes must synchronize which each other in performing various collaborative actions that cannot be

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

reliably carried out by individual nodes. Furthermore, even different independent tasks that need to be executed in the same time require coordination among nodes.

4. Challenges and open issues

So far, the research on cooperation between sensors, actuators and robots inside a wireless network, as reviewed in this paper, was mainly focused on simple and unilateral forms of interaction involving either robots assisting WSANs or vice-versa. Despite the tremendous advancements achieved on prerequisite technologies, this emerging research field is only at the beginning. The present section summarizes some critical research needs that have to be addressed in the near future to enable the development of complex real-life applications:

1) **Real-time distributed control:** From the control engineering perspective, a WSARN can be interpreted as a class of networked control systems (NCS) (Antsaklis and Baillieul, 2007; Zhang et al., 2013) where each of the classic closed-loop components (sensor, controller and actuator) is replaced by a group of spatially distributed wireless nodes working collaboratively. Regarding distributed control using WSARNs, some problems are raised: (i) the wireless communication can produce time-varying delays or packet losses in the control loop, deteriorating the overall control performance, sometimes causing instability (Zhang et al., 2001). Coping with network-induced uncertainties in NCSs, despite recent efforts, is still in a stage of early development. Existing control algorithms that include models of network transmission (Cloosterman et al., 2010) or use predictive schemes to forecast future transmissions (Onat et al., 2011; Ulusoy et al., 2011) are only one step toward solving the problem; (ii) The mechanism for aggregating the sensing information provided by different nodes becomes a critical issue in control system design, not only for the needed computational time but also because an unsuitable choice may compromise the control strategy; (iii) A WSARN can address multiple control problems in the same time, so in this case is appropriate to speak about an ensemble of control algorithms that has to be implemented including the classic periodic control or variants of aperiodic control (event-triggered and self-triggered control) (Mazo and Tabuada, 2008; Postoyan et al., 2011); (iv) the use of mobile nodes (robots) as controllers or actuators is further complicating the control strategy.
2) **Decision making:** All nodes that have computational resources can be considered as potential decision-making units. An efficient combination between centralized and decentralized methods for coping with internal (related with internal WSARN operations like nodes sleep/wakeup procedures, picking a robot to heal a specified node, etc.) or external (plant- or environment-related) events is of paramount importance. The difficulty of this issue is magnified by factors like: the scale and scopes of the WSARN, the dynamic behavior of the network, the broad range of acquired information and the high density of decisions.
3) **Task allocation:** Dynamic task allocation and scheduling plays an important role in WSARNs where nodes, endowed with heterogeneous features, have to optimally fulfill a complex mixture of tasks including sensing, actuating, decision making, data aggregation, etc. The research on this issue gets further complicated, the problem of obtaining realistic task allocation models being only partially solved for less complex networks like WSNs (Wang et al., 2014; Guo et al., 2011), WSANs (Salarian et al., 2012) or multi-robot systems (Brutschy et al., 2014; Hussein et al., 2014).
4) **Energy management:** Being designed to operate autonomously in unattended environments WSARNs' nodes are prone to failure due to energy depletion. In order to prolong their lifetime, the researchers may exploit a large set of energy-related activities that can be individually or collaboratively accomplished by WSARN nodes, like: energy harvesting (e.g. nodes equipped with devices for capturing solar or wind energy), energy transportation and redeployment (e.g. mobile robots recharged at docking stations may deliver the energy to other nodes), energy consumption, energy optimization, etc.
5) **Redundancy management:** A WSARN is characterized by physical and logical redundancy in sensing, actuating, communication and computation that allows the transfer of task accomplishment to other nodes in case of failures. Maintaining a certain level of redundancy throughout the network is, in these circumstances, a crucial issue. Using mobile robots to deploy new nodes or to replace other nodes are only two approaches that can be considered.
6) **Robotic swarm tactics inside WSARNs:** Introducing swarm tactics to robots operating as WSARN components represents a challenging research area, intended to cope with complex events arising in the environment. The mutual interactions between robotic swarms and static nodes (sensors or actuators) may lead to efficient swarm formation and task accomplishment, boosting the swarm tactics to higher levels.
7) **Security, privacy and legal issues:** By operating autonomously in unattended environments, the WSARNs are prone to a variety of malicious attacks carried out to eavesdrop, tamper or insert false information into the network or even to physically destroy or impede the nodes' functionalities. These attacks could compromise the WSARN operations by endangering the sensing, actuating, computational and communication capabilities of the nodes or affecting the robots' mobility. Moreover some legal issues can be raised when WSARNs, especially through their robot nodes, are directly or indirectly interacting with humans (Wallach and Allen, 2008; Sharkey and Sharkey, 2012; Lin et al., 2011).

