Review

The integration of mobile (tele) robotics and wireless sensor networks: A survey

Andrew Wichmann *, Burcu Demirelli Okkalioglu, Turgay Korkmaz

Department of Computer Science, University of Texas at San Antonio, United States

ARTICLE INFO

Article history:
Received 8 December 2013
Received in revised form 21 April 2014
Accepted 12 June 2014
Available online 20 June 2014

Keywords:
Wireless sensor network
Robotics
Teleoperation
Path planning
Task allocation

ABSTRACT

Researchers have been extensively, but often independently, investigating Wireless Sensor Networks (WSNs), Mobile Robotics, and Teleoperation. Lately, due to the complementary nature of these areas, there is a growing trend in integrating them to support various applications that can go beyond passive monitoring and allow us to actually interact with the environment through autonomous and teleoperated robots. Such applications can extensively be used in medicine, science, military, industry, nuclear power stations, underwater, and space explorations. In this paper, we start with a review of the history of WSNs, robotics and mobility in WSNs, and teleoperation. We then introduce a system model integrating these areas as Wireless Sensor and Robot Networks with Teleoperation capabilities (WSRNT). Using this model, we define the problems associated with WSRNT. Finally, we discuss the recent research efforts and open research challenges in merging these fields with respect to major WSRNT tasks and communication requirements.

1. Introduction

The path leading to the integration of mobile (tele-) robotics and WSNs comes from two different fields. On one hand, WSN researchers began looking for ways to more efficiently use the energy in the network and perform some extra tasks in the monitored field. Accordingly, WSN researchers have considered adding mobile robots and/or static actuators within the network [1–7,3]. This path came out of the need for more resource-rich nodes in order to perform many different functions while prolonging the lifetime of the WSN.

On the other hand, robotics researchers moved from single robot applications to multi-robot applications and began looking for ways to efficiently coordinate multiple robots and increase their awareness about the field in which they operate. Accordingly, robotics researchers have considered adding networking and multimedia sensing capabilities to the mobile robots, leading to the emergence of Network Robot Systems (NRS) [8,9]. This avenue of research has also considered the inclusion of stationary sensors in the field so the mobile robots can communicate with them and obtain additional sensory information about the environment.

Despite the differences at the beginning, both paths have eventually converged into a system integrating both NRS and WSN as well as human users for teleoperation tasks [9]. We call this integrated system a WSRNT (Wireless Sensor and Robot Network with Teleoperation capabilities) and present its main components in Fig. 1. This model can be generalized to include static actuators as in Wireless Sensor and Actor/Actuator Networks (WSANs) [1]. However, to minimize the level of interaction complexity, we just consider the interactions among sensors, mobile robots, and the base station. We give the details of this model and other assumptions in Section 3.

One of the key challenges in WSRNT is how to manage the decision making among the components of such an integrated system. We can divide the decision making process into three categories: autonomous, teleoperation, and hybrid. Autonomous decision making is a distributed approach that leaves the decisions up to the networks to decide which robots will respond to which requests by the sensors. Teleoperation decision making is a more centralized approach because it uses a human operator to control the actions of the robot(s). Teleoperation allows operators to actually interact with the environment, as opposed to passively monitoring it [10–12]. A hybrid approach tries to combine the autonomous decision making with teleoperation in an efficient way. More specifically, an operator can use one or more robots to accomplish a task through teleoperation while the other robots autonomously conduct data collection or perform event monitoring.
Most of the existing studies on NRS consider the issues related to the autonomous decision making while paying less attention to teleoperation [9]. This is due to the fact that most of the existing teleoperation applications use a single tele-robot and assume that there is a direct communication channel between the operator and the tele-robot. However, this will not be the case as the number of tele-robots increases and multiple tele-robots need to be used along with autonomous robots and WSNs. So, in general, future systems integrating robotics and WSNs will need to have both autonomous and teleoperation (e.g., hybrid) decision making mechanisms to support many new applications in various fields such as medicine, science, military, industry, nuclear power stations, human–machine interaction, communications, handling nuclear materials, underwater and space exploration [13–15].

For example, consider a search and rescue application in a disaster area. The dedicated infrastructure could very well be destroyed and certain areas may be too dangerous to send a human in blind. In situations such as these (nuclear plant meltdown, natural disasters, etc.), a WSN could be deployed in an attempt to detect where humans may be buried, or radiation leaks are occurring. In the mean time, to find a safe way to get to the trapped person and rescue him or her, autonomous mobile robots could explore and map the area with the help of the WSN. Clearly, it will be necessary to use human intervention and intelligence to deal with some complicated tasks in such an environment. In that case, some robots can be controlled through teleoperation through the underlying network. Clearly, these tasks can only be performed by a system integrating WSNs, mobile robots, and teleoperation.

A similar situation could be considered for home monitoring with the elderly, where the integrated system can be used to detect and confirm falls and then alert the proper authorities who can help the elderly person through teleoperation. Another example would be in the area of gaming. A game such as BattleBots, which was a TV show dedicated to fighting robots, could be enhanced with the integration of WSNs, mobile robots, and teleoperation.

In essence, the above envisioned applications involve performing several challenging tasks such as (i) collecting multi-sensory data including audio–video data from an environment, (ii) extracting useful information from the data, (iii) informing autonomous robots or a human operator if the situation requires human intelligence and control, and (iv) enabling the human operator to communicate with the remotely controlled robots to interact with the environment. Clearly, there are several other challenges that can only be addressed by multi-disciplinary teams.

In this survey, we consider the big picture at the high level with a special emphasis on the integration of three important areas: WSNs, robotics, and teleoperation. We then specifically consider the current research efforts and challenges related to the communication and coordination issues in such an integrated system. Due to page limitations and the breadth of discussions in this survey, we are unable to cover the details of many studies on WSNs, robotics, and teleoperation. Instead, we highlight the main issues and contributions, but, for more details, we give references to several other complementary surveys that cover specific areas and issues.

We organize the rest of the paper as follows. We first examine a brief history of WSNs, robotics and mobility in WSNs, and teleoperation in Section 2. Next, we will introduce a system model combining mobile robots, WSNs, and teleoperation in Section 3. Using this system model, we identify the major components and the interactions between them. In Sections 4 and 5 we consider several fundamental actions and communications requirements that are necessary for the successful deployment and operation of such a system. Finally, we conclude this paper and discuss future research directions in Section 6.

2. History and applications

2.1. Wireless sensor networks

Wireless Sensor Networks (WSNs) are composed of a large number of sensor nodes which are able to communicate through wireless channels to convey data to a base station [27]. These networks have been suggested for use in many applications including wildlife [28], environmental [29,30], volcano [31], water [32], and structure monitoring [33,34], as well as fire detection [35] and healthcare [36]. These networks are able to collect data on the environment (e.g., light or temperature readings) and then report this information to the base station. The benefit is that these sensors can be distributed in environments where monitoring by humans would be too hazardous or costly.

