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Development of a Platform to Combine Sensor Networks and Home Robots to Improve Fall Detection in the Home Environment

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Abstract— **Over the last decade, significant progress has been made in the development of wearable sensor systems for continuous health monitoring in the home and community settings. One of the main areas of application for these wearable sensor systems is in detecting emergency events such as falls. Wearable sensors like accelerometers are increasingly being used to monitor daily activities of individuals at a risk of falls, detect emergency events and send alerts to caregivers. However, such systems tend to have a high rate of false alarms, which leads to low compliance levels. Home robots can enable caregivers with the ability to quickly make an assessment and intervene if an emergency event is detected. This can provide an additional layer for detecting false positives, which can lead to improve compliance. In this paper, we present preliminary work on the development of a fall detection system based on a combination sensor networks and home robots. The sensor network architecture comprises of body worn sensors and ambient sensors distributed in the environment. We present the software architecture and conceptual design home robotic platform. We also perform preliminary characterization of the sensor network in terms of latencies and battery lifetime.**

I. INTRODUCTION

HOME health monitoring systems such as the *Health Buddy (Bosch)* [1] and the *Health Guide (Intel)* [2] allow caregivers to track subjects' health status in the home setting and interact with them via teleconferencing tools. These systems are revolutionizing the way health care is provided to older adults and clinical management of chronic conditions. However, such systems favor sporadic checks to continuous monitoring, they provide limited capability to respond to emergency medical situations, and they do not provide mobility in the home environment. Specifically, caregivers do not have the ability to remotely navigate in the home environment and assist subjects if a medical emergency occurs.

Telepresence robots like the *RP7i*, *Vgo* and *Kompai* provide an attractive platform to allow caregivers to respond to a medical emergency in the home setting [3]. These robots are mobile platforms, which can be controlled to navigate a remote environment. They are typically equipped with a video camera and a computer screen that enables teleconferencing capability. However, they have no sensing capability that appears to be relevant to home monitoring of older adults and generally of patients with chronic conditions. Therefore, they are not suitable to detect the occurrence of a medical emergency such as a fall in the home environment.

To capitalize on the potential of telepresence robots, while addressing their lack of sensing capability suitable for home health monitoring, we recently proposed to combine home robots and wireless sensor networks [4]. Wireless sensor networks comprise of networks of wearable sensors (i.e. body sensor networks) and networks of ambient sensors. Data gathered using wireless sensor network would provide the means to detect the occurrence of a medical emergency. An alert generated by the wireless sensor network can be relayed to the home robot, which can then respond to the alert by using its autonomous capabilities (e.g. processing of images, elaboration of sensors data) to assess the subject's condition and send an alarm message to a remotely located caregiver if necessary. The caregiver would be able to navigate the home environment using the robot and set in place the process needed to properly respond to the medical emergency.

In this paper, we present preliminary work toward the development of a platform that we call *SENSOBOT,* which combines sensors and a robotic platform to achieve home monitoring of older adults and promptly respond to falls in the home environment. Network delay and battery lifetime are two critical aspects of our sensor network. A low network delay is important for quick detection of emergency events and a long battery lifetime will enable the sensor network to function autonomously for a long period of time. We present a preliminary characterization of both these aspects of our sensor network in terms of network latencies and the effect of radio duty cycling on battery lifetime.

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II. METHODS

Hardware Platform Development

A conceptual representation of the proposed platform is shown in Figure 1. The main components of the platform are the robot, the sensor network, and the caregiver station. In this section, we provide a detailed description of the platform design and implementation achieved so far.

Robot. The project requirements are that the robot be equipped with hardware to support telepresence (e.g. a computer screen, a web-camera, a microphone, software to allow a caregiver to remotely control the robot and navigate the home environment) and wireless capability to enable communication with the sensor network.

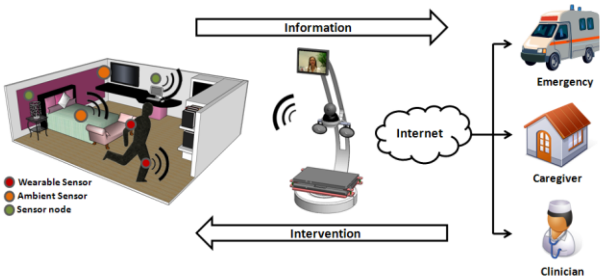

Fig. 1. Sensor nodes are connected using a wireless radio. In case a medical emergency occurs, an alert is relayed to the robot. The robot enables mobility inside the home environment while communicating with the external world.

