Design and Implementation of a Novel Cost-effective Fall Detection and Intervention System for Independent Living based on Wireless Sensor Network Technologies

A. Liu Cheng, C. Georgoulas, and T. Bock

Chair for Building Realization and Robotics, Technische Universität München, Germany
E-mail: alex.liu-cheng@tum.de, christos.georgoulas@br2.ar.tum.de, thomas.bock@br2.ar.tum.de

ABSTRACT

Physical and cognitive decline associated with the natural aging process require the implementation of integrated and ambulant assistive technologies for the elderly to sustain independence with respect to Activities of Daily Living (ADLs). These technologies, framed in the context of Ambient Assisted Living (AAL), instantiate environments where sensor modules and robotic agents mitigate and/or compensate for the declining dexterity and diminishing strength of the occupants. Research trends in this field suggest the importance of such assistive services, especially considering that all emerging industrial nations are experiencing aging-related demographic change. In this paper the authors propose the design and implementation of a low cost, *ad hoc* Wireless Sensor Network (WSN) system that integrates seamlessly into a WiFi-dependent mobile rover (i.e., TurtleBot) system, effectively creating a versatile yet robust *de facto* Cyber-Physical Network (CPN) where gathered WSN sense-data is used to trigger events in the rover. The system will first be outlined, followed by a detailing of a concrete use-case example, where a laser emitted from one WSN module to a series of photosensitive sensors in another is used to detect the presence and location of unexpected objects (e.g., collapsed person and/or furniture etc.); and where the rover is instructed to autonomously navigate to this location to further ascertain the status of said object(s). The example intends to illustrate the potential of a multi-layered, energy-efficient, self-configurable, scalable and reliable sensing-actuating system that can be added to existing WiFi networks without technical difficulty or network modifications.

Keywords –
Wireless Sensor Networks; Cyber-Physical Network; Ambient Assisted Living; Fall detection

Introduction

When people enter a stage of physical and cognitive decline typically associated with the natural aging process, their independence with respect to Activities of Daily Living (ADLs) becomes difficult to sustain [1]. If no intervention or mitigation solutions are proposed, this decline may progress prematurely and unnecessarily to the point where those affected lose the ability to care for themselves and to live independently at home. From a practical and logistical standpoint, this can become an unexpected burden to family members and/or an additional load to institutionalized nursing-care systems. These considerations are particularly important since every emerging industrial nation is experiencing a debilitating age-related demographic change [2]. Intelligent and economical solutions with respect to AmI and AAL are therefore necessary to promote and sustain a healthy independence and an active lifestyle.

There exist robotized and intelligent AAL solutions—e.g., *RoboticRoom* [3], *Wabot-House* [4], *The Aware Home* [5]—as well as ambitious AmI and AAL implementation proposals that make use of sensor networks for intelligent robots [6]. But however promising these solutions may be, their cost still makes them available to only a minority of the aging population. One reason why these and other present solutions are costly is because the research and industry sectors tend to view them as "complete solutions", "often including overlapping of almost equal or homogeneous sensors." [7]. Another reason is because the computation of self-learning methods requires considerable infrastructure to produce a useful dataset from which to draw substantial conclusions. In recent research projects such as SAMDY [8] and eHome [9], these system costs alone "are estimated [to be] between 3,500 EUR and 5,000 EUR" [10]. Yet another reason is that AmI / AAL solutions require customized planning and installation by experts, which in part cause the "enormous costs of today's single solutions[,] which are too expensive for private buyers as well as health and care insurance providers." [11]. Moreover, activity-monitoring in AAL requires the implementation of a system that is able to track the movement and positions of the user. On the whole, indoor tracking solutions, based on triangulation methods etc., provide strong and reliable performance. But “these architectures require structured environments and consequently high installation costs” [12].

Ad hoc WSN solutions, however, provide a viable alternative. These WSNs do away with the notion that AAL solutions must be “complete solutions” where sensors and actuators are deeply embedded and integrated into the very architecture. By virtue of their *ad hoc* character, these WSNs can be implemented virtually in any environment, whether indoors or outdoors, and require little (at worst) or no (at best) modifications to the environment’s architecture. Moreover, WSNs are decentralized solutions that avoid the high-costs generally associated with highly integrated systems. Georgoulas, Linner, Kasatkin, & Bock [13] showed that a solution that seeks to reduce complexity of functions—and therefore cost—should be one that does not have all services and functions centralized in a service robot or in a static location, but rather one that strategically distributes services along a decentralized controlled environment. Furthermore, *ad hoc* WSNs are more energy efficient, and sensor nodes can be configured to shut down at particular intervals depending on particular needs and/or the desired sense-data resolution. This is a significant advantage over sensor nodes running on a wired or WiFi system, since these latter cannot be intermittently turned off without sacrificing performance and functionality.