Sensor Networks were first conceived around 1980, but similar systems can be traced back to the Cold War and even as early as 1949 with the Sound Surveillance System (SOSUS) [37]. SOSUS is a system of acoustic sensors on the ocean floor which had an initial purpose of tracking Soviet submarines. Development of SOSUS began in 1949 and was first demonstrated in 1961 to track an American submarine. Its first successful detection of a Soviet submarine came the following year in June of 1962 [16]. Defense applications are a major driver for research and development of sensor networks with applications such as SOSUS and networks of air defense radars. Modern research on sensor networks started in 1978 at a Distributed Sensor Nets workshop where the technology components of a Distributed Sensor Network (DSN) were identified [19]. The Defense Advanced Research Projects Agency (DARPA) was another driver of this early research with their DSNs program in the late 1970s and early 1980s [20]. More recently, DARPA created a program called the Sensor Information Technology (SensIT) program [24] to advance the use of WSNs. A condensed version of this history, as well as those in the following sections, can be seen in Table 1.
The applications suggested and used in practice for WSNs come from a wide variety of fields and are as numerous as they are diverse. One of the most prevalent and popular avenues for researchers has been in the domain of environment monitoring. This has included everything from ice and glacial monitoring [38] to volcano monitoring [31] and fire detection [35]. Any kind of monitoring application can conceivably use a WSN with mobile robots such as pollution detection, or flood detection and warning systems. In fact, one such system, called the ALERT system [39] is already used in practice in the US. Many military and security applications can be considered as well, such as border monitoring applications or battlefield monitoring applications [40]. Healthcare is another possibility for the use of WSNs and this has a possible cross utilization with teleoperation in telecare for patients, especially the elderly, as studied in [41,42]. A more detailed list of WSN applications can be found in [27].

As technology has progressed, so have sensor networks. The ability to make all of the components smaller, as well as cheaper, has led to the progression towards the ideal sensor network of thousands of sensors distributed in a large area to sense environmental conditions. Advancing wireless technologies, as well as ad hoc algorithms and protocols, have allowed for a more robust and dynamic network of sensors. The details of the current research efforts and developments on WSNs have been discussed in various surveys. In [27,43,44] all aspects of WSNs are discussed. Data collection and dissemination strategies are surveyed in [45–48]. Security and WSNs are discussed in [49]. Routing protocols used in WSNs are synthesized in [50–52]. Finally, Wireless Multimedia Sensor Network Issues are discussed in [53].

### 2.2. Robotics and mobility in WSNs

Most research has focused on fixed WSNs, where none of the sensors are allowed to change their location after their deployment in the area. Recently, researchers have started including mobile sensor nodes because they would be useful in distributed sensing systems such as surveillance, habitat monitoring, wildlife detection, and urban search and rescue operations [54]. A mobile sensor node (e.g. a mobile robot) can change its location autonomously based on its duty. For example, Robomote [55] is a tiny mobile robot which was developed to explore problems in large-scale distributed robotics and sensor networks. CotsBots [56] is another example of a low cost robot which is used in robotics and sensor networks. MICAbot [57] is a small, inexpensive robot which explores areas in large-scale networks. The idea of designing MICAbot is the same as Robomote; however, its purpose is to improve the functionality, modularity and structural stability of the MICAbot without affecting the cost.

Mobility within WSNs has been shown to benefit connectivity, reliability, and energy efficiency within the network [47,58]. The most widely cited advantage for mobile robots is the ability to more efficiently collect data [59–65]. Using mobile robots to supplement data collection allows for both the reduction and better distribution of energy usage throughout the network. Mobile robots allow for the reduction of multi-hop forwarding down to a small number of hops or even a single hop, which means sensors simply have to forward their own data rather than that of other sensors. In addition to reducing the energy used to transmit data, the reduction of multi-hop forwarding in the network helps avoid the funneling effect, where nodes closest to the base station die sooner and thus create a disconnected network faster than what would normally be expected [66].

There are other advantages to using mobile robots such as increasing the connectivity in a sparse WSN [67,68]. This allows a disconnected network to function as a normal fully-connected network. Robots can also improve security measures within the WSN through methods such as key distribution [69,70]. On the application layer, mobile robots will allow for better and more robust surveillance [71]. All of these advantages have led researchers to more vigorously pursue mobile robots and harnessing these advantages to improve WSNs as a whole.

Robotics can be used to help solve many of the problems in WSNs, just as WSNs can be used to help solve problems associated with robotics [72]. These problems range from deployment of WSNs to path-planning for robots. Robots can be used as data mules, or for data aggregation, or even localization. Coordination of robots can be enhanced through WSNs, as can sensing for a robot.

With this mobility comes many new issues and benefits that have been researched including path-planning [40,59,73,74] and speed control [75]. Much of the early research uses only one controlled mobile robot, however, researchers have also looked into the use of multiple coordinated robots [60,9]. Moreover, operators can remotely control robots to interact with the environment, as discussed in the rest of this paper.

### 2.3. Teleoperation and robotics

Teleoperation means controlling or doing work at a distance [13]. The meaning of the distance, however, can vary. The distance can be physical, such as an operator controlling a robot at a remote location. The distance could also be a change in scale, for example, a surgeon using teleoperation to conduct a surgery at the microscopic level.

The current teleoperation systems are designed using a master–slave system model [14]. The master and slave are...
separated by some distance, but they are connected by some communication channel (e.g., the Internet, a satellite system, or a direct link). The master is a human or computer operator where control of the robot lies. The robot will be located in the field as the slave of the teleoperation system and will be used to accomplish tasks as the operator requires. The master operates the slave with motion commands in order to perform a task [76]. To improve the performance of the task, the human operator needs to get force feedback information such as visual feedback. Actually, providing direct information (e.g. force, or haptic feedback [77]) would be even more useful [78].

Using feedback in a teleoperation system is defined as bilateral teleoperation which means when operating a manipulator to interact with a remote environment, the remote environment will provide feedback to the human operator [79]. Besides visual feedback, tactile feedback to the human operator attempting to accomplish a task can help improve the performance of the system. However, delay in the system can cause instabilities in the operation being performed. This instability, which may occur because of delay, has been studied by researchers in [76]. Delay for providing force feedback can dramatically affect the task being performed and the way a human operator makes his decision while manipulating the remote robot.

