Wireless Sensors and Actuators Networks: Localization for Medical and Robotics Applications

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Abstract Wireless sensors and actuators networks (WSAN) have started to be massively deployed for a large number of diverse applications, such as military, environmental, medical, factory automation, home appliances, interactive museums and many others. These networks are usually integrated into extremely complex cyber physical systems. The nodes of these networks are either fixed, or mobile. All WSAN share some common characteristics, but they also address particular challenges, specific to each application area. A need that is common to many such networks, but has also particular requirements and constraints due to their specific application area is determining the position of certain nodes in the network. The paper reviews the most popular approaches in localization, as well as the specific requirements and constraints in medical and robotics applications and discusses the best approaches for localization in such applications.

Keywords: Wireless Sensor and Actuators Networks (WSAN), localization, distance estimation, position computation, centralized and decentralized algorithms.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) serve the purpose of gathering data from the environment in which they are installed by means of independent sensing nodes using wireless methods of communication (Puccinelli et al. (2005), Akyildiz et al. (2002)). Wireless Sensor and Actuator Networks (WSANs) are used when intervention into the environment is also necessary. WSANs evolved from classical data acquisition (DAQ) systems which forward the measurement data to a central computer or recorder, usually by means of a wired bus. Advanced WSANs are distributed systems capable of autonomous operation without a central coordinator. The nodes comprising the WSAN can function independently and can transmit data to each other as well as to a central node, enabling them make decisions and possibly take actions locally. The independent nature of WSAN nodes enables the development and deployment of highly robust systems, capable of maintaining operation in case of node malfunction, node relocation, or radio interference.

WSANs are finding increasing use in areas such as building automation, automatic metering, medicine, road traffic control, goods tracking, military (monitoring, reconnaissance, targeting), environmental (forest fire, flood detection, pollution monitoring and prevention), interactive museums, factory process control – (Akyildiz et al. (2002), Puccinelli et al. (2005))

The main hardware components of a generic WSAN node are outlined in Figure 1. The main controller drives the data acquisition and control interfaces which connect to the sensors and actuators. A high-capacity memory can also be fitted to the node for use in data-logging applications where a permanent data connection is difficult to maintain. It is possible to integrate the main controller, the communication interface and much of the analog sensor interfaces onto a single chip. Such System-on-a-Chip (SoC) solutions have been developed recently for use in WSAN applications and are available commercially. The power source is usually a primary battery, but advanced nodes can prolong their useful lifetime by harvesting energy from environmental sources such as light, temperature gradients, vibrations or biological processes. The communication interface is usually a low-power radio transceiver.

WSANs are highly constrained systems, mainly due to the limited available energy – (Puccinelli et al. (2005), Kulkarni et al. (2011)). In applications such as environmental monitoring where nodes are not easily serviceable, the battery charge must be maintained for extended durations such as several years. This imposes severe constraints on the communication interface, controller, sensors and actuators. Many physical quantities such as temperature and pressure have a slow rate of change, and applications such as presence detection deal with relatively rare events, therefore the data transmission rate required for WSANs is generally low. However, radio transceivers have a high supply current in the receive state as well and cannot be used to listen for incoming data packets permanently. Therefore low duty-cycle protocols are employed, where the nodes spend most of the time in a low-power sleep state and wake up periodically for short durations to transmit and receive data packets. The sensors and their interfaces are also optimized for low power consumption and can also be turned on with low duty cycle.

Other challenges for WSANs are the need for self-management (they are required to act as autonomous systems), the need for decentralization (which is critical especially for large-size networks) and information security (due to hardware constraints, standard security algorithms may not be suitable) – (Puccinelli et al. (2005)).

Overall, we can conclude that although a WSAN node has limited hardware resources, it is required to perform multiple functions. A generic software architecture of a WSAN node is presented in Fig. 2.

