An Investigation into the Viability of a Mobile Ultrasonic Array as a Sensor Substitute in an Autonomic Intelligent Environment

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***Abstract*— In this paper an approach to ensuring fault tolerance in intelligent environments for the elderly through the provision of mobile sensor substitution in the event of the detection of anomalous static sensor behavior, is presented. Specifically this paper focuses on the monitoring of an external door in an intelligent care home environment. A mobile robot equipped with an array of ultrasonic sensors is dispatched to monitor the door state and report a change in state to a central server. For each door state there are consistent changes in the sensor readings identified in the course of the experiments carried out within this work. The use of ultrasonic sensors provides a viable substitution option that can assist a central system in deciding whether a care assistant or maintenance engineer is required to resolve the anomalous static sensor behavior.**

Keywords-ultrasonic; intelligent environment; fault tolerance; mobile sensors

I. Introduction

The use of technology in the delivery of pervasive care has received much attention in recent years [1]. Increasingly the advances in technology as a whole are leading to a high degree of dependency on the successful and dependable operation of this equipment to assist in the care of the elderly through the use of intelligent environments which aim to encourage Independent Living [2], [3]. The need for intelligent environments suitable for elderly occupants has arisen from the changing age demographics globally. These changes are leading to an increasingly elderly population that is twinned with a lack of younger people to care for them [4]. By developing care home facilities capable of monitoring occupants whilst allowing them to carry out their everyday activities uninhibited, the independence of the individual is maintained and staff intervention is substantially reduced.

The work presented in this paper focuses on the care of those suffering from dementia due to the increasing prevalence of this condition which is a by-product of the aging population. Dementia is a condition related to Alzheimer's disease, which leads to confusion, memory loss and a reduction in cognitive abilities [5]. An additional characteristic of this illness is wandering behavior [6]. The act of wandering in particular raises safety concerns in respect of the occupants' well-being; especially in an Independent Living focused facility. If the sensing technology in an intelligent care home facility should become faulty without the knowledge of care home staff, occupants prone to wandering behavior may venture outdoors undetected and inadvertently place themselves in danger as a result.

There have been documented and publicized cases of dementia patients leaving a care home facility undetected [7], [8]. The results of these occurrences range from the patient being discovered safe and well to other instances in which the patient has been discovered a considerable amount of time later in ill health and has subsequently died [9]. These incidents prove to not only be distressing to the patient in question and their family, but also require the intervention of the police and medical personnel to locate and deliver care to the patient involved. As a result, additional resources are required which could otherwise be eliminated if the patient's absence from the care home were detected at the moment of the occurrence so that suitable intervention could be instigated.

Although the reported incidents did not occur in care homes in which intelligent sensing was employed, the occurrence of such incidents highlights the importance of efficient monitoring of external doors in care home environments in order to preserve the safety of the vulnerable occupants. In line with the expected rise in reliance on intelligent environment technologies for the delivery of care to the elderly, an important aspect to consider and address in the implementation of this technology is that of fault tolerance. By substituting suspicious, faulty or failed door sensors at the point of the detection of anomalous sensor behavior, the safety of the occupant can be ensured through the continuous provision of sensing abilities in the environment – even in the event of sensor faults.

The topology of the environment in focus within this research involves two static sensors: a floor mounted pressure sensor positioned immediately in front of the inside of the door, and a contact sensor placed on the doorframe. A central server manages the receipt and the processing of sensor activations in the environment. Upon the detection of anomalous static sensor readings, the central server then sends an instruction to a mobile robot in the environment to dispatch itself to the door in question in order to detect the door state. The robot acts as a monitor for the door through the utilization of an on-board ultrasonic array. The robot then sends information back to the

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central server to indicate the current state of the door (open or closed) and also to monitor the door state over time. The door itself is of solid consistency and opens inwards towards the pressure sensor. Upon opening the door from either side, the contact sensor is triggered. If the door is opened by an individual from the inside, the contact sensor and the pressure sensor are both activated.

