TARANTULAS: Mobility-enhanced Wireless Sensor-Actuator Networks

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Abstract

Amidst the numerous active research efforts in wireless sensor networks which aim to push beyond the limits, we aim to significantly enhance the effectiveness of wireless sensors by integrating controlled mobility to realize a networked system of mobile sensors that functions collectively as an integrated unit. The All-teRrain Advanced NeTwork of Ubiquitous mobiLe Asynchronous Systems (TARANTULAS) project builds a system of networked wireless sensors and actuators carried on mobile robots that are able to operate in all kinds of terrain. To achieve this objective involves the integration of three key research areas: robotics, ad hoc networking and, localization and positioning. We not only use the robots to improve the connectivity and localization of the sensor networks, they concurrently search for targets. In this paper, we present key elements of the algorithms and technologies developed by the project. In particular, we show that the mobile robots and static nodes mutually support each other: robots move to fill the communication gaps to enhance connectivity and localization while static nodes serve as landmark nodes to help robots search for targets.

Keywords: Sensor-Actuator Networks, Collaborative robotics, TARANTULAS

1. Introduction

The envisaged flexibility and ease of deployment of wireless sensor networks are some of the reasons for its numerous applications, such as, smart home environment, meetings/conferencing, inventory, indoor location and tracking, industrial sensors and several military applications. Furthermore, it is envisaged that such distributed sensor systems would have actuation capabilities to physically perform tasks and thereby increasing further their usefulness. Sensor and actuator networks are expected to provide high quality information ranging from physical quantities such as seismic data, acoustic data, high-resolution surveillance images such as an intruder entering an area, and critical information in search and rescue operations during disasters. Such capabilities would be facilitated by a more pro-active mode of deployment, e.g. using small intelligent mobile robots.

In this paper, we present key technical elements of the All-teRrain Advanced Network of Ubiquitous mobiLe Asynchronous Systems (TARANTULAS) project which aims to develop a system of networked wireless sensors and actuators carried on mobile robots that are able to operate in all kinds of terrain. To achieve this objective involves the challenging task of integrating technologies from three key research areas: robotics, ad hoc networking and, localization and positioning. Essentially, we use the mobile robots to improve the connectivity and localization of the sensor network, and concurrently search for targets. In particular, we demonstrate that the mobile robots and static nodes mutually support each other whereby robots move to fill the communication gaps to enhance connectivity and localization while static nodes serve as landmark nodes to help robots search for targets.

1.1 Related Work

While research on the abovementioned areas has progressed rapidly, there have been few efforts to realize a truly integrated system of collaborative robots that communicate and work with a deployed sensor network to accomplish a common goal.

The closest effort in this direction is DARPA's Software for Distributed Robotics program which aims to develop coordinated behaviours and effective user interfaces to realize large groups of small robots working together to accomplish a collective task. Efforts such as Centibots developed a framework for very large teams of costly robots that are able to perceive, explore, plan and collaborate in unknown environments [7]. Multi-robot systems that include sensor nodes and aerial/ground robots networked together have been proposed for tasks such as large scale environmental monitoring or for command and control in emergency situations [6]. But, the use of broadcast based communications may incur massive communication overheads if the network is large, thus severely limiting their scalability.

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1.2 Goals and Organization

The goal of this project is to develop the algorithms and techniques that can be easily adapted and applied on commercially available hardware and readily deployed in realistic scenarios. In this paper, we present key elements of algorithms and technologies developed by the project. We describe the approach taken and reference architecture. Then, we present the methodology and techniques used.

2. Approach and Reference Architecture

In many typical sensor network applications, location information is a critical component that cannot be easily obtained from infrastructure-based schemes like GPS or preinstalled beacons which have been destroyed. Localization has been addressed by the robotics and communications community using very different approaches. In robotics, a well-known technique is Simultaneous Localization and Mapping (SLAM) [2] while in communications, a node gets information from various reference points (or beacons) and tries to infer its location from those know reference points. Due to the harsh multipath environment that we are addressing, we focus on range-free techniques for localization, namely, hop-count based schemes [8]. Typical hop-count based schemes unfortunately fail for highly irregular network topologies, i.e. sensor networks with non-uniform node densities, where the variance in actual hop-distance is very large. Hence, a density-aware hop-count localization scheme [3] has been developed to overcome this shortcoming and for it to be deployable in realistic scenarios.

For the purpose of discussion, we assume a large indoor environment, e.g. as shown in Figure 1 which shows the floor area with rooms, and entrances into the area from either side. The multiple mobile robots (with rays defining the sensing range) enter to explore and map the area, to search for targets (e.g. trapped or unconscious victims in a burning building) and perform tasks, like deploying sensors to enhance communications and localization, undertake first level visual assessment of victims' conditions using cameras and other sensors carried by the robots, etc. Prior to sending the mobile robots into the area, beacons with accurate location information are located at the four corners outside the perimeter of the area. Similarly, sensors can be scattered in the area through windows or other openings but such a deployment strategy is unlikely to ensure sufficient coverage. Next, the mobile sensors will move into the area to perform multiple concurrent tasks; key tasks include: search for targets (victims) and communicate their locations back to the control centre (remote console) via multihop routing; identify critical areas where sensor network communications and coverage is poor (be it due to low node density or strong interference) which also results in poor localization and deploy new sensor nodes to bridge communication gaps, enhance localization, and improve coverage; and, mark areas that have been searched and communicate the status to other mobile sensors so that the same space will not be repeatedly searched by different mobile sensors.