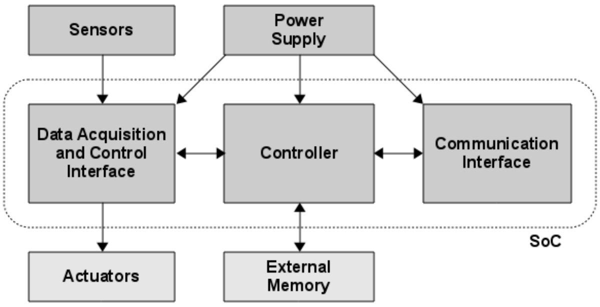

Fig. 1. Generic hardware architecture of a WSAN node

Several standards are established regarding the wireless communication in WSANs, dealing with the physical, data-link and sometimes the upper layers.

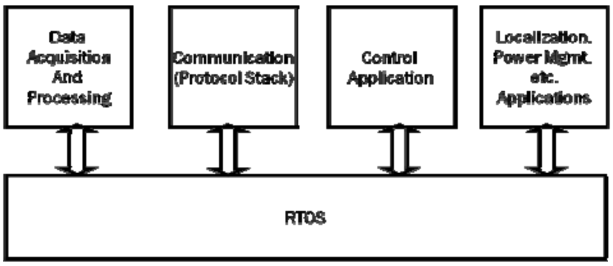

Fig. 2. Generic software architecture of a WSAN node

2. MEDICAL APPLICATIONS

Medical applications of WSANs have been growing a lot during the past years. Main reasons for this growth have been the increasing need for data collection and the mobility that they allow. In fact, this growth is stimulated also by the strategic need of addressing the issue of an increasingly ageing population and a shortage of qualified medical staff – (Dishongh et al. (2010), Latre et al. (2011), Lo et al. (2005), Mann (2004)). WSN systems are used in medicine application for measuring and analyzing various physical parameters of the patients, as well as relevant environment variables. The main areas of applications of such networks are:

a. Within the hospital/ medical center – WSNs are used for collecting data and transmitting data to the central monitoring systems, but also for alerts and location tracking.

b. Ambulance service – for the measurement of vital signals & telemedicine applications (e.g.: transmitting live data to an attending physician who can provide feedback and advice for paramedics)

c. Home care – Automatic monitoring systems can provide non-stop supervision of vital signals. Data may be automatically sent (using an existing infrastructure) to a hospital/ medical center.

d. Wearable Body Sensor Networks (WBSN) – Allow long term monitoring for specific activities, e.g. measurements of athletes vital signals during training.

Typical examples of signals that are monitored are: ECG/ rhythm, oxygen saturation, blood pressure, temperature, perspiration, respiratory rate, activity (movements).

It is worth mentioning that WSAN in medicine not only allow automatic data acquisition, but also make possible measurements in specific situations that would be difficult to address with traditional methods. For instance, it is feasible to determine certain parameters (e.g. blood pressure) when the patient is asleep, or on the contrary, during intense efforts. Furthermore, it is easy to correlate values of certain parameters and also to adapt the monitoring pattern depending on patient condition evolution, or on patient activity, etc.

3. NEED FOR LOCALIZATION IN MEDICAL APPLICATIONS

The need for localization in medical WSANs comes from the following applications – (Redondi et al. (2010), Dishongh et al. (2010)):

- personnel and equipment localization within a hospital – for instance the need to automatically determine, at any moment, if a doctor is visiting patients, or in the office, or in the lab, etc. Similarly, it is possible to keep a real-time situations of all the equipment.

- patient localization – especially for patients with higher risks of accidents, it is important to know their position within the hospital in case of emergency situations (e.g. felt down, or when critical parameters are above an alert threshold).

- for patients at home, it is important to determine if they are about to leave the house or going to bed and issue a reminder about next medications to be taken (to avoid the situation when they forget taking them).

- for certain patients with cognitive limitations (e.g. Alzheimer disease) it is important to determine where they are and assist them with appropriate indications depending on their location.