To meet these requirements, we decided to implement the robotic component of the proposed platform by using the *Create* development platform from *iRobot* in combination with a custom-built frame to position a laptop computer, an additional computer screen, a web-camera, and lights (used to facilitate navigating the home environment). The *iRobot Create* has been used for similar purposes before in projects like *TurtleBot (WillowGarage)[5]* and *The Bilibot Project[6]*. The *iRobot Create* provides a good low-cost platform for preliminary conceptual design and its barebones structure allows us to easily add our own customizations.

Sensor Network. The sensor network includes nodes worn by the subject and nodes for ambient sensing. Sensor nodes will form a mesh network and reliably communicate with the home robot. Nodes worn by the subject may collect vital signs in addition to movement data (e.g. acceleration data). Nodes with ambient sensing capability will collect data related to movement, vibrations, pressure, sounds and light to provide contextual information for improved decision making. The sensor network will also be used to determine subject's location in the home environment in order to make it possible to rapidly locate and reach the patient in case of an emergency.

Localization techniques for indoor environments using sensor nodes equipped with low-power radio have been explored in the past. Lorincz et al. [7] showed a technique based on fingerprinting using signal strength to track user location by running the localization algorithm completely on the sensor node. Using the existing mesh network will enable system deployment without the need for additional infrastructure dedicated for localizing the patient.

The above-listed project requirements can be met by using SHIMMER sensor nodes [8]. SHIMMER sensor nodes are equipped with both a low power radio (802.4.15) and a Bluetooth radio. They are equipped with accelerometers and gyroscopes as well as they can be interfaced with a host of other physiological and ambient sensors. Data can be stored on a SD (Secure Digital) card. SHIMMER sensor nodes rely on the TinyOS [9] operating system, which provides ready-to-use components that are crucial for rapid implementation of the system.

Caregiver Station. The caregiver station will enable teleconferencing in addition to managing data collected using the sensor network. The caregiver can access the robot platform using any web-enabled device such as a laptop or smart phone. The design of this component of the proposed platform is mostly focused on functionalities to be enabled by a web interface. It is worth mentioning that previous work by our team [10] has led to the development of a system allowing one to achieve remote access to data collected using SHIMMER nodes via a web-application. The system is referred to as MercuryLive and it is of great relevance in the context of the new platform herein proposed that combines sensor networks and home robots.

Software Platform Development

Figure 2 schematically represents the software architecture of the implemented prototype. To achieve our first design prototype we decided to implement components like remote control of the web-cam and of the robot using *Python*.

The current video-streaming implementation relies on *Video Lan Client (VLC)*. *VLC* is used to capture video-frames from a web-cam (Logitech QuickCam ® Orbit AF) and stream the video data in a real-time fashion over the network. The decision of using *VLC* is made based on expectation for future project requirements. *VLC* fully satisfies the requirements for the prototype infrastructure without spending an enormous effort on optimizing the video-stream. We anticipate that a more advanced video stream system will be required to recognize objects (e.g. a subject lying on the floor) or perform other image processing tasks. Hence, we are currently exploring alternative solutions based on *OpenCV* (an open-source library for image

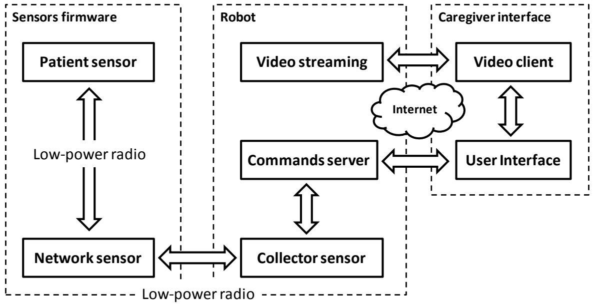

Fig. 2. Software architecture of the proposed platform. The software architecture reflects the components of the hardware platform.

processing) in combination with a more advanced video-streaming server like *Red5*.

The remote control component (*Commands Server* in *Figure 2*) of our system requires a lightweight communication protocol for web-based remote control of the robot. Therefore, we decided to use *XML-RPC*. *XML-RPC* is a particularly lightweight protocol working over *HTTP*. In addition, the use of *XML-RPC* facilitates addressing portability issues related to using a variety of remote clients.

Preliminary System Characterization

The most critical aspect of the proposed platform is the functionality of the sensor network. Therefore, our initial studies concerning the characterization of the system have been focused on two main aspects of the network functionality, i.e. packet transmission delays and power consumption by the nodes.