The first implementation of bilateral teleoperation goes back to the 1940s. Raymond Goertz designed the first mechanical master–slave system to handle radioactive materials [17]. Then, in the 1960s, mechanical manipulators were replaced with an electrically coupled master–slave systems. This opened up new avenues for manipulators and vehicles that would take advantage of these teleoperation techniques [14]. The 1960s also brought the first implementation of underwater teleoperation using submersible devices with cameras. In the 1970s, teleoperation studies were extended to space exploration. Teleoperation applications have spread from their original uses to many different fields including space, surgery, military, and underwater applications [13,14].

Today, teleoperation experiences wide use in many different fields. Examples of these fields include military-defense, space, underwater, and offshore exploration [80]. Space exploration and experimentation is a great candidate for teleoperation applications because permanent human presence is impossible with current technology. Thus, teleoperation can and does aid in repairs and exploration in space because it is more suitable than the presence of an actual human in space. Space exploration (such as landing robots like NASA's Rocky I-IV), satellite communications, and reliable weather forecasting are all examples of teleoperation applications in space [14].

Like space applications, military applications are risky because of the possible loss of life. Both Unmanned Aerial Vehicles (UAV) and Unmanned Ground Vehicles (UGV) are primarily used in military applications. UAVs are usually piloted by radio or satellite links and can use GPS for target identification. Similarly, UGVs are used for reconnaissance, surveillance, and land mine detection and they can also be equipped with GPS for localization techniques [13,81].

As mentioned in previous paragraphs, underwater vehicle operations were one of the early teleoperation implementations and these vehicles are generally known as remote operated vehicles (ROVs). ROVs are used in a wide range of tasks including surveys, oceanography, and inspection. ROVs are taking over the roles of humans in underwater operations in order to reduce the exposure of humans to risk. Most ROVs are controlled using joysticks and have video capability to provide feedback; however, this trend is changing with the autonomous functionality of robots [81]. We have discussed a few applications in detail, but some of the other important applications for teleoperation reside in the fields of security [82], telesurgery [83,84], and forestry [85].

Additionally, there has been a trend toward using multiple robots concurrently in order to benefit from the combined power of multiple robots [15,86,87]. Clearly, multi-robot systems would have more advantages compared with single robot systems [55–57,88]. Despite the advantages and potential applications of multiple robots in a variety of applications, their use is not widespread due to challenges in providing coordination and communications among the participating entities as they require real-time interaction.

3. System model

A WSRNT (Wireless Sensor and Robot Network with Teleoperation) consists of many interacting components, as shown in Fig. 1. Due to the integration of WSNs, mobile robots, and teleoperation through two different paths, there is no unified terminology, resulting in a confusion of terms. Here we will first try to define a concise set of terms that we will use in this survey and then list what terms they encompass in different fields. We will then characterize the information flow and the interactions among the components of the integrated system so that we can better understand the communication and coordination issues in WSRNT.

When unifying the terms from the two paths, we will approach them from the WSN path. Accordingly, we begin by defining the different terms and components of WSRNT as follows.

- A Wireless Sensor Network (WSN) is a set of spatially distributed sensors that can monitor environmental phenomena and exchange that information with each other over wireless channels. This term originally came from DARPA's Distributed Sensor Networks (DSNs) [19] and is also similar to Wireless Ad Hoc Networks. However, the term WSN is now widely used and no longer has very many derivations in recent literature. We will use the term WSN to also describe sensor-sensor interactions.

- A Mobile Robot Network (MRN) is a set of mobile robots that are capable of moving to a given location, performing various tasks, and communicating with each other over wireless channels. Mobile robots are also capable of communicating with sensor nodes. We use MRN instead of the terms like Network Robot Systems (NRS) from the robotics field [8] and Mobile Ad Hoc Networks (MANETs from the field of networking). We will also use the term MRN to describe robot-robot interactions.

- The base station (BS) signifies the place where data is ultimately sent and analyzed, and human operators make decisions. In teleoperation systems, the BS has also been called either a master or operator while mobile nodes are called slaves.

- Wireless Sensor and Robot Network with Teleoperation (WSRNT) is the combination of WSN, MRN, and the base station. It also describes the sensor- and robot-base station interactions.

Note that, to minimize the level of interaction complexity, we just consider mobile robots/nodes (as in Mobile Ad Hoc Networks) rather than any other static node actors (as in Wireless Sensor and Actor Networks) or actuators (as in Wireless Sensor and Actuator Networks) [1,3]. However, they can easily be integrated into a WSRNT.

3.1. Information flow

To better understand the communication and coordination problems involved among the components of the WSRNT, we need to first analyze the details of the information flow throughout the system. For this, we created an Information Flow Diagram in Fig. 2. We break up this diagram into three modules: the environment
monitoring module, the teleoperation module, and the control module.

The environment monitoring module contains the WSN and the MRN. This module will collect data on the environment and send this information to the base station to help improve the knowledge and understanding of the environment being monitored. The teleoperation module includes robots with the ability to provide audio and visual feedback, as well as perform certain tasks that may be necessary (depending on the application). The control module is located in the base station and includes command and control of the robots, a human operator, and analysis abilities. The base station is connected to both the WSN and the MRN through some communication link. It is important to note that the robots in the environment monitoring module and the teleoperation module are not necessarily mutually exclusive.

The most consistent flow of data will come from the environment monitoring module. In this module, the base station will be able to send configuration data to the WSN and MRN, if necessary. The more important flow, however, will be in the opposite direction. The WSN will have the ability to prioritize data and, if necessary, send real-time environment data back to the base station. Otherwise, most of the data in the WSN will be collected by the mobile robots and then sent to the base station in order to reduce energy consumption in the WSN.

The largest amount of data and most time-sensitive data will flow between the remotely controlled robots and the base station in the teleoperation module. These communication lines will require much more bandwidth, as well as guaranteed Quality of Service (QoS). Teleoperation will require real-time audio-visual and force feedback in order to maintain high performance standards for teleoperation tasks. The reverse flow, base station to mobile robots, will require similar guarantees so control messages do not get dropped too often.

The control module will be handling all of the data collected by the WSN and MRN and will synthesize it for the human operator. It will also alert the operator of any real-time data received from the WSN. Then the control module will take inputs from the human operator and send the proper control messages to the robot(s) being teleoperated.

### 3.2. Interactions between WSRNT components

In this section we will discuss at the high-level what each interaction means and in the following sections we will refer back to these interactions when discussing the communication and coordination problems that are in the literature.

#### 3.2.1. Sensor–sensor

These interactions are akin to WSNs. WSNs have been studied for a long time (as stated in Section 2). Many of the issues associated with WSNs continue to be studied and will remain issues in this type of system. These include routing, connectivity, localization, and QoS. WSNs require efficient energy use to maintain longer lifetimes for the network at large. The limited energy supply compounds these problems which have required innovative solutions, as has been discussed in the previous sections.