In a recent overview of “emerging concepts in collective sensing”, Badi & Mahgoub [14] identify four main requirements for *ad hoc* WSNs:

1. *Low energy-consumption*—sensors are typically battery powered;
2. *Self-configurability*—Either due to failure, energy exhaustion, or general malfunction of nodes, the network must be able to reconfigure itself. [14];
3. *Scalability*—the theoretical limit of the number of nodes in a network is determined only by the controller’s ability to process the information effectively and efficiently in a timely manner; and
4. *Reliability*—Wireless Sensors, from individual components (i.e., *Sensor, Controller, Transceiver, External memory,* and *Power source*) to their deployment in WSNs must perform in a consistently robust way with minimal failure (counter-measured, perhaps, with a justified degree of redundancy).

Over the last decade, work on Wireless Sensors and WSNs, particularly in the last five years (see for example, [15–19]) demonstrate excellent performance and reliability, giving them a solid track-record for future development. Furthermore, Badi & Mahgoub suggest that CPNs, which involve the integration of sensing and physical processes, are an extension of WSNs [14]. This agrees with current trends, where robotized agents constantly inform and are informed by wireless sensors.

Concept and Approach

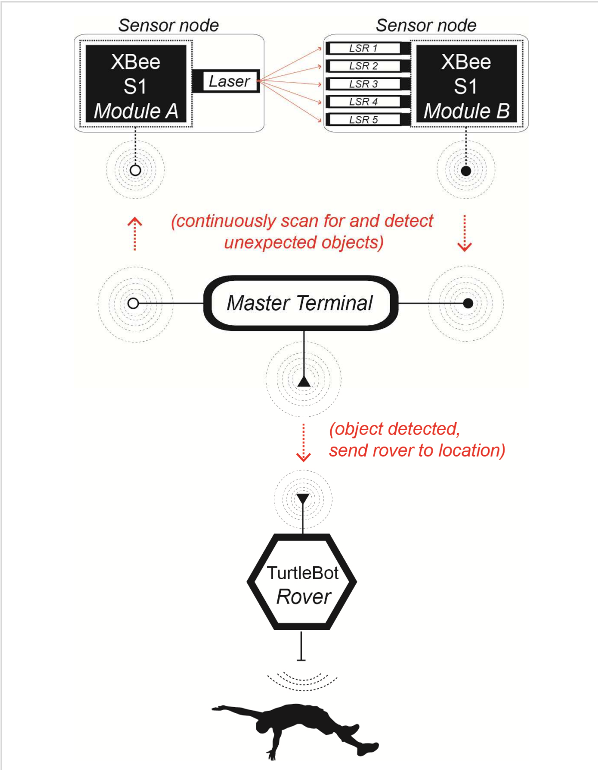

Figure 1. Diagram of overall concept.

The present paper describes a CPN based on the tandem and complementary operation of a set of *XBee S1*-based WSNs and a WiFi-dependent rover, where the WSNs are responsible for the gathering and transferring of sensed-data, whose processed output is used to trigger events in the rover via SSH commands on a WiFi network. This distribution of tasks is attuned to the strengths of each technology. *XBee*-based WSN modules are energy-efficient, can be battery-powered, and turn on and off as required by the system or as predetermined by the user. WiFi networks, on the other hand, are designed to maintain a continuous high-speed and high-bandwidth connection idea for power-hungry applications such as those involving live high-definition audio and video streaming.

Admittedly, there is a particular simplicity in solutions that base their communication on a single technology. But this simplicity does not justify the resulting staggering inefficiency. Moreover, this apparent simplicity does not translate into economy, for a sensor network based on WiFi-dependent modules would be much more expensive to build, run, and maintain. Nor would it translate to efficiency, for an *XBee*-based WSN would not be able to perform at a WiFi network's *baud* rate without depleting its energy prematurely, not to mention that *XBee*'s bandwidth is considerably smaller than that of WiFi's. Similar remarks can be made of solutions based on any other single technology, may this be RFID or Bluetooth etc. An intelligent solution will use a variety of technologies appropriate to or required by the scope, scale, and magnitude of given tasks.

The work detailed in this paper partly builds on a WiFi-dependent assistive robotic system previously developed and deployed [20] at a real scale (i.e., 1:1) AAL environment in the *Robotic Laboratory* (see Figure 2) of the *Chair for Building Realization and Robotics* (BR^2) at *Technische Universität München* (TUM). The feature of this system pertinent to the present work consisted in a TurtleBot rover being controlled via a *Graphical User Interface* (GUI) that triggered *Secure Shell* (SSH) commands to execute *Robot Operating System* (ROS) routines from a central terminal. These routines would take the rover to a series of predetermined destinations, specified by the coordinates of the environment's map previously generated in ROS's proprietary 3D visualization tool, *Rviz*. In the present work, the authors have added an *ad hoc* WSN layer that feeds sensed-data to the same central terminal from which SSH commands are sent to the rover via WiFi.