5. Conclusions

Surveying the current state of the art in integrating mobile robotic systems with wireless sensor and actuator networks, this paper defines a new integrated concept aimed to perceive and control remote environments or complex distributed plants-wireless sensor, actuator and robot network. Its high level of autonomy, rapid deployment, fault tolerance and adaptability propose various new and exciting applications. However, the implementation of WSARNs needs to satisfy a wide set of requirements deriving from the nature of the physical environment where they are deployed, the type of events and controlled processes they address and the heterogeneity of networks' components. In this context, there are still many issues to be solved requiring new methods and technologies to close the gap between the WSARN conceptual framework and related real-life applications.

References

Abbasi AA, Akkaya K, Younis, M. A distributed connectivity restoration algorithm in wireless sensor and actor networks. In: Proceedings of the 32nd IEEE conference on local computer networks—LCN 2007, IEEE; 2007. p. 496–503.

Akhtar F, Rehmani MH. Energy replenishment using renewable and traditional energy resources for sustainable wireless sensor networks: a review. Renew Sustain Energy Rev 2015;45:769–84.

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E. Wireless sensor networks: a survey. Comput Netw 2002;38(4):393–422.

Akyildiz IF, Kasimoglu IH. Wireless sensor and actor networks: research challenges. Ad Hoc Netw 2004;2(4):351–67.

Amato G, Broxvall M, Chessa S, Dragone M, Gennaro C, López R, et al. Robotic ubiquitous cognitive network. In: Proceedings of the 3rd international symposium on ambient intelligence, software and applications—ISA2012, Berlin, Heidelberg: Springer; 2012. p. 191–5.

Amato G, Bacciu D, Broxvall M, Chessa S, Coleman S, Di Rocco M, et al. Robotic ubiquitous cognitive ecology for smart homes. J Intell Robot Syst 2015:1–25.

Antsaklis P, Baillieul J. Special issue on technology of networked control systems. Proc IEEE 2007;95(1):5–8.

Batalin M, Sukhatme GS, Hattig M. Mobile robot navigation using a sensor network. In: Proceedings of the 2004 IEEE international conference on robotics and automation—ICRA'04, IEEE, vol. 1; 2004. p. 636–41.

Batalin MA. Symbiosis: cooperative algorithms for mobile robots and a sensor network [Ph.D. dissertation]. Los Angeles (CA, USA): University of Southern California; aAI3180329.

Bergamo P, Mazzini G. Localization in sensor networks with fading and mobility. In: Proceedings of the 13th IEEE international symposium on personal, indoor and mobile radio communications – PIMRC2002, IEEE, vol. 2; 2002. p. 750–4.

Bekris KE, Argyros AA, Kavraki LE. Angle-based methods for mobile robot navigation: Reaching the entire plane. In: Proceedings of the 2004 IEEE international conference on robotics and automation—ICRA'04, IEEE, vol. 3; 2004. p. 2373–8.

Bhadauria D, Tekdas O, Isler V. Robotic data mules for collecting data over sparse sensor fields. J Field Robot 2011;28(3):388–404.

Brutschy A, Pini G, Pinciroli C, Birattari M, Dorigo M. Self-organized task allocation to sequentially interdependent tasks in swarm robotics. Auton Agent Multi-Ag 2014;28(1):101–25.

Cheng L, Wu CD, Zhang YZ. Indoor robot localization based on wireless sensor networks. IEEE Trans Consum Electr 2011;57(3):1099–104.