#### 3.2.2. Robot–robot

One of the main issues with robot to robot interactions is the dynamic nature of these interactions. A robot could be connected with another robot at one moment and not be the next. All of the same issues connected with WSNs can also be found in MRNs, although solutions can be found in different ways with the added mobility of the robots. MANETs are a similar type of network and have been studied for quite some time.

#### 3.2.3. Sensor–robot

Sensor to robot communication and coordination has been found to increase the lifetimes of networks because the robots have more capabilities than the sensors and can take on more responsibility from the sensors, allowing the sensors to reduce their energy use by not having to forward as many packets as in a strictly WSN. The added capabilities of robots in the network makes tasks such as localization and connectivity easier than in strictly WSNs, as well.

#### 3.2.4. Base station–WSRN

We combine the base station to WSN and the base station to MRN interactions here due to the fact that the differences are simply nominal. Teleoperation requires a communication channel between the human operator and the robots in an environment. In a small-scale system, one may use a dedicated direct link from the human operator to each robot. In general, however, we need more cost-effective solutions that would allow the human operator to communicate with the mobile robots through a MRN. Due to involvement of MRNs in conjunction with other variable delay communication channels to connect the operator to the MRN, most of problems associated with teleoperation in WSNRT will be similar to problems in Internet-based teleoperation. The reason for this is twofold. First, the connection from the base station to the WSNRT in the field could be internet-based. Second, the connections within WSRNT will be wireless and thus subject to variable delay, as in internet-based communication, due to the noise problem found in wireless communications.
4. Fundamental actions in WSRNT

Within the lifetime of a WSRNT system, many actions must be performed and coordinated to complete the mission of the network. Here we discuss four of the main issues involved in the lifetime of the network. The first problem that needs to be solved is the deployment of the network. The deployment problem can also be applied to redeployment and replacement of sensors and (tele) robots as well. Next, the problem of localization will be required to define the locations of each robot and sensor in order to more efficiently complete tasks assigned to the network. If a robot is required to complete a task (e.g., environment monitoring, data collection, etc.) at a given location, then the robot must travel to the location of the task and do so in an efficient way to minimize the response time. For this, we will study the problem of path planning and navigation for mobile robots. As the environment creates more tasks for the network to complete, these tasks must be assigned to the proper entities in an efficient way such that we can minimize the energy use of sensors and robots to maximize the lifetime of the network. As the last issue, we will study task allocation issues in the following subsections. A summary of these actions and their definitions can be found in Table 2.

4.1. Deployment

Many researchers have studied the deployment of WSNs and its affect on the subsequent performance of the network. This has been shown to have a significant effect depending on the strategies used [107]. Autonomous deployment of WSNs by mobile robots can be highly effective in the case of disasters because such a situation would require certain ad hoc features. In [12] the authors use mobile robots to deploy a WSN for human existence detection. In the case of a disaster, responders will want to gather information within the target area and make sure the entire area is covered. To do this, the authors of [12] propose using cooperative Simultaneous Localization and Mapping (SLAM) during deployment to communicate through the WSN and make decisions on when and where to place sensors. Exploration strategies are also important for cooperative exploration in order to maximize the efficiency of the mobile robots. Of the three strategies studied in [12] (frontier-based [108], market-driven [109], and role-based exploration [110]), the chosen strategy was a role-based exploration strategy where there are two types of robots, namely explorers and relays. The explorers are used to discover unexplored territory, while the relays maintain connection between the explorers and the control center.

Another aspect of the SLAM process is the mapping of the unknown area, which can be done using two different approaches – a centralized and a distributed map building approach. The authors ran multiple SLAM simulations to determine the number of robots and the speed the robots should travel in order to maximize the efficiency of the map building. The simulations showed that their approach of Extended Kalman Filtering was able to sufficiently estimate the location of a robot as well as the sensor nodes. Their experiments and simulations also demonstrated that the speed of the robots increased, the absolute trajectory error also increased.

The strategies studied for deployment of the sensor nodes were from [107] and the authors of [12] chose to use what they term the DS\(S\) scenario which is defined in this way: uniform traffic generation, homogeneous sensor capabilities, uniform initial energy assignment, and a single static sink. They then ran experiments

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with commercially available sensor nodes to test the network lifetime using their proposed system. From these experiments, the authors conclude that the Telos sensor nodes are more suitable for their proposed system because they have a longer battery life and also support the low-power IEEE 802.15.4 protocol [12].

Using a teleoperated robot to deploy wireless camera nodes is proposed in [89]. The authors propose deploying sensors when the estimated data transfer speed falls below a certain threshold. In order to do this, a scheme for estimating the data transfer speed in a network is proposed. To test their proposal, the authors of [89] ran experiments using a prototype of their system and were able to show that the network maintained the required transfer rate (19 Kbps for the proposed application) throughout the network's lifetime. This setup is similar to that which was used in [90]. Here the authors demonstrate the use of a teleoperated robot to deploy sensors to setup a WSN for cases of disaster where existing infrastructure may have been disconnected.

Autonomous deployment is often studied in conjunction with WSNs. For example, the authors of [91] propose and deploy an electric vehicle which they use to carry and deploy smaller search robots automatically for search and rescue operations. They propose using a Distributed Control System (DCS) which is able to create three closed loop control systems that control the steering, speed, and deployment mechanism for the vehicle. Through the implementation of this system, the vehicle was able to traverse terrain and deploy search robots in certain locations with significant effect on the controllers performance due to the network delays.

A more distributed approach to the deployment of MRNs is studied in [92]. Here the authors propose using a neural network to control the locations of the robots in order to maximize coverage. Training of these neural networks is required and the authors propose using a genetic algorithm in order to achieve this training. The authors were able to show that the neural network approach, in terms of coverage area, was able to improve upon both a random deployment and an approach based on virtual forces called VFA [93]. The authors of [92] believe their approach can be adapted to solve different problems within the realm of QoS as well.

4.2. Localization

Localization in WSNs has been studied for many years and the added capabilities of mobility have been found to make this localization easier. As discussed before, SLAM has been used quite often to both map and localize an area and the robots within that area [107]. Other ways to work on localization include the use of received signal strength indicators (RSSI). This is used in both [111,94]. In [94] they actually use both SLAM and RSSI by utilizing robots which use an extended Kalman filter adapted to use RSSI distance estimation. Another possible localization algorithm can take into account the movement of a robot rather than the exact position. If you have the speed, time traveled, and the angular rotation of a robot, then you can calculate the new location of the robot at any point in time [95].

In [96] the authors study both sensor localization and robot localization. They use only sensor to sensor interactions to localize the sensors by constructing a network with reference nodes, which can self-localize, interspersed in the network with many normal nodes. The self-localizing nodes are then able to triangulate the other nodes to help localize them. In the same paper, the authors discuss robot localization. Their algorithm starts with the robot sending out a localization service request to sensors, the localized sensors then send the localization information back to the robot and the robot uses this information to calculate its own position keeping in mind its speed and travel direction.