Figure 2. 1:1 scale AAL environment in BR^2's Robotic Laboratory at TUM.

In order to demonstrate the potentials of *ad hoc* WSNs, the modules in the added WSN layer are concerned with detecting unexpected objects and their specific locations via a laser reflectivity scheme developed by Pyo, Hasegawa, Tsuji, Kurazume, & Morooka [21]. However, it is worth noting that the present work's implementation does not use a *laser range finder* as in Pyo *et al.*'s [21]. Instead, it uses a low-cost laser and a series of *Light Sensitive Resistors* (LSRs). The detected unexpected objects, for example, could represent elderly people who have accidentally collapsed. Once the sensed-data is sent to the central terminal, the system can determine the *Rviz* coordinates for the unexpected object. An SSH command is triggered to instruct the rover to arrive at the specified coordinates to further verify and confirm the status of the object (both tactile confirmation via contact sensors as well as visual confirmation via the TurtleBot's Microsoft *Kinect* camera). If the unexpected object is confirmed to be an article of furniture—via an examination of its approximate dimensions, for example—that tipped over, the rover's returned confirmation to the central terminal, which will instruct the WSN modules to ignore the object and to consider it accounted for. If, however, there is a high probability that the object is a collapsed person, the rover's returned confirmation to the central terminal will cause it to adopt a variety of appropriate and urgent measures such as contacting care-takers and/or emergency workers.

Methodology and Implementation

The following steps will detail the methodology and implementation of the *ad hoc* WSN system, since the development and deployment of the underlying WiFi-dependent rover system has already been described in detail elsewhere [20]:

First, the authors used a set of *Digi XBee* shields, each with a set of *XBee S1* antennas—one on the shield and another on the *XBee Explorer* dongle connected to the central terminal (see Figure 3)—and corresponding microcontrollers to create Modules A and B (see Figure 4).

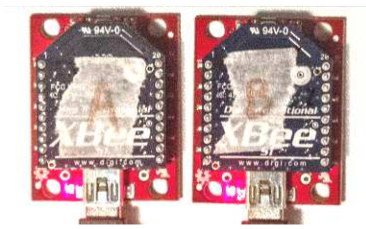

Figure 3. *XBee Explorer* dongles corresponding to Modules A and B.

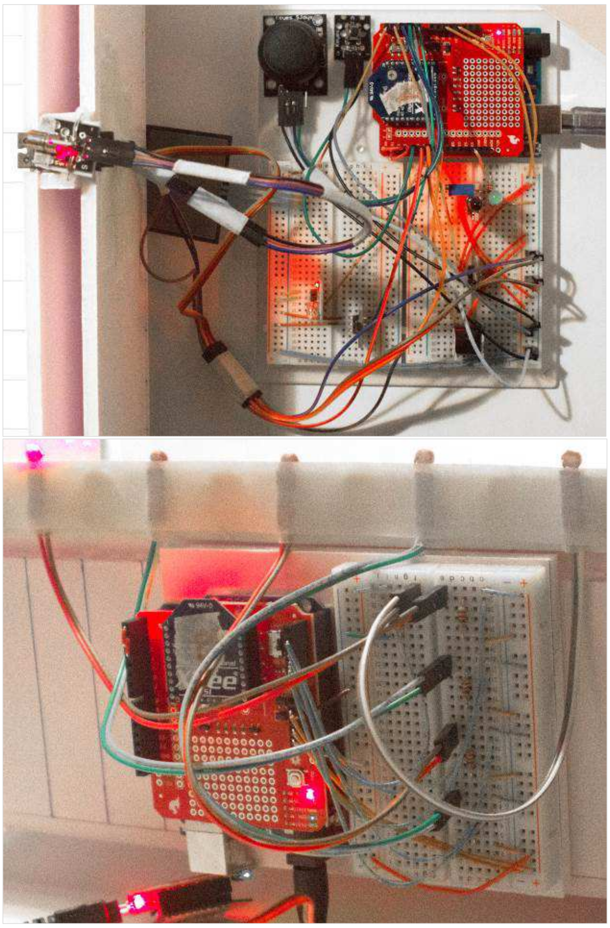

Figure 4. *Top*: Module A. *Bottom*: Module B.

Digi's proprietary *XCTU* software is required to pair *XBee S1* antennas by matching *Personal Area Network* (PAN) IDs together and to make sure that their *baud* rate be configured to 9600—faster rates consume excessive power without providing significant performance enhancement, which is an important consideration for battery-powered *ad hoc* WSN modules. After this, the dongles in Figure 3 are matched to Modules A and B in Figure 4.