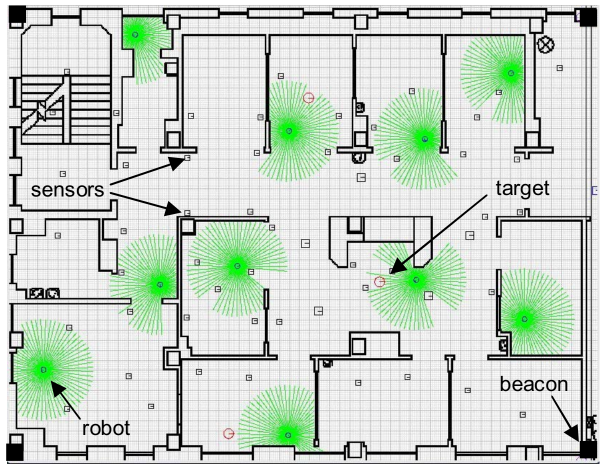


Figure 1. Typical Indoor Deployment Environment

The uniqueness of our wireless sensor network architecture lies in the hybrid mobile/static network comprising a number of mobile sensors that work closely with the significantly larger number of static nodes to provide coverage of an area by maximizing the overall network connectivity through controlled mobility. The static sensor network can be viewed as a supporting infrastructure for the mobile sensors which are able to provide better coverage. By combining the controlled mobility of mobile robots, we are able to enhance the connectivity and performance of typical sensor networks which in a realistic deployment scenario is unlikely to be ideally distributed. Conversely, the sensor network is able to assist the mobile robots by providing beacons to help the robots in their navigation without the need for them to perform localization themselves. Similar attempts have been made to use beacons embedded in the environment and assumed to provide location information [4]. However, such assumptions are hard to realize in a realistic scenario and we avoid this assumption. Instead, we adopt an approach where the sensor network performs localization after deployment, and the localization accuracy is continually improved with the assistance of the mobile robots which in turn uses the sensors as beacons for navigation. The mobile and static sensors are therefore mutually cooperating to enhance each other's performance.

3. Methodology

Wireless sensors are randomly deployed over the area to be searched, e.g. dispersed into the area through windows and/or other openings in the walls/partitions, resulting in more sensors cluttered near these points and few sensors located further away.

3.1 Density-aware Hop-count Localization

After the initial deployment, the wireless sensors localize themselves using a density-aware hop-count localization scheme [3]. The success of this and other schemes depends heavily on the network being connected. Depending on the degree of connectivity and sensor distribution, the localization process may not be able to provide good location estimation or even fail totally if sensors are unable to find paths to at least three of the reference beacons.

3.2 Identifying Critical Communication Gaps

The mobile sensors then enter the area to be searched and spread themselves apart to maximize coverage [5]. The mobile sensors search for both targets (e.g. victims) and critical communication gaps among the static wireless sensor nodes. While searching for targets can be arguably more important from the application viewpoint, the need to ensure network connectivity is equally important for information regarding targets to be reliably delivered to the control centre for critical decision making.

After the localization phase described in the previous section, every sensor node keeps an *n*-tuple record of its hopcount distances from all the *n* beacons (here, n=4 since there are 4 beacons, and the initial hopcount values are set to a large number.) A pair of sensors that are adjacent and within each other's transmission range will have their *n*-tuple hopcounts differing by not more than one. Each sensor transmits periodic Hello messages, which carry this *n*-tuple, to announce its presence to other nodes nearby.

As a mobile sensor explores the area, it constantly listens for transmissions from the sensor nodes as well as detects their presence using its other onboard sensors. If a mobile sensor receives largely differing *n*-tuple hopcounts from sensors around it, it identifies the area as a critical region. It then tries to find a suitable spot to bridge the gap by deploying a new sensor. The newly deployed sensor will then broadcast a localization packet to update the *n*-tuple hopcounts in the sensors around the region; sensors that receive this packet will update their *n*-tuple records (with lower hopcounts indicating that shorter paths to the beacons have been established) and propagate the packet further, or drop the packet if no change is needed.

3.3 Cooperative Search Algorithms

To improve the connectivity and localization of the sensor networks, the mobile nodes need to find the communication gaps; to accomplish the mission, e.g., surveillance, the mobile nodes need to find targets. Therefore, the main task of the mobile nodes is to search for the targets (e.g. victims) and communication gaps completely and efficiently. In the reference architecture, the gaps and targets are typically stationary which makes the searching problem identical to the exploration problem that aims to maximize the coverage of the entire area by shortest travel length.

