Wireless sensor networking of everyday objects in a smart home environment

Dipak Surie, Olivier Laguionie, Thomas Pederson
Department of Computing Science,
Umeå University, SE-90187 Umeå, Sweden
Dipak@cs.umu.se, Olla0002@student.umu.se, Top@cs.umu.se

Abstract

Within a smart home environment the information processing is supposed to be thoroughly integrated into everyday objects. This introduces the need to keep track of the everyday objects and their state changes produced based on the user's interaction with them. Such information is useful in recognizing the user's activities, situations, etc. In this paper we present a ZigBee communication protocol based wireless sensor networking [1] of 42 everyday objects (embedded with 81 simple state change sensors of 8 sensor types) in a living laboratory smart home environment. The system was evaluated in a realistic setup with background noise. The sensing module has shown promising results with an overall system precision of 91.2 % and a recall of 98.8 % in keeping track of the state changes to everyday objects. The signal strength measure above the acceptable limit of >10 dB to obtain reliable data communication was found to be 97.5% checked at 8 different locations in a home environment. Finally the transmission-reception range was evaluated to be 33 m with a single wall obstruction and 19 m with multiple wall obstruction in an indoor environment.

INTRODUCTION

Within a smart home environment the information processing is supposed to be thoroughly integrated into everyday objects that provide functionalities beyond their primary purpose, there by enhancing their characteristics, properties and abilities [2]. By correlating the sensor output of such everyday objects, the wireless sensor network (WSN) as a whole can potentially provide functionality that an individual everyday object cannot. Such functionalities include situation and activity awareness (using a middleware) of an inhabitant within smart home environments. The everyday objects that are present in a user's environment have shown to provide valuable cues for inferring the user's current situation and activity [3, 4]. There are several wireless micro sensor motes including Mica2Dot [5], Mica-Z [6], iMotes [7], tMotes [8], BTNodes [9], Smart-Its [10], Smart-Its Particles [11], etc. available to the research community. Even though many of such motes have their own advantages, they do not meet the general requirements of a smart home environment in sensing the state changes to everyday objects including home appliances, furniture, simple objects, etc. [12]. The ease of installation, usability and adequate performance in realistic setups has also motivated us to go for the deployment of a custom made WSN infrastructure. Wireless body area network for providing proactive healthcare is described in [13]. Cooperative artefacts are physical objects that are embedded with sensing, communication, computation and actuation technologies that are not dependent on any external infrastructure, but operate by sharing knowledge [14]. Such an approach is interesting, but is not suitable for computation intensive applications. Mediacup [15], Interfacing-the-foot [16], AwareMirror [17], etc. have focused on individual everyday objects instead of WSN of all the relevant everyday objects in a smart home environment. Many related works [5, 7, 8, 9] have focused on mesh network topology (considering the self-configuration and unlimited coverage area advantages) that increases the cost of the entire system and the complexity involved, and are more not suitable for novice researchers using networked sensors.

WSN REQUIREMENTS IN A SMART HOME ENVIRONMENT

We had conducted a workshop with 8 subjects in establishing the requirements for deploying WSN in a home environment. Based on the discussions, we have imposed the following requirements:

- **Usability/Availability/Installation (non-functional):** The subjects preferred systems that are readily available off-the-shelf at an affordable price and are easy to be installed. They also preferred not to carry too many devices as part of their wearable outfit (1 device was informed to be the acceptable limit). They also preferred not to change the way they would interact with everyday objects, had the WSN not been installed at the first place.
- **Performance (functional):** The subjects preferred to use a system (on the first place) that is reliable with adequate performance. Hence the sensing precision and recall values for the system as a whole are important evaluation aspects. The transmission-reception range is an important parameter to consider as well, but we approach this issue by proposing a mobile receiver that is part of the user's wearable outfit and hence is more often than not within the range of the sensor nodes activated based on the user's interaction with the concerned object. Battery life of the sensor nodes were considered more important since it is difficult to charge all the nodes often, while the receiver node was expected to have a good battery life with a slightly lesser priority.

SYSTEM OVERVIEW

The system to be described in this paper consists of a set of everyday objects present in a smart home environment connected to a wearable personal server [18] worn by the user and running an activity-centered computing middleware [19].