Module A bears a variety of low-cost sensors (see Figure 5) and a laser component. There may be different sensor-combinations, depending on the function(s).

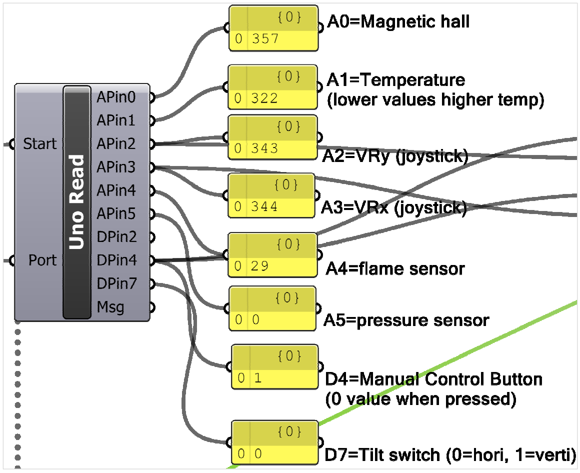

Figure 5. Sensed-data from Module A (in *McNeel's Rhino 5.0* & the plug-ins *Grasshopper + Firefly*).

These sensors work in concert to improve the probability resolution of potential emergency events. For example, if the *infrared* sensor detects a particular reading associated with a predetermined dangerous threshold, it may or may not mean that there is an unintended fire within its range. But if this reading is correlated with similarly alarming readings from *smoke-detection* sensor and a *temperature* sensor, then the probability of an accurate unintended fire-related event increases. All readings from these sensors are monitored and recorded in the central terminal over a user-specified amount of time. Module A's laser component, which is linked to a micro-servo controller that enables its 180º rotation, is the only component in the module that requires another module (i.e., Module B) to serve its purpose. Module A's laser is capable of finding the rotation angle at which it will find each LSR from Module B. Once detected by the LSRs, the data is read by Module B and fed to the central terminal, thereby closing the loop—i.e., Module A and B share no physical connection, yet their independent readings are fused together in the same central terminal to ascertain particular conclusions.

Second, a simplified scaled-model of the AAL environment was built to test the system. Module A was put at one longitudinal end of the model and Module B with its corresponding LSRs on the other (see Figure 6).

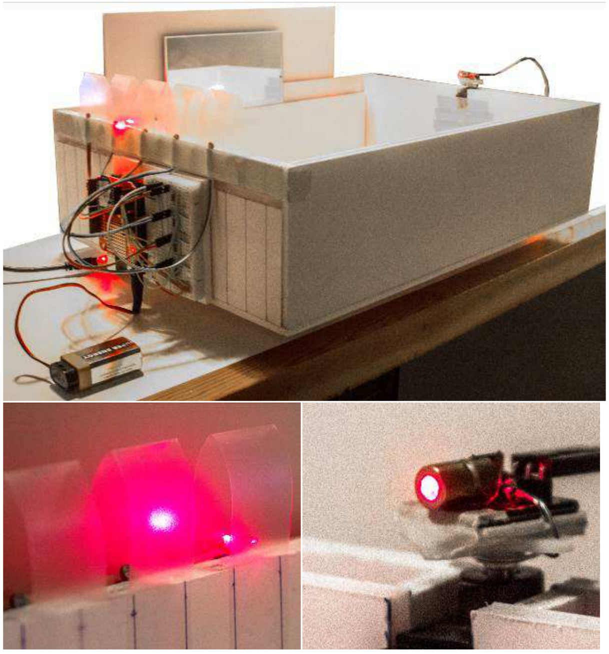

Figure 6. *Top*: Scaled-model of the AAL apartment at BR^2's Robotics Lab. *Bottom-left*: Module B's LSR 2 detecting a significant laser incidence. *Bottom-right*: Module A's laser component.

Module B reads the values of five LSRs. It would be possible, of course, to have more. But for present purposes this number suffices to demonstrate the feasibility of the concept. LSRs were chosen for their low-cost and simplicity. One possible criticism against their use would be that their readings are influenced not only by Module A's laser but also by the surrounding environmental lighting conditions, whether natural or artificial. While this is true, it is not a real impediment. Module B does not look for a specific value-range with a fixed mean-value to deviate from in order to confirm a sensed-laser event. Instead, it first looks at the average values gathered by all LSRs in the use-case environment before the laser is triggered; it then checks to see if at any given moment any of the LSRs deviate excessively from this mean. For example, the average LSR readings for the experiment's environment ranged from 58 to 72 (in the microcontroller's analog input scale—i.e., 0-1023—and using 220 ohm resistors for the LSRs in an average indoor-illumination laboratory environment.) As soon as Module A's laser struck Module B's LSR 1, the corresponding reading spiked to 588 (see Figure 7).