The authors of [112] also consider robot localization, but they focus on measuring the error introduced with respect to the distance from Distributed Intelligent Network Devices (DINNs). The authors find a directional error of no more than 3.5° and a positional error of less than 17 cm, but only when the robot is seen more than 75% of the time.

For ease of localization, GPS can be used to accurately find a specific robot’s position. The problem with this approach is that using GPS uses a lot of energy and therefore can degrade the lifetime of a robot. Using anchor nodes is another approach used in the literature, but this also requires certain sensors or robots to know their position beforehand. The authors of [97] propose a GPS- and anchor-free directional localization algorithm called dual wireless radio localization (DWRL). Their algorithm involves two steps. The first they call semi-localization where they use trigonometry to localize an unlocalized sensor with respect to an already localized sensor. The second is called rigid-localization in which an unlocalized sensor is localized by two separate localized sensors to make sure the graph is globally rigid. Through simulation the authors are able to show that if the inter-radio distance is sufficient, then the algorithm was able to localizes nodes with a high degree of accuracy. This is just a brief synopsis of some of the work done in the field of localization.

4.3. Path planning and navigation

4.3.1. Path planning

In the early 1970s, researchers focused on autonomous navigation of mobile robots. The International Joint Conferences on Artificial Intelligence (IJCAI 1969) published the very first navigation systems for mobile robots [18]. However, these systems only contained some of the seminal ideas in autonomous navigation of mobile robots. In 1969, a grid-based approach was used by the mobile robot, Shakey, to search and form an understanding of the environment [98]. Another example of autonomous navigation was developed by Thompson in 1977 and uses a visibility graph. In Thompson’s research, the visibility graph was used to define the corners of obstacles [99].

The prevalence of sensor networks has increased in recent years and static sensor nodes have become a new research topic to help develop robot navigation systems [9]. In [100], researchers studied the problem of coverage and exploration of an unknown, dynamic environment using a mobile robot. In their experiment, the authors of [100] do not use global information, such as a map or global positioning system (GPS). Instead, a network of radio beacons is placed in the area to guide the robots.

A similar idea was illustrated in [101], where researchers use two potential field maps: one as a danger field map and the other as an exit field map. These maps are built immediately after an event is detected by a sensor node. Danger field maps obviously indicate dangerous areas, while the exit field maps show the safest areas by constructing virtual walls around the hazard areas. After the event is detected, the robot must move to the closest event region using the danger field map. In [101], the researchers also devised an algorithm to determine the robot’s motion. According to the motion strategy, the robot selects a sensor node with the lowest potential value within its communication range and then moves in that direction. This motion strategy is also used for directing people to a safe exit area. After finding victims, the robot begins to use the exit field map to guide victims to the exit.

In [102], the authors consider mobile robots which can directly communicate with sensors and use this idea to develop a gradient propagation (GP) algorithm. Each sensor independently executes the GP algorithm and then broadcasts its gradient value through the network. As a result, a network-wide gradient can be established by all sensors. In the algorithm, there are two terms used – hot and
cold values. If the sensor is close to the event region, the sensor assigns itself a hot value, otherwise, the sensor concludes that the event is far away and assigns itself a cold value. Following this step, the robot uses its sensor to find its way to the target by searching for hot values. The movement strategy is the same as in [101].

Moreover, in [101], researchers also propose a navigation scheme for when the destination node is within the robot's communication range. Their algorithm is called 1-Hop-Wide navigation which uses a radio wake-on component enabling wireless communication between the robot and sensor nodes. A radio wake-on component uses hardware-based low power listening without intervention of the microcontroller. In this case, the robot does not need sensory information to find its way. Each robot uses a directional antenna to find the maximum Received Signal Strength (RSS) and then the robot rotates in the direction of the maximum RSS and moves in that direction.

4.3.2. Visual-based navigation

When a robot traverses an area, the robot must avoid obstacles. However, the robot may hit objects behind it or to the side if it only has unidirectional information. As a result, omnidirectional information around a robot is required to understand objects and avoid obstacles within an area. There are three methods for gathering such information including acoustic sensing, passive vision, and active vision [103]. Acoustic sensing can provide information around the robot, but the ranging capability of acoustic sensors are poor. Therefore, finding the precise location of the objects is difficult.

An active sensor provides more accurate information of objects when compared with an acoustic sensor [103]. For example, a real-time omnidirectional active sensing method is developed in [113], where a conic mirror and sheets of light are used to get omnidirectional information. Unfortunately, Jarvis and Byme report that the quality of the image is not good enough to be used.

Many devices have been used for passive imaging including fish-eye lenses, conic mirrors, or rotating cameras in order to get omnidirectional information from the area [103]. A rotating camera provides an omnidirectional view, however, obtaining a picture takes a long time and this is not suitable for real-time applications. Also, a fish-eye lens gives a wide view of the area. However, the image resolution is not good enough to monitor objects around the robot.

As a result, these three methods do not provide efficient and useful information to avoid obstacles and guide robots. To deal with these problems, researchers have begun to use omnidirectional sensors. In [103], the authors develop a new omnidirectional image sensor, COPIS (Conic Projection Image Sensor). COPIS uses passive sensing to get an omnidirectional image of the environment. The proposed method detects the azimuth of each object in the omnidirectional image. This allows the robot to predict its own location and motion because the COPIS sensor captures a 360 degree view.

In [114], omnidirectional sensors are used as sensors to help robots navigate. Researchers claim that other types of sensors are usually used for navigation such as GPS and laser scanners. They argue, however, that GPS is not suitable for indoor environments or narrow places because they need a direct line of sight to the satellites. Thus, they propose a vision-only solution to navigation.

In [115,116], the authors describe a method for visual-based navigation of a mobile robot in indoor environments using a single omnidirectional camera. In both papers, researchers propose two navigation schemes – topological navigation and visual path following. When using topological navigation, the knowledge of the exact position of the robot is not needed. A robot can travel long distances using topological navigation. Also, topological maps are used to illustrate a robot's global environment. To test this navigation scheme, Winters et al. conducted an experiment. They collect pictures from the omnidirectional camera every 50 cm along a corridor in order to build a topological map. Then, the robot moves along the corridor to get to the specified room. However, more precise information is required when entering a room or going through a door. Therefore, for local and precise navigation the robot will use visual path following. A robot can move to a specified location using visual path following by using a closed-loop controller to navigate the robot to the desired destination. As the robot moves toward the destination, visual tracking of landmarks is used to guide the robot.