A. Wireless Personal Area Network

The everyday objects are embedded with stick-on nodes that sense the internal states and state changes (based on the user's interaction with it) to the objects and transmit this information wirelessly using ZigBee communication protocol [20] to the user's personal server. ZigBee was preferred over Bluetooth for wireless personal area networking considering its usage of low-power digital radios intended for low data rate, long battery life and secure networking applications. ZigBee supports up to 65,000 nodes on a network, introducing the possibility to include additional everyday objects to be a part of the proposed system in the future. Generic communication boards are designed with easily replaceable sensor connectors to facilitate multiple sensors by only replacing the onboard sensor and microcode. Maxstream XBee 802.15.4 transceiver and Atmel ATMEGA88-20PU microcontroller are used in individual generic communication boards. The XBee transceiver operates at ISM 2.4 GHz frequency, 1mW (0 dBm) power output and allows for data rates of up to 250 Kbps. The average data rate of all the sensor nodes was 20.4 Hz (with a maximum of 100 Hz for some nodes and a minimum of 10 Hz for a majority of the nodes). The microcontroller is run at 8 MHz. The communication boards embedded onto everyday objects include a 2.4 GHz omni directional antenna with ½ λ wavelength and a gain of 2.90 dBI. The generic communication boards require 3 Volts, and are powered by three 1.2V 2600mA NiMH battery in series. The receiver node connected to the user's personal server include a Maxstream XBee 802.15.4 transceiver and a circuitry board for USB connection to a Sony vaio VGN-UX70 with 1 GHz processor and 512 MB RAM. The USB connection is considered as a serial port within the personal server.

The majority of the sensor nodes (70%) operate at a low sampling rate of 10 Hz considering our current application where the nodes transmit only when there is a change in the sensor reading range defined by threshold values in the microcontroller. The internal states and state changes of the respective everyday objects are calibrated in the personal server based on their unique identities. Such a double-step calibration allows for introducing additional internal states for everyday objects within the Personal Server based on the requirements from other components within the middleware and also the applications running above the middleware. We are currently working on high sampling rate cases (e.g. accelerometer (150 Hz), RFID reader for sensing a set of objects in a space surrounding the user [4], etc.) where a dedicated channel is allocation for communication between the sensor nodes and the receiver node. The sensor nodes transmit the sensed data three times (default ZigBee protocol value that could be increased, but was found to be sufficient for our purpose considering the probability of correctly receiving 113488 packets at the receiver node) to the receiver node before a time-out. According to [21], the probability of correctly receiving packet at the receiver node increases with the number of retransmissions. This is important to consider since channel noise and collisions are issues that exist in real world scenarios and need to be handled. However, too many retransmissions can block-up the network bandwidth, there by requiring a threshold for number of retransmissions. Within the sensor node, the microcontroller sends the data four times (experimentally found out to be the ideal number of times, but further work is required to reduce the overhead) through a USART to the XBee Transceiver and expects an ACK message in return.

The data format used for communication include Object Identity (3 bytes), Sensor Data (S_1, S_2…Sn), and end-of-frame (1 bit). The length of the Sensor Data depends on the everyday object. (S_1, S_2…Sn) values are between 4 bytes (minimum length) and 17 bytes (maximum length). Sensor Type information is not included in the data format to reduce the size of the data frame. Even though the current data frame size is not an issue for our current application, we are working on including RFID readers for modelling everyday objects in a home environment where the data frame size might become an issue. The Object Identity information is used within the personal server to query a database containing information about everyday objects present in the user's environment