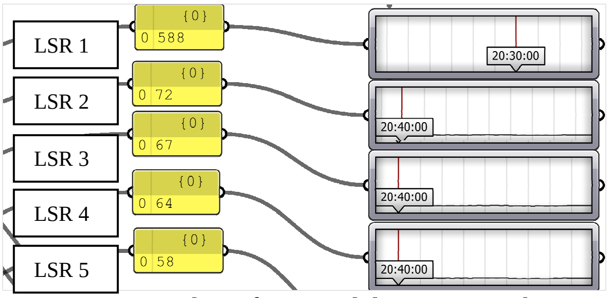

Figure 7. Readings from Module B's LSR, where a direct laser beam is detected by LSR 1.

It would be very difficult to survive in an environment where the average mean-value of an LSR were constantly around 588. Therefore even if the environment were to be twice or thrice as bright as that of the conditions present in this experiment, the spike of 588 on LSR 1 would still be considered anomalous, and therefore probably influenced by a light-source other than the environment.

Since the LSRs are spaced at specific distances from one another, the central terminal controlling Module A's laser component's rotation can ascertain at which degrees it will touch each LSR. It is important to note, however, that even if the LSRs were not distributed at specific distances, Module A's laser would still be able to determine at which degrees it found each LSR by simply scanning its horizon in a complete 180 degrees (or 360 degrees, if the laser's rotation origin should be at the center of a room). Once found, the degrees would be stored in the central terminal for future reference. This is important since the system needs this information in order to compute the coordinates of unexpected objects etc. to send to the rover.

The scaled-model's setup represents a typical enclosed environment with four boundaries. The laser rotates around the middle (with respect to *Plan* view) of the wall on which it is installed. The boundary opposite to this is where the LSRs are found, and one of the lateral boundaries contains a mirror to identify intersections via laser reflection. The right boundary (with respect to the origin of the laser) has been chosen in the present experiment. In the concept as outlined by Pyo *et al.* [21], the laser first shoots directly across to the opposite boundary to register a reading with the corresponding LSRs. The laser then turns to the mirror and rotates within this latter's extents in order to strike the LSRs indirectly. The laser's direct and indirect lines of sight create theoretical intersections (see Figure 8). In this experiment, the authors have focused on only a small area of the scaled-apartment. But it can be imagined that the area in question would be much larger if the entire right boundary were a continuous mirror.

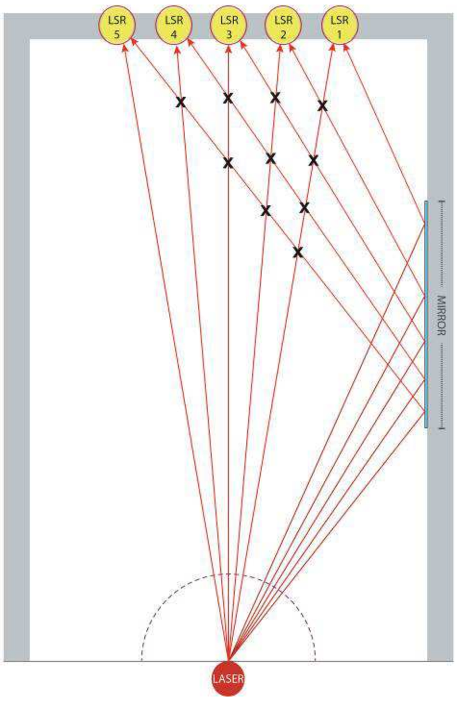

Figure 8. Conceptual illustration of scaled-model using Pyo *et al.*'s [21] proposed method. **X**s indicate theoretical intersections.

Imagine a case where the laser is detected in direct line of sight at LSRs 2, 3, 4, and 5, but not at 1. This would mean that at least one object is blocking LSR 1's line of sight. But *where* along this line (see Figure 9)?

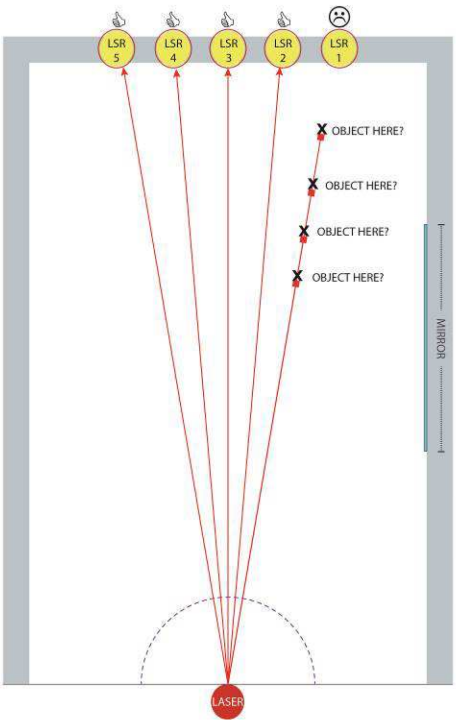

Figure 9. LSR 1's ambiguous blockage.