4. ROBOTICS APPLICATIONS AND NEED FOR LOCALIZATION

Robotics has been a very dynamic area in the past 50 years. There is a huge variety of robotics applications today, from industrial robots, medical robots, rehabilitation robots, up to space and underwater robots – (Garcia et al. (2007)). An important category of robots are mobile robots, with several main applications domains, such as exploratory, domestic, surveillance, etc. For such robots, localization is critical – (Garcia et al. (2007)). There is of course a large variety of localization methods employed, from sun position (in space robots) to GPS (for many outdoor robots), but in indoor environments such methods are not possible and special localization techniques have to be applied. Such techniques include landmarks (optical, laser, etc.) – (Tomizawa et al. (2007)), but wireless localization systems have been developing a lot in the past years. Moreover, an important research direction has been the use of existing, standard wireless networks, such as Bluetooth or WiFi – (Raghavan et al. (2010), Ladd et al. (2004)), or existing WSN networks (ZigBee) for robot localization – (Hung et al. (2010)).

5. LOCALIZATION IN WSANS

Localization in a WSAN is the process of determining the position of unknown network nodes – (Bachrach et al. (2005), Bal et al. (2009)). Practical applications of localization range from determining the position of patients, personnel or equipments into a hospital, to position determination within a swarm of robots working in a collaborative way toward a common mission.

In principle, a typical and straightforward solution for localization is the GPS system, but this cannot be used in all applications. First of all, in the case of indoor systems, the GPS signal is very faint and direct connection to the GPS satellites is not possible usually. However, even for outdoor systems, there are situations where the presence of obstacles block the direct communication with the satellite (e.g. within dense forests, for fire detection systems) – (Pal et al. (2010)). Furthermore, for WSN nodes, GPS has several other issues, such as power consumption, cost and size – (Pal et al. (2010)). Consequently, in many WSN applications it is useful to solve the localization problem using network specific parameters, such as characteristics of the received radio signal and position of some fixed nodes (also called beacons or anchors).

Localization problem in WSN can be divided into two main levels – (Bachrach et al. (2005), Bal et al. (2009)):

- Estimating the distance between pairs of nodes in the network
- Determining the position of all unknown nodes in the network.

6. DISTANCE ESTIMATION

The distance estimation problem is solved in principle based on parameters of the received radio signal and it is addressed in all types of wireless localization systems – (Liu et al. (2007)). There are several techniques that can be used – (Liu et al. (2007), Bachrach et al. (2005)). The main criteria that are relevant for comparing these methods are: position accuracy and precision, software computational power required, special hardware requirements and robustness of the method – (Liu et al. (2007)).

Position accuracy – shows how close can the estimated position, using a particular technique, be to the real position. Accuracy is normally measured through the mean distance error. Clearly, the higher the accuracy, the lower this offset and the better the quality of the localization.

Position precision – measure how consistently the system works, in other words how often certain accuracy is reached. It can be measured by the standard deviation in the position error. The higher the precision, the more often certain accuracy is reached.

Software computational power – indicates the computational requirements of the software algorithm used for localization. This is an important metric, because it affects the power consumption of the node and may also affect the choice of the processor. Ideally, the lower the computational power, the better.

Special hardware requirements – indicates whether or not the localization technique requires special hardware features, normally not needed for that node. Examples include directional antennas or multiple antennas (array of antennas). Such requirements affect the system cost and may also affect other parameters, such as size.

Robustness – is the property of the system indicating how well it can function when some of the input parameters are not available, or have a corrupted value.

There are several approaches for estimating the distance between two nodes: received signal strength (RSS), time of arrival (TOA), time difference of arrival (TDOA), round-trip time of flight (RTOF), as well as angle of arrival.

RSS-based method uses the strength of the received signal to quantify the distance from the transmitter. The received signal strength depends on this distance, but it also depends on the actual propagation channel, due to multipath effects, such as fading and shadowing.

TOA- method is based on the principle that signal propagation time depends on the distance. The transmitted signal incorporates the value of the time of transmission, which the receiver subtracts from the time of receiving to obtain the propagation time. Of course, in order to work, the clocks at the receiver and transmitter have to be periodically synchronized.