4.4. Task allocation

During the lifetime of the network, robots and sensors will have certain jobs they are required to complete. In order to efficiently accomplish these tasks, researchers want to assign tasks to the proper sensors or robots in order to save time and energy. Many researchers have discussed and classified task allocation problems. In [1], the authors classify tasks first into two separate categories, namely single-actor and multi-actor tasks (SAT and MAT, respectively). Then they classify decision making into two categories as well, centralized (CD) and distributed (DD). The authors of [9] also categorize tasks into both single-robot (SRT) and multirobot tasks (MRT), but the secondary classification they use is with respect to the time tasks are allocated. Here they have two categories based on instantaneous assignment (IA) and time-extended assignment (TA). Basically, IA does not consider future tasks when assigning a task to a robot, whereas TA attempts to optimize performance based on the entire set of tasks (present and future).

Approaches to solve this problem have been discussed in [9] as well, where they break approaches into two categories. Market-based approaches are based negotiations, or auctions, where the robots communicate with each other and the robot with the highest bid is assigned the task. The second category is behavior-based where individual tasks are not considered, but knowledge of the state of the network is used to assign tasks in a distributed fashion. For a more thorough discussion of individual research and solutions, the reader is directed towards [2,9,117,118].

Auction-based task allocation is studied in [104] by using auctions to improve the recent information mesh (iMesh) based distance sensitive service discovery approach. The idea was to improve on iMesh's ability to find the closest service 95% of the time. To do this, the authors introduced localized auctions. So, after using the iMesh lookup to find the closest robot, this robot will begin an auction by using a localized auction aggregation protocol by beginning an auction with its neighboring robots to see if any of them can better provide the service. Through simulation results, the authors were able to show an 86% improvement on the average.

Event prediction is another way for WSRNRT to reduce response times to events and to better accomplish the problem of task allocation. This is precisely what the authors of [106] attempt to achieve. The authors use a maximum likelihood estimation to predict events and use a Markov decision process to control the movement of the robots in the network. Their protocol was able to improve on a random walk in both time and energy efficiency. This approach is able to save energy for the robot as well as the underlying sensor network because the sensors did not have to forward their data as far to reach the robot in the network.

Clearly, the human operator cannot oversee all the tasks that the robots are expected to perform. In most cases, mobile robots must have some autonomy to perform various tasks including navigation, path planning, and data collection. Also there must be some advanced information extraction mechanisms at the base
station that will process the collected data and inform the human operators when there is a situation requiring human intelligence and control. Then the human operators will start teleoperating some of the robots in the environment through the networking support that we discuss in the next section. One specific task can be data collection and surveys on data collection are numerous and thorough [59–64].

5. Communication requirements in WSRNT

In order to successfully complete the aforementioned major tasks in an efficient way, all of the components in a WSRNT need to be able to communicate with each other without depleting too much energy. Efficient communication will require many different things to be considered, which is summarized in Table 3, including connectivity, routing, and QoS. These are among the issues associated with communication in WSNs and MRNs and we will expand upon these topics in the following sections.

5.1. Routing protocols

The first and most obvious issue is how to successfully and efficiently deliver packets in WSRNT. To address such issues in WSNs and MRNs, researchers have been investigating various routing algorithms and comparing their performance. For example, the authors in [119] test four widely used ad hoc routing protocols, namely the Ad hoc On-demand Distance Vector (AODV) routing protocol, the Dynamic Source Routing (DSR) protocol, the Optimized Link State Routing (OLSR) protocol, and the Better approach to mobile ad hoc networking (B.A.T.M.A.N.) routing protocol. Specifically, they set up three relay nodes at three corners around an obstacle and attempt to move the mobile robot around the obstacle. The obstacle blocks direct communication to the robot after the first turn.

The experiments show that of the four protocols, B.A.T.M.A.N. was never able to reestablish a connection to the robot after the loss of line-of-sight. When using AODV, the robot was able to traverse its entire route through communication between the PC, the nodes, and the robot. When attempting to re-route, however, reestablishment of the connection sometimes took longer than 30 s which is infeasible for a teleoperation system. The OLSR protocol was generally slower and took longer to both re-route packets and then deliver these packets to the robot. This all led to the robot taking longer to traverse its route than when AODV was used to route the packets. Finally, the best protocol found was DSR because it was able to re-establish routes within 2 to 3 s with only about 11% of packets lost during a test run. Obviously, the authors surmised that DSR is the best protocol to use. However, as a best-effort protocol, DSR would not be enough to support stringent QoS requirements in WSRNT (e.g., real-time transmission of telecommand and visual feedback between the robots and base station), calling for QoS-based wireless networking support that we discuss in the next subsection.

Another consideration when routing is power consumption of the network. One problem that arises is the hotspot problem, where sensors closer to the sink die off faster than others in the network due to the increased forwarding of data near the hotspot. The authors of [120] take this into consideration when creating a hybrid routing algorithm in order to minimize this problem. They accomplish this task by creating a hybrid algorithm of both flat multi-hop routing and hierarchical routing. By using hierarchical routing outside of the hotspot area, the network is able to compress data and send a reduced amount of data into the hotspot area. After the data has reached a node inside of the hotspot area (e.g. close to the sink), flat multi-hop routing is employed to minimize the power consumption per unit of transmission.

To get around some of the limitations in just relying on networking techniques, researchers have considered using mobile robots. For example, some researchers have used multiple mobile robots to aid in routing information over long distances for teleoperation [121,122]. Still others have looked into using the pervasiveness of mobile communication networks (e.g. iPhones, PDAs, etc.)

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Communication requirements in WSRNT.</th>
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<tr>
<td><strong>Goal and key challenges</strong></td>
<td><strong>Main contributions</strong></td>
</tr>
<tr>
<td><strong>Routing</strong></td>
<td>Efficiently send packets to the base station, or some other node while maintaining a certain level of energy efficiency. Mobile networks provide an added layer of difficulty when trying to route data successfully.</td>
</tr>
<tr>
<td><strong>QoS</strong></td>
<td>Guarantees certain minimum performance metrics (bandwidth, delay, jitter, etc.) in a network throughout its lifetime. The difficulty comes in providing these services for differing applications, as well as differing environments.</td>
</tr>
<tr>
<td><strong>Connectivity</strong></td>
<td>Maintain a certain level of connectivity in the network in order to successfully transmit data among the network. Maintaining connectivity while moving nodes (robots) throughout the network is very challenging, especially when coupled with efficient task allocation.</td>
</tr>
<tr>
<td><strong>Teleoperation</strong></td>
<td>Send data to and from the master and slave in the environment in a real-time manner without a significant amount of delay or jitter. One of the key challenges is maintaining high QoS performance metrics in a dynamic and unreliable environment such as the wireless channels used in WSNRT.</td>
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to control remotely located robots through the Internet [123]. Cooperative multi-robot systems are a largely studied topic for a multitude of reasons and have many advantages over single robot systems. These systems also have unique problems that have been and must continue to be addressed [88]. Multi-robot systems allow for parallelism, which can reduce the time required to accomplish certain tasks, including area exploration. These systems are also useful because it is easier to build several smaller resource-bounded robots, than relying on a single powerful robot.