Chessa S, Gallicchio C, Guzman R, Micheli A. Robot localization by echo state networks using RSS. In: Bassis S, Esposito A, Morabito FC, editors. Recent advances of neural network models and applications. Springer International; 2014. p. 147–54.

Cloosterman MB, Hetel L, Van De Wouw N, Heemels WPMH, Daafouz J, Nijmeijer H. Controller synthesis for networked control systems. Automatica 2010;46 (10):1584–94.

Corke P, Hrabar S, Peterson R, Rus D, Saripalli S, Sukhatme G. Autonomous deployment and repair of a sensor network using an unmanned aerial vehicle. In: Proceedings of the 2004 IEEE international conference on robotics and automation—ICRA'04, IEEE, vol. 4; 2004. p. 3602–8.

Corke P, Peterson R, Rus D. Localization and navigation assisted by networked cooperating sensors and robots. Int J Robot Res 2005;24(9):771–86.

Dargie WW, Poellabauer C. Fundamentals of wireless sensor networks: theory and practice. John Wiley & Sons; 2010.

Deshpande N, Grant E, Henderson TC. Target localization and autonomous navigation using wireless sensor networks—a pseudogradient algorithm approach. IEEE Syst J 2014;8(1):93–103.

Dragone M, Abdel-Naby S, Swords D, O'Hare GM, Broxvall M. A programming framework for multi-agent coordination of robotic ecologies. In: Dastani M, Hübner JF, Logan B, editors. Programming multi-agent system. Berlin, Heidelberg: Springer; 2013. p. 72–89.

Dunbabin M, Corke P, Vasilescu I, Rus D. Data muling over underwater wireless sensor networks using an autonomous underwater vehicle. In: Proceedings of the 2006 IEEE international conference on robotics and automation—ICRA 2006, IEEE; 2006. p. 2091–8.

Ekici E, Gu Y, Bozdag D. Mobility-based communication in wireless sensor networks. IEEE Comun Mag 2006;44(7):56–62.

Eren T, Whiteley W, Belhumeur PN. Using angle of arrival (bearing) information in network localization. In: Proceedings of the 45th IEEE conference on decision and control, IEEE; 2006. p. 4676–81.

Fernández JC, Martinez-de-Dios JR, Maza I, Fabresse FR, Ollero A. Ten years of cooperation between mobile robots and sensor networks. Int J Adv Robot Syst 2015;12(70):1–12.

Fletcher G, Li X, Nayak A, Stojmenovic I. Randomized robot-assisted relocation of sensors for coverage repair in wireless sensor networks. In: Proceedings of the IEEE 72nd vehicular technology conference—VTC2010-Fall, IEEE; 2010. p. 1–5.

Gil P, Maza I, Ollero A, Marrón P. Data centric middleware for the integration of wireless sensor networks and mobile robots. In: Proceedings of the 7th conference on mobile robots and competitions – Robotica2007, IEEE; 2007. p. 1–6.

Guerrero E, Xiong HG, Gao Q, Cova G, Ricardo R, Estévez J. ADAL: a distributed range-free localization algorithm based on a mobile beacon for wireless sensor networks. In: Proceedings of the international conference on ultra modern telecommunications & workshops—ICUMT'09, IEEE; 2009. p. 1–7.

Guo W, Xiong N, Chao HC, Hussain S, Chen G. Design and analysis of self-adapted task scheduling strategies in wireless sensor networks. Sensors 2011;11 (7):6533–54.

Henderson TC, Grant E. Gradient calculation in sensor networks. In: Proceedings of the 2004 IEEE/RSJ international conference on intelligent robots and systems—IROS2004, IEEE, vol. 2; 2004. p. 1792–5.

Houaidia C, Idoudi H, Saidane LA. Improving connectivity and coverage of wireless sensor networks using mobile robots. In: Proceedings of the 2011 IEEE symposium on computers & informatics – ISCI2011, IEEE; 2011. p. 454–9.