TDOA- actually refers to two different classes of methods. The first is based on the difference in propagation times of identical signals sent by two transmitters (as opposed to the absolute propagation time). Thus, if the difference in propagation time from two transmitters is determined, the node is located on the hyperboloid given by equation:

$$d(P,1)-d(P,2)=\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}$$
$$-\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}=k\tau$$

where τ is the difference in the propagation time from the two transmitters. Combining measurements of τ from transmitters 1,2 and 1,3, the position could be determined at the intersection of the two hyperboloids. The difference τ is not measured, but determined mathematically, as the value for which the correlation of the two received signal (which

correspond to the same sent signal) is maximum. Consequently, it is important that the two transmitters have a synchronized clock, but there is no such requirement on the unknown node.

Table 1. Performance of distance estimation methods

Method	Accuracy	Precision	Sw complexity	Special hw/ other requirements	Robustness	Cost
RSS	1-5 m	90% < 5 m	Moderate	-	Good	Low
TDOA	2-3 m	50% < 3 m	Moderate	Synch. clocks (for Tx nodes)	Good	Low
RTOF	1m	50% < 1m	Medium	-	Generally good; inadequate for short distances	Low
Combined RSS + RTOF (ultra-sonic)	15 cm	50% < 15 cm	Medium	Ultrasonic microphone and speakers	Good	Med-High
Unidirectional, combined	<30 cm	50% < 30 cm	High	Unidirectional antenna	Poor	Med-High

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$$d(P,1) - d(P,2) = \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} - \sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2} = k\tau$$

where τ is the difference in the propagation time from the two transmitters. Combining measurements of τ from transmitters 1,2 and 1,3, the position could be determined at the intersection of the two hyperboloids. The difference τ is not measured, but determined mathematically, as the value for which the correlation of the two received signal (which correspond to the same sent signal) is maximum. Consequently, it is important that the two transmitters have a synchronized clock, but there is no such requirement on the unknown node.

The second class of methods is based on measuring the delay in propagation between a radio signal and an acoustic (or ultrasonic) signal, each travelling with a different speed. For this, a microphone and a speaker are also needed.

It is important to mention that TOA and TDOA methods are severely affected by multipath propagation (more than RSS) and are usually employed when a line of sight exist between transmitter and receiver.

RTOF – Roundtrip time of flight is based on measuring the total time between the moment a signal is sent and a response is received. The clock synchronization is not as important as in TOA and TDOA, but the drawback is the fact that the response delay cannot be easily determined and it affects especially the estimation of short distances.

POA – Phase of arrival (or received signal phase method) is based on determining the delay of pure sinusoidal signals transmitted by several nodes, delay which can be expressed as a phase of the received signal. Again, it needs a line of sight in order to provide good results.

AOA – Angle of arrival is based on determining the angle (to a common direction) of the signals received from two or more transmitters. This method requires special hardware, i.e. either directional antennas or array of antennas, which are relatively large and expensive. Again, this method needs a line of sight for good results.

Based on the results presented in (Liu et al (2007)), we can summarize the performance that can be obtained by systems employing such methods – see Tab.1.

From these data, we can draw several conclusions, which may be useful when selecting the most appropriate method for distance estimation in WSAN:

- Best accuracy and precision is obtained by systems that employ combined methods, but they usually require special hardware and have also a higher cost.
- Typical distance estimation accuracy we can expect from methods that work on standard hardware is in the range of 1-5 m.
- TDOA method is attractive only if clock synchronization can be performed periodically (at least for some nodes, which will act as transmitters).
- Depending on distance ranges, RSS and RTOF might be combined, as they tend to complement each other (RSS parameter has high variance for shorter distances and cannot be used effectively for higher distances, while RTOF quality is limited for short distances).