In [124], the authors propose a protocol called WISER. This protocol is designed for session control and exploits the controlled mobility in Multi-Robot Sensor Networks to transfer a huge amount of data efficiently. In this design, the performance of a session is related to the robot's movement because the robot's movement enables communication within the network. The protocol requires the source node to determine the balance between a movement and wireless communications using local information such as the location, maximum velocity, and buffer size of surrounding nodes.

In [124], the authors present three models. The first one is a no helper-node model. Here a source node will transmit data by moving to the destination node. In the second model, called the Sufficient Helper-Nodes Model, there are helper-nodes between the source node and destination node which are used to construct communication lines. However, a source node may not be able to transmit data because a path to the destination is not available. In this case, the last model is used which is called the No Availability of Sufficient Helper-Nodes Model. Sufficient helper nodes are not available, thus, some helper nodes need to move towards the destination node in order to ensure successful transmission of the data to the destination. In [124], they also describe a state transaction diagram which depicts each node's operation.

5.2. Quality of Service (QoS)

QoS-based networking has been extensively investigated in the context of wireline networks [146]. Similar QoS issues appear in the context of wireless networks as well, but they become much harder and more complicated due to the dynamic characteristics of mobile nodes and wireless links. Nevertheless, supporting QoS requirements in wireless networks has become an increasingly important and is a challenging task. Accordingly, researchers have extensively been investigating and proposing various QoS solutions [147–152].

In general, the proposed QoS solutions for wireless networks can be classified as MAC layer (e.g., 802.11e [125], DBASE [126]), Network layer (Ticket-based routing [127,128], PLBQR [129], BR [130], OLMQR [131]) or complete framework solutions (e.g., INSIGNIA [132], INORA [133], SWAN [134]). Many of these solutions require some kind of resource reservation. However, given the dynamic characteristics of WSRNT (e.g., node movements, unpredictable link behavior etc.), reserving resources or maintaining these reservations will often be impossible and will cause highly inefficient use of scarce resources. On the other hand, the solutions that do not require resource reservation cannot provide QoS guarantees (e.g., SWAN). Therefore, one of the open research challenges is how to provide QoS support without requiring explicit reservations.

Another key issue in QoS-based networking is how to identify a feasible path(s) that can meet desired QoS requirements (e.g., bandwidth, delay, jitter, reliability) while maintaining high utilization of network resources [153]. Even if such a path is determined, it is not enough to provide any QoS support unless the availability of resources is checked (e.g., admission control is applied) and some resources are allocated along that path. In the wireline networks, various signaling protocols have been proposed to achieve resource allocation (e.g., RSVP [154]). However, allocating resources per-flow is known to be problematic in terms of scalability. Moreover, as we discussed before, reservation-based approaches will not be feasible in a wireless network due to its dynamics. Despite all these efforts, QoS-based networking is still in its infancy in the context of multi-hop wireless networks, calling for further theoretical and experimental research on reservation-less solutions.

While providing the envisioned reservationless QoS support, it is also important to consider unauthorized nodes that may not respect the underlying QoS mechanisms and degrade the QoS capabilities through various attacks (e.g., DoS, unauthorized access to the network, delete messages, inject false packets, or impersonate a node). Accordingly, there is a need to develop necessary security mechanisms and integrate them into the QoS mechanisms so that various attacks/intrusions can be detected and avoided while maintaining the QoS-based operation of the network.

5.3. Connectivity

Using multiple robots, as in [121], will also increase the effective range within which a task can be completed. Specifically, the authors propose an architecture composed of three physical components, including a Remote Operating Center (ROC), Follower Robots (FBOTs), and a Tank Robot (TBOT). These robots cooperate to transfer task data from the ROC to the TBOT through possibly multiple FBOTs. The difficulty is maintaining connectivity and the authors of [121] propose two mechanisms to help maintain communication. The first uses region modeling to help predict disconnection by using returned RSSI and LQI values. The second mechanism is used to control the movements of the robots by using a virtual force model based upon the region of each robot. This approach was able to receive video and location information of the robots and continue to maintain connectivity without using any pre-placed infrastructure.

Having certain designations for each robot is an approach similar to the work done by other researchers. In [135], researchers use mobile robots to construct an ad hoc network. They propose classification of robots as either search robots or relay robots. Search robots only look for victims of a disaster, while relay robots receive packets from the search robots and transmit them to the base station. In this design, relay robots are intermediate nodes and are only interested in transmitting packets. This requires, however, each robot to keep the communication links between itself and its neighbor robots live. If the communication link is broken, then the robot must move towards its neighbors to maintain the communication links.

The importance of maintaining communication links can best be explained through the example of exploration and rescue systems. After a disaster occurs, the areas that need to be accessed could be too dangerous or too obstructed for humans to enter. Moreover, existing communication infrastructure could be destroyed during a natural or man-made disaster. Thus, mobile robots might be used instead of humans to form an ad hoc network in order to get information about the area and victims. Network performance, however, can depend on the robot's motion in the area [9] and network performance is obviously very important in teleoperation. When a robot moves away from its neighbor robots and sensors, communication could be broken. As a result, network performance is affected because data cannot always be transmitted to its destination [155].

The degree of connectivity can play an important role in a WSRNT. In [136], the degree of connectivity is maintained by the mobile robots autonomously by using a gradient descent approach to the Friedler eigenvalue of a Laplacian matrix. The authors then allow for fine-tuning of the flexibility of the graph through a
human operator. Theoretically, the authors prove the stability of such a system, as well as run simulations to validate the analysis.

Fault tolerance is another aspect of WSRNT that can be extremely helpful. In order to be fault tolerant, a network must be at least biconnected so a loss of a single robot will not disconnect the network. To do this, the authors of [137] use the concept of virtual angular forces to act upon the robots to create a biconnected network while minimizing the distance traveled by the robots. These forces are able to maximize coverage by using repulsion, while at the same time using attraction to maintain connectivity. In [137], they were able to achieve biconnectivity in more than 90% of the cases up to 200 nodes.

### 5.4. Communication channel for teleoperation

As explained in the previous section, teleoperation requires a communication channel between the human operator and the robots in an environment. In a small-scale system, one may use a dedicated direct link from the human operator to each robot. In general, however, we need more cost-effective solutions that would allow the human operator to communicate with the mobile robots through a MRN. Due to involvement of MRNs in conjunction with other variable delay communication channels to connect the operator to the MRN, most of problems associated with teleoperation in WSRNT will be similar to problems in Internet-based teleoperation.