An ideal wireless sensor network would provide continuous connectivity while maximizing the node lifetime. These requirements are in conflict as maximizing the node lifetime requires duty-cycling the radio and use of the sensing components on the node. Continuous connectivity would require that all the resources of the wireless sensor network be available (and active) at any point in time. A thorough characterization of the wireless sensor network is necessary to assure reliable performance of the network. Such system characterization will allow us to achieve an optimal trade-off between the requirement of continuous connectivity and that of maximization of the node lifetime.

Tests concerning the assessment of packet transmission delays were performed in a room placing sensors at sufficient distance so that data transmission could only occur between adjacent nodes (because of the nodes' limited radio range). Packet delays were characterized for a single hop as well as for multiple hops (up to four). This is a critical piece of information in a deployment scenario. In addition to depending on the number of hops involved in packet transmission, the packet transmission delay is expected to be a function of the routing protocol chosen for delivering packets. *TinyOS* provides a series of components that implement standard routing protocols. We chose *Collection Tree Protocol (CTP)* [11] to perform our tests. We defined the packet transmission delay as the time difference between the time when the packet is sent by a node and the time when it reaches the destination node. It is worth mentioning that, for multi-hop transmissions, the estimated transmission delay includes the time spent on intermediate routing nodes. Time synchronization between nodes on the network was performed using the *flooding time synchronization protocol (FTSP)* [12].

A second series of tests was performed to assess power consumption by the sensor nodes and estimate the node lifetime under different radio duty cycling conditions. We specifically chose to focus on radio duty cycling as radio activity is the most power hungry operation on our sensor node. This type of characterization has been the focus of previous work by our team and others. Nguyen et al. [13] studied the power consumption behavior of the *TelosB* nodes. Lorincz et al. [14] studied the power consumption behavior of the SHIMMER nodes, but in conditions that are not applicable to our platform. Specifically, data was sampled and a higher sampling rate (100 Hz) than the one of interest in this project (25 Hz) and it was continuously logged whereas in the case of the proposed project data does not have to be logged. In the tests performed for this study, we simulated the detection of events. We set one node so that it transmitted a sequence of alarm messages for 3 s every time an event was detected, and we also set the node so that it transmitted 3s of data buffered before the occurrence of the event and 3s of data after the event. The interval of 3s is chosen based on empirical evaluation made during our preliminary experiments.

In a deployment scenario, we envision enabling the radio only when alarm messages need to be sent. The transmission of alarm messages requires that the radio be active just after the detection of an event. However, the use of routing protocols and time synchronization requires using the radio more frequently. We take into account all these factors as we estimate the impact of duty-cycling the radio on the node lifetime. To calculate the node power consumption, we measured the current drawn by the sensor while executing the operations described above and multiply it by the operating voltage of the sensor nodes. Tests were performed with radio duty-cycling intervals set to 25 ms, 100 ms, 250 ms, and 500 ms.

TABLE I
PACKET TRANSMISSION DELAY

# of Hops	Delay (ms)
0	14
1	34
2	53
3	56
4	76

III. RESULTS

Table 1 summarizes the results of the tests performed to assess the magnitude of the packet delays when multiple hops are necessary. Delays in the worst case scenario of 4 hops were around 76ms, which means that packet transmission delays associated with the sensor network can be tolerated for the application at hand (i.e. fall detection).

The results of the tests performed to assess power consumption of the sensor network were also encouraging. Figure 3 shows the power consumption profile for a simulated event in which the radio wake-up interval of the patient node was set to 1 min (i.e. the radio was switched off for 1 min after transmitting data following an event detection). The plot shows two intervals (at the beginning and end of the observed time period) in which the radio was off. In the middle of the observed period, the radio is on and intervals of data transmission and alarm transmission are present.

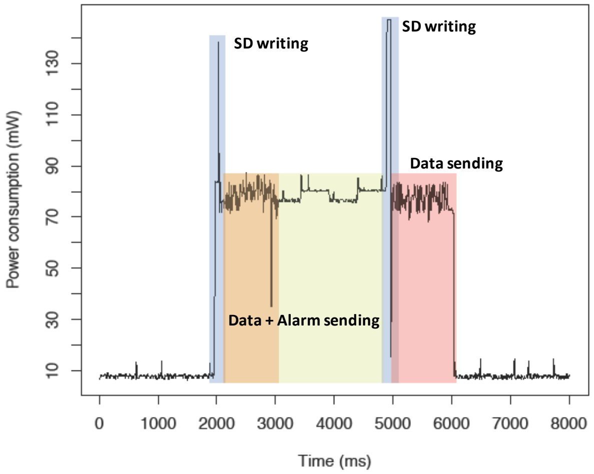

Fig. 3. Energy consumption profile: colored regions represents various operations performed when an event is detected. *Data sending* and *alarm sending* are overlapping for about one second after the event occurred (orange zone). Nevertheless a clear difference in power consumption is visible during different operations.