Our goal is to develop algorithms to be applied to real sensor networks and mobile robots, which are commercially available. In this paper, we propose three kinds of search models for the multiple robots/nodes to cooperatively search for communication gaps and targets in the reference architecture.

3.3.1 Potential field based searching

The idea of potential field based search is to assume the obstacles and neighbor nodes (both mobile and static) as repulsive force sources and let the mobile nodes move under these forces, such that the mobile nodes can be dispersed within the whole area [1]. However, when the mobile nodes are only influenced by the repulsive forces and if there are no repulsive forces (no obstacles nearby) or the repulsive forces are balanced (in equilibrium states), the mobile nodes will not move to further explore the environment. To overcome this, we calculate the summation of the forces ($\vec{F}_{sum}$) to drive the mobile nodes in searching as shown in Eqn (1) where, $\vec{T}_{Random}$ is the attractive force randomly applied to make the mobile node move, $\vec{R}_i$ is the repulsive force from neighbor mobile node *i*, and $\vec{O}_j$ is the repulsive force from obstacle *j*.

$$\vec{F}_{sum} = \vec{T}_{Random} - \sum_i \vec{R}_i - \sum_j \vec{O}_j \qquad (1)$$

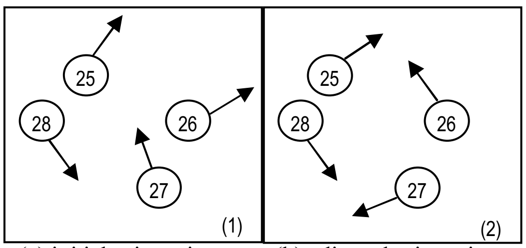
Since the proposed potential field based search only relies on local sensing by the mobile node, it is totally distributed and scalable for any number of mobile nodes. However, cooperation in searching is at a low level since there is no communications among mobile nodes. Nodes may repeatedly search in the same area resulting in poor coverage of the whole region.

3.3.2 Swarm-like searching with collaboration

Swarm intelligence based search is proposed to solve the problem faced by potential field based search using the following methodology: when a sensor, *i*, is moving, it will periodically broadcast its ID (*i*) and heading (H_i) to its neighbors. This is a one-hop broadcast that is only heard by the neighbors. At the same time, when a sensor is moving, it also keeps listening to the wireless channel and can receive the neighbors' broadcasts. Algorithm 1 shows how a mobile sensor changes its heading according to its neighbors' broadcast. R is the ID of the nearest neighboring mobile sensor. Initially R is set to infinite (∞) to indicate there are no neighbors.

```
Input ( i : sensor_id )
1.  Set initial values: R_neighbor = ∞,
2.  Repeatedly listen for a period of time
        if something is heard from neighbor j
            if (j > i) and (j < R_neighbor)
                let R_neighbor =j,  H_neighbor= H_j
3.  if R_neighbor • ∞,
        change heading to H_i = H_neighbor+ 90 degree
4.  goto 1.
```

Algorithm 1: Swarm-like intelligence for searching



(a) initial orientations (b) adjusted orientations

Figure 2. Inter-mobile Sensor Intelligent Searching

Based on Algorithm 1, a mobile sensor will change its heading only if its neighbor's ID is higher. If the sensor has more than one neighbor with higher ID, it will change its heading with respect to the closest higher ID. Figure 2(a) shows the initial headings of four mobile sensors while Figure 2(b) their adjusted headings after applying Algorithm 1.

3.3.3 Intelligent Searching with collaboration

To enable the mobile sensors to search effectively, it is important to let the sensors search the uncovered region. Without the need to build a map of the area we propose inter mobile-static sensor intelligence to avoid re-searching of covered regions and encourage the searching of uncovered regions. The scheme lets some static sensors serve as landmarks, which can remember the visit history of their neighborhood, and share this information with sensors moving into the vicinity to help them decide the search regions.

As a mobile sensor moves, it detects its neighboring static sensors (landmark nodes) and sends its relative orientation and location to these sensors. Using this information, the static sensor (landmark node) computes the relative locations of mobile sensors, updates this information in its own memory and periodically broadcasts to its mobile neighbors. When a mobile sensor receives the broadcast from a landmark node, it will decide which direction to move based on this information.

4. Conclusions and Future Work

In this paper, we presented the TARANTULAS project which has developed a heterogeneous system of mobile and static wireless sensors. The novelty of the system lies in the collaboration among the sensors to maximize network connectivity to improve localization that in turn improves the sensing capabilities of the mobile sensors. We proposed three search algorithms without mapping that are distributed in nature and therefore control is simple and scalable. The potential field based search algorithm and swarm-like searching algorithm only rely on cooperation among mobile nodes while intelligent searching involves cooperation among mobile and static nodes. Since the static nodes can be seen as landmarks, theoretically this algorithm can achieve comparable performance as the searching algorithm with map building, and the route of the searching robot would be more deterministic than potential field based searching and swarm-like searching. The performance of our system has been validated using simulation studies, and experimentally with proof-of-concept prototypes.

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