Hu L, Evans D., Localization for mobile sensor networks. In: Proceedings of the 10th annual international conference on mobile computing and networking – Mobicom2004, ACM; 2004. p. 45–57.

Hussein A, Adel M, Bakr M, Shehata OM, Khamis A. Multi-robot task allocation for search and rescue missions. J Phys Conf Ser 2014;570(5):052006.

Jiang JR, Lai YL, Deng FC. Mobile robot coordination and navigation with directional antennas in positionless wireless sensor networks. Int J Ad Hoc Ubiq Co 2011;7 (4):272–80.

Katsikiotis C, Zorbas D, Chatzimisios P. In: Mitton N, Gallais A, Kantarci ME, Papavassiliou S, editors. Connectivity restoration and amelioration in wireless adhoc networks: a practical solution. Ad Hoc Networks, Springer International Publishing; 2014. p. 255–64.

Khalid O, Sualeh M. Comparative study on mobile wireless sensor network testbeds. Int J Comput Theory Eng 2013;5(2):204–8.

Kotay K, Peterson R, Rus D. Experiments with robots and sensor networks for mapping and navigation. In: Corke P, Sukkariah S, editors. Field and service robotics. Berlin, Heidelberg: Springer; 2006. p. 243–54.

Kumar Somappa AA, Øvsthus K, Kristensen LM. An industrial perspective on wireless sensor networks—a survey of requirements, protocols, and challenges. Commun Surv Tuts 2014;16(3):1391–412.

LaMarca A, Brunette W, Koizumi D, Lease M, Sigurdsson SB, Sikorski K, et al. Making sensor networks practical with robots. In: Mattern F, Naghshineh M, editors. Pervasive computing. Berlin, Heidelberg: Springer; 2002. p. 152–66.

Li Q, De Rosa M, Rus D. Distributed algorithms for guiding navigation across a sensor network. In: Proceedings of the 9th annual international conference on Mobile computing and networking – Mobicom2003, ACM; 2003. p. 313–25.

Li X, Falcon R, Nayak A, Stojmenovic I. Servicing wireless sensor networks by mobile robots. IEEE Commun Mag 2012;50(7):147–54.

Lin P, Abney K, Bekey G. Robot ethics: Mapping the issues for a mechanized world. Artif Intell 2011;175(5):942–9.

Liu Y, Yang Z, Wang X, Jian L. Location, localization, and localizability. J Comput Sci Technol 2010;25(2):274–97.

Martinez-de Dios JR, Lferd K, de San Bernabé A, Núñez G, Torres-González A, Ollero A. Cooperation between uas and wireless sensor networks for efficient data collection in large environments. J Intell Robot Syst 2013;70(1–4):491–508.

Martini S, Di Baccio D, Romero FA, Jiménez AV, Pallottino L, Dini G, Ollero A. Distributed motion misbehavior detection in teams of heterogeneous aerial robots. Robot Auton Syst 2015;74:30–9.

Mazo Jr M, Tabuada P. On event-triggered and self-triggered control over sensor/actuator networks. In: Proceedings of the 47th IEEE conference on decision and control—CDC 2008. IEEE; 2008. p. 435–40.

Melodia T, Pompili D, Gungor VC, Akyildiz IF. Communication and coordination in wireless sensor and actor networks. IEEE Trans Mobile Comput 2007;6 (10):1116–29.

Menegatti E, Zanella A, Zilli S, Zorzi F, Pagello E. Range-only slam with a mobile robot and a wireless sensor networks. In: Proceedings of the 2009 international conference on robotics and automation—ICRA'09. IEEE; 2009. p. 8–14..

Moazzez-Estanjini R, Paschalidis IC. On delay-minimized data harvesting with mobile elements in wireless sensor networks. Ad Hoc Netw 2012;10(7):1191–203.

Nayak A, Stojmenovic I. Wireless sensor and actuator networks. John Wiley & Sons; 2010.

Niculescu D, Nath B. Ad hoc positioning system (APS) using AOA. In: Proceedings of the 22nd annual joint conference of the ieee computer and communications societies—INFOCOM2003, IEEE, vol. 3; 2003. p. 1734–43.