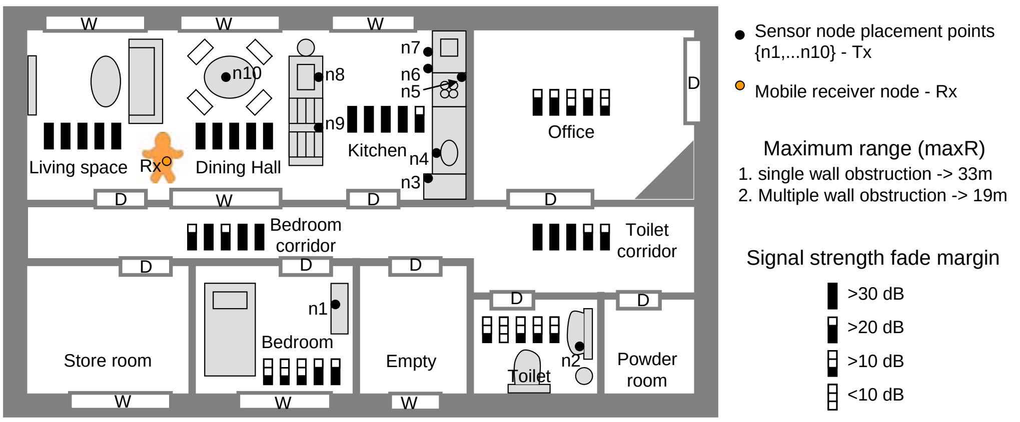

Fig. 1: A living laboratory home environment with Tx /Rx node placement points and signal strength measures.

including the sensor types used for sensing their internal states.

The wireless sensor network consists of a star network topology considering its simplicity (removes the need for complex routing or message passing protocols), better performance (removes the need to pass data packets through unnecessary nodes), power efficiency and isolation of everyday objects that are actually not changing their internal state with everyday objects that actually do so. The primary disadvantage of high dependence on the functioning of the receiver is of lesser importance in this context since the receiver is supposed to work 100% anyway for the personal server to manage the everyday objects. A star network topology demands that all the sensor nodes are within the vicinity of the receiver node. In our case, the receiver node is worn by the user creating mobile context within a home environment. Since the state changes that we are interested in are those created by the user based on their interaction with environmental everyday objects, the sensor nodes invariably fall within the receiver node proximity. However, in order to cover for exceptional cases we

Fig. 2: Sensor nodes embedded onto everyday objects in a home environment.

evaluated the range within which the receiver node can receive sensor data (button on-off) with acceptable noise (< 5%). It turned out to be 33 meters with a single wall obstruction and 19 meters with multiple (greater than two) wall obstruction. Refer to Fig. 1. For application cases that require a range greater than the ones mentioned above, repeater nodes could be easily integrated to the proposed architecture. We have embedded 81 sensors (from the 8 sensor types described in Appendix 1) onto 42 everyday objects in a live-in laboratory home environment as shown in Fig. 2. The receiver node is designed to receive sensor data from the sensor nodes that are designed based on a combination of the basic eight sensor types described in Appendix 1. Additional sensor types with RS232, I2C, or SPI output can be easily included by making minor firmware modifications. Analog sensors could also be included within the sensor node, but with an external circuit that condition the signal to the ADC input voltage range of 3V.

B. Personal Server running an Activity-Centered Computing Middleware

The sensor data from the everyday objects are received and processed within the object manager, a software component part of an activity-centered computing middleware described in [19] (Refer to Fig. 3). We will focus on the object manager alone within the scope of this paper. This component maintains a real-time model of all the everyday objects present in the user's environment. Such information was shown to be important for monitoring the user's situation and activities in our earlier work [4, 22]; and is also used for our current work

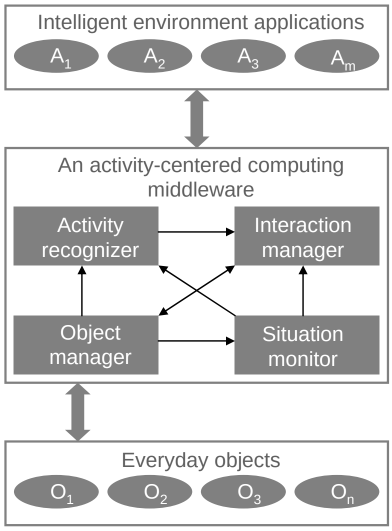

Fig. 3: An activity-centered computing middleware, adapted from [19].

on distributed multimodal interaction [23]. The middleware is implemented in C#. The object manager is responsible for the following: 1) to discover the set of everyday objects present in the user's environment; 2) to query a database during the initialization phase for additional information about the everyday objects based on their unique identities similar to [24]. A mock-up database is used with an assumption that in the future the everyday object manufacturers would maintain such a database online considering the interest shown by the industry and academia in the *Internet of Things* [25]; 3) to initialize and manage communication with the everyday objects; and 4) to provide information about the everyday objects to other middleware components and the intelligent environment applications as shown in Fig. 3.