To calculate the average power consumption we measured the current consumption in milliamps (mA) by setting the duty-cycling to 0, 25, 100, 250 and 500ms and simulating multiple fall events on the sensor node. Average power consumption was calculated using several fixed conveniently chosen window of 15s (each window includes one simulated event). *Table 2* shows the estimated average power consumption values and the corresponding expected node lifetime values using different radio wake-up intervals. Our results indicate that the sensor network can operate for sufficiently long periods of time to achieve the goals of the proposed fall detection application.

TABLE II
SENSOR NODE PROFILE LIFETIME

Interval (ms)	Consumption (mW)	Lifetime (hours)
0	75	12
25	42	21
100	34	26
250	29	30
500	28	32

IV. CONCLUSIONS

In this paper, we presented our preliminary work toward developing *SENSOBOT,* a system that combines home robots and wireless sensor networks for the detection of falls in the home environment.

We focused our work on a preliminary characterization of the effect of system performance on the functionality of the wireless sensor network. The results obtained in this study are encouraging and suggest that the sensor network implemented so far is suitable for fall detection.

Future work is needed to address a number of additional aspects of the platform design. A crucial aspect of the system that requires implementation and testing is the localization of the subject and robot at the time of a fall event. We are exploring and implementing an approach based on [7] for subject localization. Initial tests provide encouraging results, achieving room-level precision with less than 10 nodes in a 3 room configuration.

A second aspect of the proposed platform that is of paramount importance is providing the home robot with autonomous functions, such as autonomous navigation of the home environment, processing of video information to assess subject's status and integration of ambient sensors. Finally, deployment of the system in the home environment is expected to bring about challenges that will need to be addressed via a careful design of the human computer interface.

REFERENCES

[1] *Health Buddy (Bosch)*. Available: HTTP://WWW.BOSCH-TELEHEALTH.COM/CONTENT/LANGUAGE1/HTML/5578_ENU_XHTML.ASPX

[2] *Health Guide (Intel)*. Available: HTTP://WWW.CAREINNOVATIONS.COM/PRODUCTS/HEALTHGUIDE/DEFAULT.ASPX

[3] E. Guizzo, "When My Avatar Went to Work," *Spectrum, IEEE,* vol. 47, pp. 26-50, 2010.

[4] P. Bonato, "Wearable sensors and systems. From enabling technology to clinical applications," *IEEE Eng Med Biol Mag,* vol. 29, pp. 25-36, May-Jun 2010.

[5] *TurtleBot*. Available: HTTP://WWW.WILLOWGARAGE.COM/TURTLEBOT

[6] *The Bilibot Project*. Available: www.bilibot.com

[7] K. Lorincz and M. Welsh, "MoteTrack: a robust, decentralized approach to RF-based location tracking," *Personal Ubiquitous Comput.,* vol. 11, pp. 489-503, 2007.

[8] A. Burns*, et al.*, "SHIMMER: A Wireless Sensor Platform for Noninvasive Biomedical Research," *Sensors Journal, IEEE,* vol. 10, pp. 1527-1534, 2010.

[9] P. Levis*, et al.*, "TinyOS: An operating system for sensor networks," in *in Ambient Intelligence*, ed: Springer Verlag, 2004.

[10] C. Bor-Rong*, et al.*, "A Web-Based System for Home Monitoring of Patients With Parkinson's Disease Using Wearable Sensors," *Biomedical Engineering, IEEE Transactions on,* vol. 58, pp. 831-836, 2011.

[11] O. Gnawali*, et al.*, "Collection Tree Protocol," in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys'09)*, ed. Berkeley, CA, USA, 2009.

[12] M. Maroti*, et al.*, "The flooding time synchronization protocol," ed: ACM Press, 2004, pp. 39-49.

[13] H. A. Nguyen*, et al.*, "Sensor Node Lifetime: An Experimental Study," *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems,* 2011.

[14] K. Lorincz*, et al.*, "Mercury: a wearable sensor network platform for high-fidelity motion analysis," in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems*, ed. Berkeley, California: ACM, 2009, pp. 183-196.