Ollero A, Bernard M, La Civita M, Van Hoesel L, Marron PJ, Lepley J, De Andres E. AWARE: platform for autonomous self-deploying and operation of wireless sensor-actuator networks cooperating with unmanned AeRial vehiclEs. In: Proceedings of the IEEE international workshop on safety, security, and rescue robotics—SSRR2007. IEEE; 2007. p. 1–6.

Ollero A, Kondak K, Previnaire E, Maza I, Caballero F, Bernard M, et al. Integration of aerial robots and wireless sensor and actuator networks. The aware project. In: Proceedings of the 2010 IEEE international conference on robotics and automation – ICRA2010, IEEE; 2010. p. 1104–5.

Onat A, Naskali T, Parlakay E, Mutluer O. Control over imperfect networks: model-based predictive networked control systems. IEEE Trans Ind Electron 2011;58 (3):905–13.

Postoyan R, Tabuada P, Nešić D, Anta A. Event-triggered and self-triggered stabilization of distributed networked control systems. In: Proceedings of the 50th IEEE conference on decision and control and European control conference—CDC-ECC2011. IEEE; 2011. p. 2565–70.

Rahimi M, Shah H, Sukhatme GS, Heideman J, Estrin D. Studying the feasibility of energy harvesting in a mobile sensor network. In: Proceedings of the 2003 IEEE international conference on robotics and automation—ICRA'03, IEEE, vol. 1; 2003. p. 19–24.

Salarian H, Chin KW, Naghdy F. Coordination in wireless sensor–actuator networks: a survey. J Parallel Distrib Comput 2012;72(7):856–67.

de San Bernabé A, Martínez-de-Dios JR, Regoli C, Ollero A. Wireless sensor network connectivity and redundancy repairing with mobile robots. In: Koubaa A, Khelil A, editors. Cooperative robots and sensor Networks. Berlin, Heidelberg: Springer; 2014. p. 185–204.

Senturk IF, Akkaya K, Yilmaz S. Relay placement for restoring connectivity in partitioned wireless sensor networks under limited information. Ad Hoc Netw 2014;13:487–503.

Sharkey A, Sharkey N. Granny and the robots: ethical issues in robot care for the elderly. Ethics Inf Technol 2012;14(1):27–40.

Sheu JP, Hsieh KY, Cheng PW. Design and implementation of mobile robot for nodes replacement in wireless sensor networks. J Inf Sci Eng 2008;24(2):393–410.

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013

Shih CY, Capitán J, Marrón PJ, Viguria A, Alarcón F, Schwarzbach M, et al. On the cooperation between mobile robots and wireless sensor networks. In: Koubaa A, Khelil A, editors. Cooperative robots and sensor networks. Berlin, Heidelberg: Springer; 2014. p. 67–86.

Sichitiu ML, Ramadurai V. Localization of wireless sensor networks with a mobile beacon. In: Proceedings of the 2004 IEEE international conference on mobile ad-hoc and sensor systems – MASS2004, IEEE; 2004. p. 174–83.

Ssu KF, Ou CH, Jiau HC. Localization with mobile anchor points in wireless sensor networks. IEEE Trans Veh Technol 2005;54(3):1187–97.

Suzuki T, Sugizaki R, Kawabata K, Hada Y, Tobe Y. Autonomous deployment and restoration of sensor network using mobile robots. Int J Adv Robot Syst 2010;7(2):105–14.

Tekdas O, Isler V, Lim JH, Terzis A. Using mobile robots to harvest data from sensor fields. IEEE Wirel Commun 2009;16(1):22–8.

Todd M, Mascarenas D, Flynn E, Rosing T, Lee B, Musiani D, et al. A different approach to sensor networking for SHM: remote powering and interrogation with unmanned aerial vehicles. In: Proceedings of the 6th international workshop on structural health monitoring – SHM2007, Destech; 2007. p. 11–3.

Torres-González A, Martinez-de Dios JR, Ollero A. Robot-wsn cooperation for scalable simultaneous localization and mapping. In: Koubaa A, Khelil A, editors. Cooperative robots and sensor networks. Berlin, Heidelberg: Springer; 2014. p. 25–41.