EXPERIMENTAL SETUP

The experiments were performed in a living laboratory home environment prepared for ubiquitous computing research at the 4th Floor MIT Huset, Umeå University, Sweden. Refer to Fig. 1 for the plan of the home environment. In our earlier work [4, 22, 19], we had focused on the kitchen activities considering the number and variety of activities possible. We have continued along a similar track, however have also included activities beyond the kitchen domain. Four subjects (not part of the system development team) were recruited for the experiments. They were compensated with food and mouth-of-praise. The experiments were performed individually by individual subjects for a week's duration. In addition to the system components (wearable personal server + receiver node), the subjects were also given a wearable camera connected to a mobile digital video recorder (DVR) for obtaining the ground truth (state changes to everyday objects) as shown in Fig. 4. We have discarded the sensor readings (not used for evaluation), if an event performed by the subject was not captured on the wearable mini camera. We have used a similar wearable mini camera and DVR set-up for ethnographical studies on "how people perform everyday activities in a home environment?" with acceptable reliability [26]. Experience sampling method [ESM] [27, 28] is a commonly used method to obtain the ground truth where the subject is supposed to manually enter the events produced by them while performing activities onto a PDA (usually) running the ESM software. However such an approach was shown to be inaccurate for obtaining the ground truth from the subjects due to wrong event selection; not using the ESM software for short activities like toileting; delay between sensor firing and experience sampling; etc. [29]. Indirect observation of sensor activations for activity recognition, situation monitoring, etc. results in a situation where the sensing errors are comfortably missed due to the unavailability of ground truth [29]. In our work, we try to evaluate the wireless sensor networking (WSN) within scenarios consisting of everyday activities. In our future work, we intend to use the data collected for activity recognition, etc. with the knowledge of the precision and recall values of the sensing system.

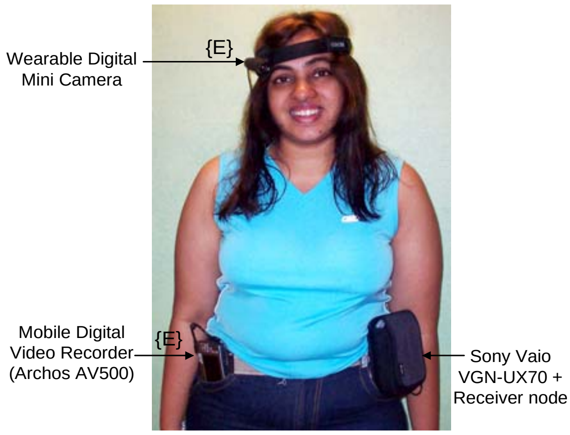

Fig. 4: A subject wearing our system during the experimentation session (The camera and the video recorder were used for obtaining the ground truth and is not part of the proposed system)

The subjects were asked to collect ground truth for the set of 10 activities presented in Table 2. Time-based synchronization was used to map the sensor firings with the ground truth. The subjects were not restricted on how to perform the activities, however were briefed on how to use the system. For the two sensitive activities of toilet routine and changing clothes, the subjects were part of the evaluation process in identifying the ground truth. The activities were performed between a minimum of 7 times and a maximum of 20 times during a week. The subjects were interviewed after the experimentation period for qualitative evaluations.

EVALUATION

A. *Wireless Communication: Transmission-Reception Range and Signal Strength measures*

The transmission reception range is usually evaluated in an outdoor environment with line of sight and free of obstructions. However, such evaluations are of lesser importance compared to evaluating the transmission reception range in a typical home environment for ubiquitous computing applications. Hence we evaluated the transmission reception range (33 meters with a single wall obstruction and 19 meters with multiple wall obstruction as mentioned earlier) and signal strength measures in a home environment with a certain amount of background noise, created when the everyday objects like the fridge, microwave oven, regular oven, vacuum cleaner, etc. are turned on. Since the live-in laboratory was within the university premises, there were other wireless networks outside the context of our system that created background noise as well. In Fig. 1, one of the subjects was asked to be at the location near the dining hall marked by Rx. The signal strength from the various sensor nodes were evaluated by a push button (on-off event) recorded 5 times at 8 different locations in a home environment. Table 1 shows that 97.5% of the times, the signal strength values at the 8 different locations are acceptable (>10 dB). In both the "toilet – toilet corridor" case and the "bedroom – bedroom corridor" case, the state of the door (closed or open) seems to be an important factor to consider. Similarly, the line-of-sight cases (living space, dining hall and kitchen) have performed better than cases having wall obstructions.