This is why using the laser's direct line of sight alone is not enough to ascertain precise planar coordinates. This issue disappears if indirect (i.e., reflected) lines of sight are considered. In this example, the planar position of the obstructing object is found by the absence of laser detection in the direct line of sight for LSR 1 *in conjunction with* the indirect line of sight for LSR 3 (see Figure 10).

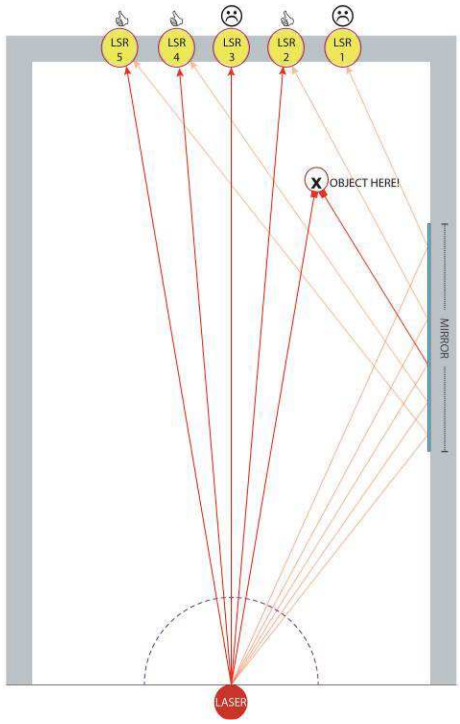

Figure 10. Finding the obstructing object with LSR 1's direct and LSR 3's indirect (i.e., reflected) lines of sight.

The recorded values of direct hits over time (see Figure 11) show that LSRs 2-5 were struck by the laser at several instances over a period, but that LSR 1 never registered any significant hits in that period.

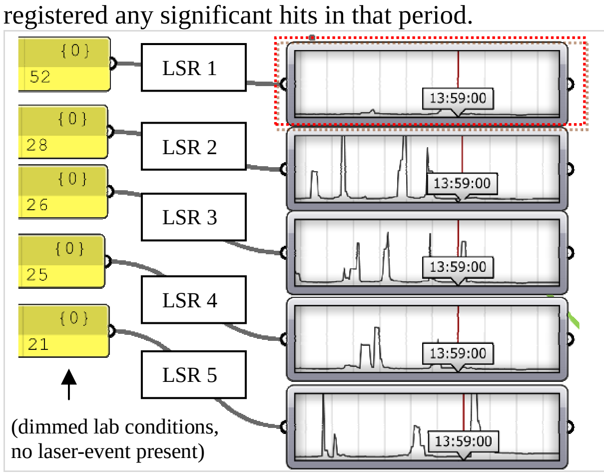

Figure 11. Recorded LSR values over time.

The anticipated effectiveness of this concept can be observed in the results obtained from various trials with the physical scaled-model (see Figure 12), which will be discussed at the end of the paper.