Truong TT, Brown KN, Sreenan CJ. Multi-objective hierarchical algorithms for restoring wireless sensor network connectivity. Ad Hoc Netw 2015;33:190–208.

Tuna G, Gulez K, Gungor VC. Communication related design considerations of WSN-aided Multi-Robot SLAM. In: Proceedings of the 2011 IEEE international conference on mechatronics – ICM2011, IEEE; 2011. p. 493–8.

Tuna G, Mumcu TV, Gulez K, Gungor VC, Erturk H. Unmanned aerial vehicle-aided wireless sensor network deployment system for post-disaster monitoring. In: Huang DS, Gupta P, Zhang X, Premaratne P, editors. Emerging intelligent computing technology and applications. Berlin, Heidelberg: Springer; 2012. p. 298–305.

Tuna G, Gungor VC, Gulez K. An autonomous wireless sensor network deployment system using mobile robots for human existence detection in case of disasters. Ad Hoc Netw 2014;13:54–68.

Tuna G, Güngör VÇ, Potirakis SM. Wireless sensor network-based communication for cooperative simultaneous localization and mapping. Comput Electr Eng 2015;41:407–25.

Ulusoy A, Gurbuz O, Onat A. Wireless model-based predictive networked control system over cooperative wireless network. IEEE Trans Ind Inform 2011;7(1):41–51.

Verdone R, Dardari D, Mazzini G, Conti A. Wireless sensor and actuator networks: technologies, analysis and design. Academic Press; 2010.

Verma A, Sawant H, Tan J. Selection and navigation of mobile sensor nodes using a sensor network. Pervasive Mob Comput 2006;2(1):65–84.

Viana AC, Dias de Amorim M. Sensing and acting with predefined trajectories. In: Proceedings of the 1st ACM international workshop on heterogeneous sensor and actor networks, ACM; 2008. p. 1–8.

Villas LA, Guidoni DL, Maia G, Pazzi RW, Ueyama J, Loureiro AA. An energy efficient joint localization and synchronization solution for wireless sensor networks using unmanned aerial vehicle. Wirel Netw 2015;21(2):485–98.

Wallach W, Allen C. Moral machines: teaching robots right from wrong. Oxford University Press; 2008.

Wang H, Yu K, Yu H. Mobile robot localisation using ZigBee wireless sensor networks and a vision sensor. Int J Model Ident Contr 2010;10(3–4):184–93.

Wang F, Han G, Jiang J, Qiu H. A distributed task allocation strategy for collaborative applications in cluster-based wireless sensor networks. Int J Distrib Sens Netw 2014:964595.

Wichmann A, Okkalioglu BD, Korkmaz T. The integration of mobile (tele) robotics and wireless sensor networks: a survey. Comput Commun 2014;51:21–35.

Younis M, Lee S, Gupta S, Fisher K. A localized self-healing algorithm for networks of moveable sensor nodes. In: Proceedings of the 2008 IEEE global telecommunications conference—GLOBECOM2008, IEEE; 2008. p. 1–5.

Yuan B, Orlowska M, Sadiq S. On the optimal robot routing problem in wireless sensor networks. IEEE Trans Knowl Data Eng 2007;19(9):1252–61.

Zanella A, Menegatti E, Lazzaretto L. Self-localization of wireless sensor nodes by means of autonomous mobile robots. In: Proceedings of the wireless communications 2007 CNIT thyrrenian symposium. Springer; 2007. p. 309–20.

Zhang L, Gao H, Kaynak O. Network-induced constraints in networked control systems—a survey. IEEE Trans Ind Inform 2013;9(1):403–16.

Zhang W, Branicky MS, Phillips SM. Stability of networked control systems. IEEE Control Syst Mag 2001;21(1):84–99.

Please cite this article as: Curiac D-I. Towards wireless sensor, actuator and robot networks: Conceptual framework, challenges and perspectives. Journal of Network and Computer Applications (2016), http://dx.doi.org/10.1016/j.jnca.2016.01.013