B. *Sensing Precision and Recall values*

The accuracy in sensing the object state changes based on the user's interaction with those objects is an important factor to evaluate. The sensing system was evaluated within scenarios where in the subjects were performing a set of everyday activities. Such an approach was considered due to the following evaluation criteria: 1) the sensing system should be evaluated as a whole instead of sum of the individual parts in isolation; 2) the sensing system should be evaluated in a realistic setup where the subjects are performing everyday activities by interacting with everyday objects; and 3) to use the data collected for activity recognition with the additional information known about the accuracy of the sensing system. In our previous work [4, 22], we have used multiple Hidden Markov Models (HMMs) in parallel to accommodate individual information channels like *objects grabbed/released*, *objects' state changes,* and *objects around the user's body* for recognizing activities. We define precision and recall as follows:

Table 1: Evaluation of signal strength at 8 different locations in a home environment with the subject located near the dining hall as shown in Fig. 1.

Signal strength	Living Space (%)	Dining Hall (%)	Kitchen (door open) (%)	Bedroom Corridor (%)	Bedroom (door closed) (%)	Toilet (door closed) (%)	Toilet Corridor (%)	Office (door open) (%)
Best (>30 dB)	100	100	80	60	0	0	60	0
Good (>20 dB)	0	0	20	40	40	0	40	60
Medium (>10 dB)	0	0	0	0	60	80	0	40
Low (<10 dB)	0	0	0	0	0	20	0	0

$$Precision = \frac{True\ Positives}{(True\ Positives + False\ Positives)}$$

$$Recall = \frac{True\ Positives}{(True\ Positives + False\ Negatives)}$$

Table 2 shows that the sensing system has an overall precision value of 91.2 % and an overall recall value of 98.8 %. The results are promising considering the amount of background noise present in the environment (for wireless communication) and the fact that sensing some of the internal state changes of objects was tricky. For instance, the ambient light present in the user's environment affected the decision of determining if the dust bin (uses light sensor) was full or empty. Hence, there was a need for performing ambient light noise cancellation for cases involving the light sensor. The location, number and type of sensors embedded onto everyday objects are important factors to address for obtaining high performance measures. Sensor fusion is an interesting approach to reduce the sensing errors, which we would perform in the future.

Table 2: Precision (in percentage) and recall (in percentage) values in sensing the object state changes to objects for a set of 10 everyday activities performed by the subjects.

Activity Name	Sensing Precision	Sensing Recall
1. Drinking coffee	84.1	98.8
2. Baking cake, bread, etc.	100.0	98.8
3. Doing the dishes	90.0	100.0
4. Repairing the coffee machine	74.7	88.0
5. Changing clothes	91.0	99.0
6. Heating up the frozen food	93.6	100.0
7. Toilet routine	99.0	99.0
8. Preparing dinner	87.6	99.0
9. Setting-up the table	100.0	95.7
10. Having dinner	100.0	100.0
Global	**91.2**	**98.8**

C. Installation Time and Usability

The installation of the WSN was performed by 2 subjects separately. One subject took 65 min while the other subject took 45 min to install 81 sensors onto 42 objects. The mobile receiver connected to the personal server weights 0.632 Kg with a dimensions of 15*10*4 Cm^3. All other sensor nodes are instrumented in the environment instead of including them in the user's wearable outfit. Note that the wearable camera and DVR were used only for the experimentation purpose and is not part of the actual system.