The first Internet-based teleoperation system was developed by Ken Goldberg in 1994 as part of the Mercury project [23]. Since then, this group has expanded on Internet-based teleoperation to include desktop control [23] as well as collaborative teleoperation via the Internet. With the Internet, multiple users were able to control a remote robot both simultaneously and separately [156]. The latest use of Internet-based teleoperation is associated with the robot TeleBot [138]. Here the authors tested the usability of TeleBot by creating a task-oriented user study which involved navigating TeleBot to a location and using TeleBot's arm to touch an “X” on a door. The users used two different forms of controlling TeleBot, namely a keyboard and a gamepad. In general, the gamepad was better able to control the robot as participants were able to complete the task faster, as well as with fewer errors. There are numerous problems, however, that come with using the Internet to control a remote robot. Among these problems are variable time-delay and data loss.

In general, the control of a system with variable time delay (jitter) is very difficult because the force feedback will be inconsistent. Earlier researchers tried to mitigate the jitter by simply considering the maximum round trip time and use it to design a worst-case controller, but the authors in [139] showed that such a system may remain unstable. Another approach to minimizing jitter is for the incoming packets to be stored in a buffer [140]. But, because of the delay, the performance will still suffer particularly in the case of real-time control. Performance problems due to packet loss, however, have been studied much less [141]. It had only been shown that an n-step predictor is able to compensate for some packet loss [143].

The authors of [141] note that while delay and jitter problems have been studied separately, their experiments were intended to get an idea of the effect on control systems of both problems simultaneously. The authors of [141] were able to show the difference between a local connection and a remote connection with respect to delay and jitter. The loss of packets, as well as delay and jitter, leads to a less smooth force applied to the remote robot because loss tends to destabilize a teleoperation system. This happens because a human operator tends to apply more force when a packet loss is perceived.

In [142], the authors attempt to analyze and predict the jitter associated with one-way time-delay for teleoperation systems. The problem with jitter is that it means control messages will get to the robot in an aperiodic way and thus terminate current commands in a delayed way. To mitigate this problem, time delay jitter should be known (or at least approximated) in advance. The authors analyze three different data sets statistically and then use this analysis to see if they can predict the jitter of these data sets. The maximum absolute prediction error was \(-5.1\) ms which shows that the sparse multivariate linear regression method can give precise estimation of the jitter even when the jitter values can change rapidly.

Another approach to action synchronization and control of telerobotic systems over the Internet is to use a non-time based scheme. Traditionally, the action reference used is time. In this case a task schedule or action plan with respect to time is used to describe the actions for the remote robot. This leads to synchronization issues due to clock skew, jitter, delay, and loss. To overcome such issues, the authors in [144] introduce a new type of clock to synchronize the actions of the operator and the remote robot. Specifically, instead of using time as an action reference, they propose an action plan for the remote robot which is parameterized by an event-based reference (e.g., a sensor measurement, such as distance traveled by the robot). This allows the stability of the system to be independent of both the human operator and randomized time delays. However, much work still needs to be done to show if a system using this new type of clock is stable enough to be viable in practice [145].

The main problems within teleoperation is the communication between the operator and the remote robot. Control messages must be sent to the remote robot and environment information must be sent back to the operator. In essence, these problems become harder and complicated because the flow from the operator to the robot (or vice versa) requires reliable and robust routing for the time-sensitive packets. In WSRNT the issues for communication are similar to what we have seen in Internet-based teleoperation systems. Variable delay of packets will be just as large of an issue in WSRNT as it is in Internet-based teleoperation. Another consideration required in WSRNT is the variability of wireless communication channels and the byproduct of such channels, dropped packets. Dropped packets are usually mitigated through retransmissions, but in WSRNT this will be a problem due to the energy constraints of the underlying WSN. Also, if time-reference action synchronization continues to be used for teleoperation, then clock drift in different sensors will be an issue that must be addressed to create a stable WSRNT.

When considering the flow of data from the robot back the operator, one must consider the dynamics of the environment in order to maintain smooth force feedback. Any teleoperation system in dynamic environments such as WSRNT is required to be adaptive as the underlying conditions are constantly changing. Adaptive control is used to transmit the correct force felt by the remote robot back to the operator in order to create telepresence. Telepresence is the degree to which an operator feels as if he is actually at the remote location. Transparent telepresence describes full telepresence. In other words, the operator feels that he is at the remote location and not at a different site. In essence, the force felt by the operator is the same as the force in the slave environment [157]. Adaptive Control has been extensively studied in teleoperation [158–160], but the advantages of using the information provided by WSNs to enhance adaptive control in WSRNT is a new unexplored area, calling for further research. Using the 4-channel approach to teleoperation, information from the environment is used to send the force data back to the operator. To do this in a WSN environment, one will need to decide on what to send from the WSN. In this case, data aggregation methods and selective data
sending can be used to synthesize data from the WSN to aid with improved telepresence.

6. Conclusions and future work

In recent years, there has been a growing trend in integrating WSNs and (tele-) robotics. In this survey, we have discussed current research efforts toward combining these complementary fields and discussed various open issues. Specifically, we reviewed the history and applications of WSNs, robotics, and teleoperation. We then introduced a system model integrating WSNs and multiple networked (tele-) robots, leading to a network which we define as a Wireless Sensor and Robot Network with Teleoperation (WSRNT). Using this model, we characterized the interactions between the components of WSRNT. We then considered several issues mainly related to communication and coordination mechanisms in WSRNT.

As can be seen, there are many areas associated with WSRNT which continue to be studied. One of key challenges in WSRNT would be the fact that the degree of autonomy in a robot will vary throughout the lifetime of the network. For example, while a mobile robot is autonomously helping to improve data collection, it might be called to perform some tasks under a human operator through teleoperation. These different degrees of autonomy will require different data to be collected and sent through the network. In general, switching the robots from fully-autonomous mode to human–controlled mode and vice versa will cause several challenging problems in managing the mobile robots. Managing these robots will require consideration of connectivity, QoS, and task allocation to name a few.

The future for WSRNT is promising due to the complementary nature of (tele) robotics and WSNs. A system integrating both can be used to replace a human presence in areas too dangerous to send humans. This complementary nature merits further study of applications that could benefit from these uses, such as search and rescue or military operations to name a few. Research into energy efficient realtime protocols and control mechanisms will spur these networks forward into more practical and wide-ranging applications. This requires energy aware systems that continue to provide the necessary QoS required by teleoperation systems. Advancing technologies and production will help the furtherance of WSRNT research.

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