7. POSITION DETERMINATION

These algorithms use the estimated distance between pair of nodes as well as known positions of fixed nodes to determine the position of all unknown nodes. Such algorithms can be classified as – (Bachrach et al. (2005)):

- Centralized algorithms – which are run at some centralized locations (also referred to "base stations", i.e. more powerful nodes). They receive the inter-node ranging and connectivity data in their region and determine the absolute positions of the unknown nodes in this region. This position information is usually sent back to the respective nodes. Thus, the centralized algorithms benefit of the high computational power of the base stations computers, but involve a supplementary traffic throughout the network. There are several centralized algorithms, such as multi-dimensional scaling (MDS) and minimum Least-Square (MLS) optimization – (Bachrach et al. (2005), Pal et al. (2010), Niewiadomska et al. (2009)).

Distributed algorithms are run throughout the network, thus benefitting of parallelism and inter-node communication, but using the nodes limited computational power. There are two main categories of distributed algorithms. In the beacon-based algorithms, nodes determine their own position relative to a few (neighbor) beacons. Once their position is thus determined, they can serve as beacons for other nodes in their turn. Global metric algorithms solve the localization problem by minimizing a certain metric over the entire network. Beacon-based algorithms include diffusion, boundary box, APIT, gradient (multilateration). Global metric algorithms include relaxation-based distributed algorithm, coordinate system stitching, hybrid localization algorithms, error propagation aware localization algorithm (EPA), interferometric localization algorithms (Pal et al. (2010)).

Based on (Pal et al. (2010)), all centralized methods have a high accuracy, but also a high computational and communication cost. Meanwhile, most distributed methods have a low cost, but only a few have a high accuracy too. Such methods include the hybrid localization, consisting on either MDS + proximity distance mapping (PDM), or MDS + ad-hoc positioning system (APS). These methods apply the two algorithms in a sequence. For instance, in the case of MDS + PDM, MDS is run first and, starting from the known anchors it determines a set of secondary anchors. After that, PDM locates all the remaining nodes, based on the known position of the extended set of anchors.

8. LOCALIZATION FOR MEDICAL AND ROBOTICS APPLICATIONS

As discussed in section 2, medical portable devices are very constraint in terms of energy, size and computation power. This means that, if possible, no additional hardware should be added for distance estimation and also that centralized algorithms for position determination may be preferred. As mentioned in section 6, the accuracy that can be obtained using standard hardware only and moderate software complexity, such as in RSS method, is in the range of 1-5 m. If this accuracy can be reduced to a couple of meters, it would be enough for most medical localization needs. Consequently, we can conclude that a promising direction in medical localization applications is employing RSS method for distance estimation and centralized network algorithms for position determination. In order to reduce the supplementary traffic, it would be indicated to limit the nodes to be localized to those that are really important, e.g. patients with higher accident risk.

On the other hand, in most mobile robotics the constraints are less severe. The electronic hardware power consumption is marginal compared to the power needed for motors and so is its size. However, for navigation purposes, the estimated position has to be more accurate, usually in the order of 10-30 cm. These considerations suggest that special hardware may be used for increasing the accuracy of the distance estimation, although increasing accuracy with standard hardware, but through several measurements, may be also interesting – (Graefenstein et al. (2009)). Furthermore, position determination algorithms can be run on the robot. In fact, in some applications the robot would compute its own position, while in the case of multiple robots (e.g. robot swarms), distributed WSAN algorithms would be used.

9. CONCLUSIONS

In this paper we reviewed the localization techniques used in WSANs and discussed their suitability for medical and robotic applications. For this, we first looked at the main characteristic of generic WSANs as well as at those used in medical and robotics, then reviewed most relevant current approaches for the two localization stages: inter-node distance estimation and position determination. As seen, the constraints as well as the requirements of these two application areas are quite diverse. Consequently, we concluded that different approaches would be most appropriate for each of them. Based on these concluded, we intend to study improvements in the centralized approach, using standard hardware, in order to increase the accuracy and implement it for medical localization. We also intend to study optimal solutions for different robotics applications.

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