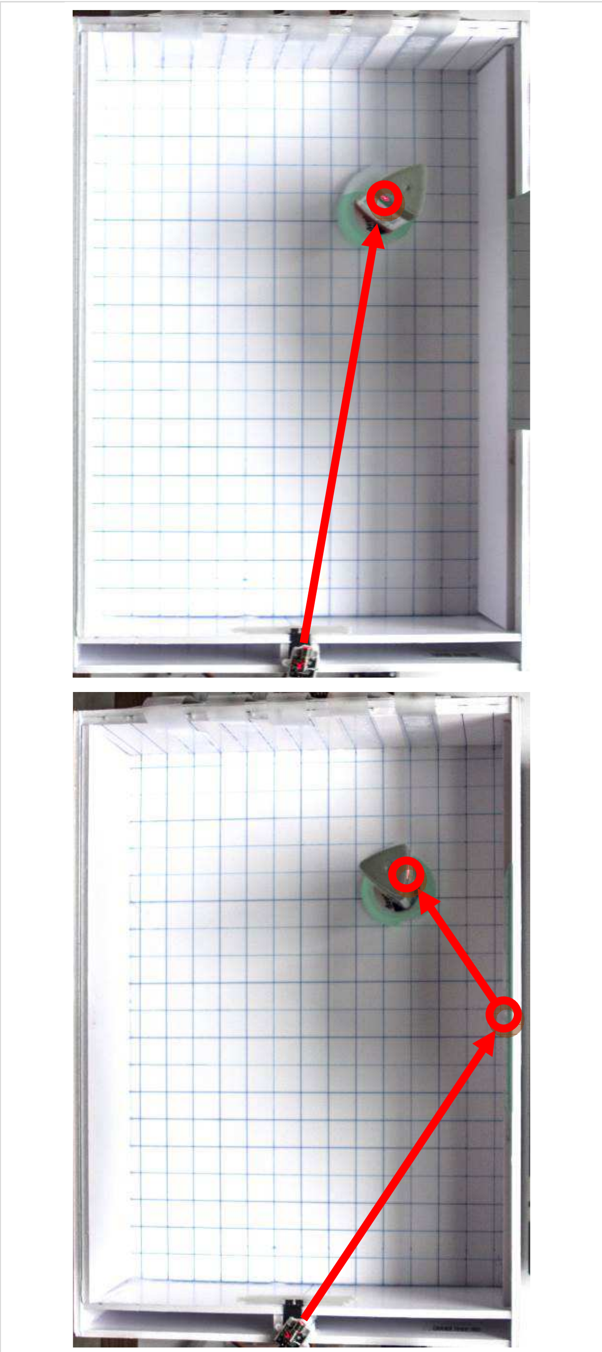

Figure 12. Physical scaled-model version of Figure 10. *Top*: Object blocking LSR 1's direct line of sight. *Bottom*: Object blocking LSR 3's indirect (i.e., reflected) line of sight.

Now that an unexpected object was detected at the intersection of LSR 1's direct and LSR 3's indirect (i.e., reflected) lines of sight, the system uses basic trigonometry to find the object's *X*- and *Y*-translations with respect to the *origin* at the laser's rotation pivot (see Figure 13).

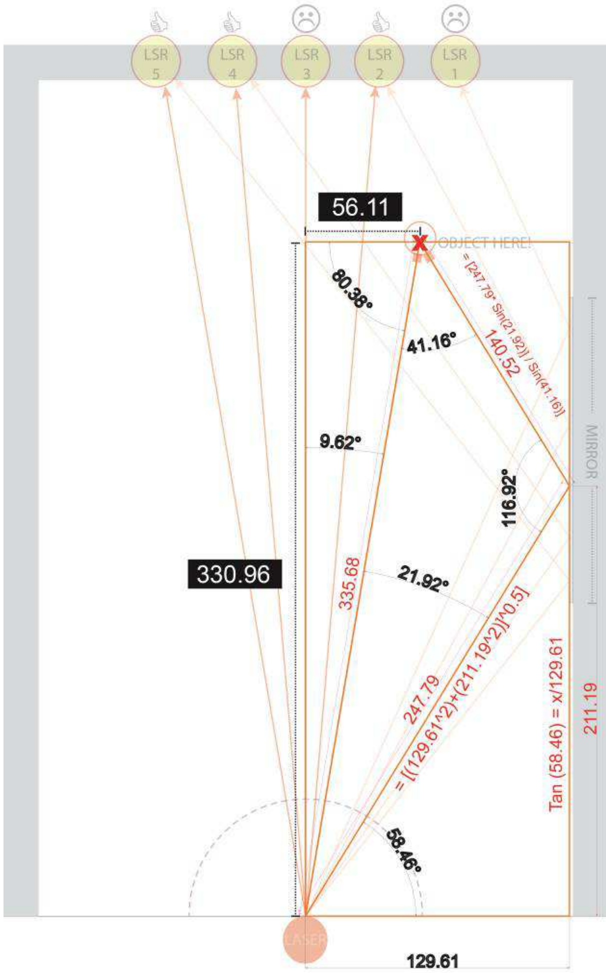

Figure 13. Calculations to find the planar position of the obstructing object (scaled-model units in millimeters).

Finally, once the *X*- and *Y-translations* are known, the rover may be provided with and guided to corresponding and/or equivalent coordinates relative to the real-scale apartment's map generated in *Rviz* (see Figure 14).