CONCLUSIONS

This paper has shown the results obtained from an actual deployment of a WSN in a living laboratory home environment for ubiquitous computing research. The state changes to everyday objects present in the user's environment were sensed with an overall precision value of 91.2% and an overall recall value of 98.8%. The signal strength measures were also shown to be acceptable 97.5% of the time evaluated in 8 different locations in a home environment. The transmission-reception range considering wall obstructions common in a home environment has also shown promise. Finally we have also addressed some of the non-functional requirements imposed by the subjects.

REFERENCES

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless Sensor Networks: A Survey", Computer Networks, Vol. 38(4), pp. 393-422, 2002.

[2] D. Norman, "The Design of Everyday things", The MIT Press, Aug 1998.

[3] M. Philipose, K. Fishkin, M. Perkowitz, D. Patterson, D. Fox, H. Kautz, D. Hähnel, "Inferring Activities from Interactions with Objects", IEEE Pervasive Computing, Oct 2004.

[4] D. Surie, T. Pederson, F. Lagriffoul, J-E. Janlert, D. Sjölie, "Activity Recognition using an Egocentric Perspective of Everyday Objects", In Proceedings of IFIP Conference on Ubiquitous Intelligence and Computing, 2007.

[5] Crossbow Technology Inc., "MICA2DOT Wireless Microsensor Mote." 2005 [Cited Sept. 14th, 2008]. Available from http://www.xbow.com/Products /Product_pdf_files/Wireless_pdf/MICA2DOT_Datasheet.pdf.

[6] Crossbow Technology Inc., "MICAz Wireless Measurement System", 2005 [Cited Sept. 14th, 2008]. Available from http://www.xbow.com/Products/ Product_pdf_files/Wireless_pdf/MICAz_Datasheet.pdf.

[7] R. Kling, "Intel Mote: An Enhanced Sensor Network Node," Proc. Of the International Workshop on Advanced Sensors, Structural Health Monitoring and Smart Structures, Keio University, Japan, 2003.

[8] Moteiv., "tmote Sky: Ultra Low Power IEEE 802.15.4 Compliant Wireless Sensor Module", 2005 [Cited Sept. 14th, 2008]. Available from http://www.moteiv.com/products/docs/tmote-sky-datasheet.pdf.

[9] BTnode Project, "BTnodes: A Distributed Environment for Prototyping Ad Hoc Networks", 2005 [Cited Sept. 14th, 2008]. Available from http://www.btnode.ethz.ch

[10] W. Gallersen et.al., "Physical Prototyping with Smart-its, IEEE Pervasive Computing Magazine, Vol. 3, 2004.

[11] C. Decker, A. Krohn, M. Beigl, T. Zimmer, "The particle computer system", Proceedings of the ACM/IEEE 4th International Conference on Information Processing in Sensor Networks, 2005.

[12] T. Rodden, S. Benford, "The Evolution of Buildings and Implications for the Design of Ubiquitous Domestic Environments", CHI 2003, ACM Press, pp. 9-16, 2003.

[13] C. Otto, C. Sanders, E. Jovanov, "System architecture of a wireless body area sensor network for ubiquitous health monitoring", Journal of Mobile Multimedia, Rinton Press Vol. 1, No. 4, pp. 307-326, 2006.

[14] M. Strohbach, G. Kortuem, H. Gellersen, "Cooperative Artefacts - A Framework for Embedding Knowledge in RealWorld Objects", UbiComp 2005.

[15] H. Gellersen, M. Beigl, H. Krull, "The MediaCup: Awareness Technology Embedded in an Everyday Object", In Proceedings of International Symposium on Handheld and Ubiquitous Computing (HUC99), LNCS 1707, 1999.

[16] J. Paradiso et. al., "Interfacing the Foot: Apparatus and Applications", CHI extended abstracts, 2000.

[17] K. Fujinami et. al., "AwareMirror: A Personalized Display using a Mirror, Pervasive 2005.

[18] R. Want, T. Pering, G. Danneels, M. Kumar, M. Sundar, J. Light, "The Personal Server: Changing the way we think about Ubiquitous Computing", UBICOMP, 2002.

[19] D. Surie, T. Pederson, "An Activity-Centered Wearable Computing Infrastructure for Intelligent Environment Applications", EUC, 2007.