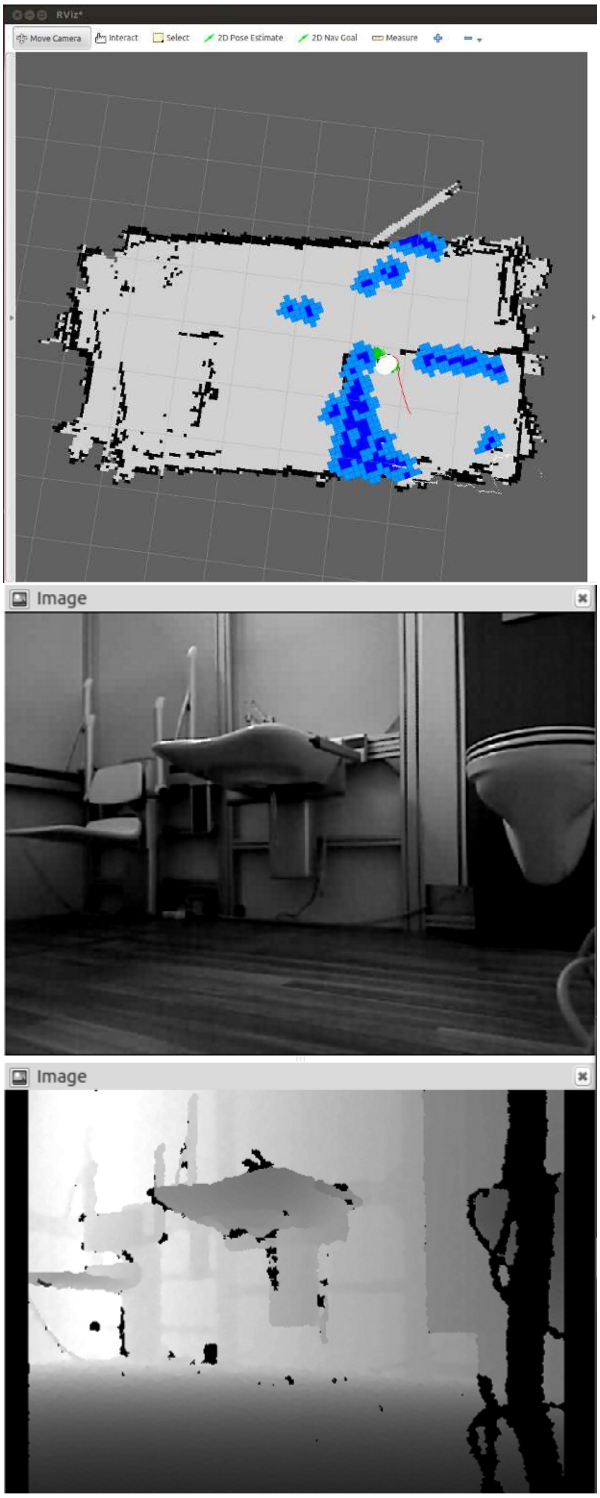

Figure 14. Visualization of the mobile rover navigation to the designated target point, according to the equivalence between the scaled-model and Rviz map

Discussion and Conclusions

Given the scale of the physical model and the simplicity of the laser-reflectivity scheme, the system was able to detect an object at any theoretical intersection point every time. This was expected, as the laser rotation angles are fixed to the line of sight of the LSRs, if it succeeded in finding LSR 1 one time it would succeed every time until the micro-servo controller suffered a mechanical failure, and/or the LSR was damaged, and/or the laser simply burnt out. But even with low-cost components, the solution proved to be satisfactorily reliable.

In the present paper, finding an unexpected object in the physical scaled-model served to represent finding an unexpected object in a corresponding real-scale apartment. The authors opted to test the robustness of the *ad hoc* WSN system and Pyo *et al.*'s [21] laser-reflectivity scheme in an abstracted manner first before implementing it in real-scale, as is currently being done. Naturally, there are contingencies to account for in the scaled-model that would be unnecessary in the real-scale apartment. For example, the *origin* of the scaled-model was determined to be the middle of the boundary on which the laser would pivot. Since the *X*- and *Y-translations* of the identified obstructing object are values relative to this *origin*, before they can be used to send the actual TurtleBot rover to the corresponding position inside the real-scale apartment, the authors would need to create an equivalence between the scaled-model's coordinate system and that of the apartment's map generated via *Rviz*. The *origin* of an *Rviz* map depends on the location from where the TurtleBot rover's on-board *Kinect* camera began acquiring spatial information about the flat. But at any rate, being mindful of this, it would be easy to generate said equivalence—but it would be unnecessary in the real-scale implementation. In the real-scale implementation there would not be a scaled-down model coordinate system to translate into an *Rviz*-generated map, since this latter would be the only map the system would be based on.

The authors believe that the combination of *ad hoc* WSN systems with already existing communication technologies provides flexibility, resilience, and promise. The promise largely lies in the fact that certain sensor-based services and solutions are no longer bound to expensive proprietary technologies. For example, the total cost of the technical components for the *ad hoc* WSN layer (i.e., two *XBee shields*, two corresponding *XBee Exlorer* dongles as well as two communications-enabling *XBee S1 antenna*s; a variety of sensors and multiple LSRs*)* used in the work detailed above amounts to no more than EUR 200.

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