[20] ZigBee Alliance, 2007 [Cited Sept. 14th, 2008]. Available from http://www.zigbee.org/en/index.asp

[21] E. Tapia, S. Intille, L. Lopez, K. Larson, "The design of a portable bit of wireless sensors for naturalistic data collection", PERVASIVE 2006.

[22] D. Surie, F. Lagriffoul, T. Pederson, D. Sjölie. "Activity Recognition based on Intra and Extra Manipulation of Everyday Objects", In Proceedings of IFIP Conference on Ubiquitous Computing Systems, 2007.

[23] T. Pederson, D. Surie, "A Situative Space Model for Distributed Multimodal Interaction", Dept. of Computing Science, Umeå University, report UMINF-08.11, 2008.

[24] U. Kulkarni, J. Vadavi, S. Joshi, K. Sekaran, A. Yardi, "Ubiquitous Object Categorization and Identity", International Conference on Advanced Computing and Communications, IEEE Computer Society, Issue 20-23, pp. 585-588, 2006.

[25] N. Gershenfeld, R. Krikorian, D. Cohen, "The Internet of Things", Scientific American, 2004.

[26] R. Bhatt, "Comparing the Performance of ADLs in "Virtual" and "Real Life" Environments", Dept. of Computing Science, Umeå University, report UMINF-06.40, 2006.

[27] S. Intille, J. Rondoni, C. Kukla, I. Anacona, L. Bao, "A context-aware experience sampling tool", In Proceedings of the Conference on Human Factors and Computing Systems: Extended Abstracts, ACM Press, 2003.

[28] S. Intille, E. Tapia, J. Rondoni, J. Beaudin, C. Kukla, S. Agarwal, L. Bao, K. Larson, "Tools for studying behavior and technology in natural settings", Proceedings of UBICOMP'03, Vol. LNCS 2864, 2003.

[29] E. Tapia, S. Intille, K. Larson, "Activity Recognition in the Home Using Simple and Ubiquitous Sensors", Second International Conference, PERVASIVE 2004, Linz/Vienna, Austria. LNCS 3001, April 2004.

Appendix 1: Summary of available sensor types and performance parameters.

Sensor Type	Measures	Sensor(s)	Range	Resolution	Power Consumption
Temperature	Temperature	Dallas DS18S20 Thermometer	-55°C to +125°C	±0.5°C	Active mode: 1 to 1.5mA Sleep mode: 750 to 1000nA
Ambient light	Ambient light intensity	Omnidirectional light sensor (TAOS TSL250R light sensor)	0 to 255	137 mV/(W/cm^2) at 635nm	Active mode: 1.1 to 1.7mA
Pressure pad	Spot(s) where pressure is applied within an area	Network of multiple pressure sensors (Omron microswitch SS-5) spread across a surface	Depends on the size of the pressure pad. We have used a 50cm * 10cm pressure pad	4cm^2	Active mode: 1mA
Touch /Press button	Button touched /Pressed	Push button	Binary: 0 or 1	-	Active mode: 1mA to 2mA
Touch /Press pad	Button(s) touched /pressed	Network of multiple push buttons spread across a surface	Depends on the size (no. of push buttons included) of the touch /press pad. We have used 35cm * 15cm and 20cm * 10 cm pads	Resolution of the touch /press button	Depends on the power consumption of an individual push button and the number of push buttons included in the network
Appliance feedback light	Feedback light intensity	Light sensor (TAOS TSL250R) made unidirectional	0 to 255	137 mV/(W/cm^2) at 635nm	Active mode: 1.1 to 1.7mA
Open-Close	Light intensity	Network of light sensors (TAOS TSL250R) spread across surfaces	Depends on the size (no. of light sensors included) of the object. We have worked between 15.75 decimeter^3 to 270 decimeter^3 volumes.	Depends on the light sensor and the ambient light	Depends on the power consumption of an individual light sensor and the number of light sensors included in the network
Containment limiter	Light intensity	Network of light sensors (TAOS TSL250R) spread across surfaces	Depends on the size (no. of light sensors included) of the object. We have worked between 6.6 decimeter^3 to 44 decimeter^3 volumes.	Depends on the light sensor and the ambient light	Depends on the power consumption of an individual light sensor and the number of light sensors included in the network