The primary concern of this work is the detection of the egress of an occupant from the environment to the outside world. This research aims to establish if a mobile ultrasonic array can effectively provide sensor substitution for the determination of door states. Subsequently the central system focuses on the expected activation of both the contact sensor and pressure sensor in order to determine that an occupant has left the environment. The central server will instruct the robot to dispatch itself to the door in question if inconsistent signals are received from the static sensors, such as the absence of the activation of the contact sensor when a pressure sensor has been activated. By utilizing its ultrasonic array, the robot is capable of determining if the door is opened or closed by the variation in the identified thresholds of the readings received from the array sensors. The additional information provided by the robot to the central system aids in deciding whether a maintenance engineer or simply a care home assistant should be alerted to resolve the static sensor's apparent anomalous behavior.

The successful utilization of a robot-based ultrasonic array as a substitution mechanism in intelligent environments could lead to the widespread use of this technology as an efficient and cost-effective means of ensuring fault tolerance.

II. Motivation for the Study

The deployment of static sensors in an intelligent environment facilitates the monitoring of the activities of the environment occupants. The data obtained from these sensors can be analyzed in order to determine specifically what the occupant is undertaking. The analysis of this data then paves the way for the delivery of pervasive care at the point of need when a problem is detected through unusual sensor activity. Whilst the sensing technology serves to monitor the occupant, the question arises as to how the technology itself is monitored. Autonomic computing is a proposed approach for addressing this question through self-management. An approach to the initial implementation of this method is outlined in [10]. Autonomic monitoring utilizes a heartbeat function in the environment sensors. The primary function of the heartbeat monitor is to generate a signal that denotes "I am Alive". This signal may be used in order to transmit further information on the health of a given sensor such as a sensor that is currently working but anticipates failure due to a low battery. This information is useful for the determination of the presence of a sensor fault. The absence of a heartbeat signal from the sensors would then be indicative of a sensor failure. The signal obtained from the sensor in the form of the heartbeat or an absence thereof is a useful indicator of the need for the sensor in question to be investigated through the deployment of the mobile robot sensors. It is upon this work that the approach proposed in [11] is based.

In this research the monitoring of a fire door is the primary focus of attention. A fire door is a key health and safety requirement and so it cannot be locked or otherwise secured. In the event of the detection of anomalous behavior of the sensing technology associated with internal doors in a care home facility it would be possible to secure the door until a maintenance engineer has reached the facility to carry out repairs if necessary – this is not a viable option for fire doors. The utilization of a mobile robot as a sensor substitute in the absence of a heartbeat signal or one that denotes low sensor health provides a means of guarding the door at which anomalous sensor behavior has been detected. The presence of the robot as a substitution mechanism would ensure that whilst the door is awaiting repair; any activity at that door would not go undetected. Herein lies the advantage of the mobile robot sensors in contrast to the static environment sensors; the mobile sensors may be dispatched to the point of need when the information obtained from the static sensors depicts anomalies or where their ability to conclusively detail what activity has occurred in the environment is in doubt. This self-deployment at the point of fault or failure detection based on the heartbeat signal leads to an autonomic intelligent environment that is in the initial stages of self-management through sensor substitution.

III. Experimental Design

A. *Experiment Theory*

There exists a large body of research in the area of computer vision and image analysis [12], [13], [14]. Whilst it is a viable option to select computer vision as a means of sensor substitution for the identification of door state, there are several factors which led to the investigation of ultrasonic sensors as an alternative sensing modality in this research. In a care home environment the use of computer vision would raise issues of privacy and ethical concerns. The continuous use of image analysis could lead to serious privacy concerns among the occupants of the environment. This may in turn then lead to discomfort within the intelligent environment and hinder the Independent Living, which such environments endeavor to promote. In addition to this, image analysis techniques are not infallible. This would result in the need for a human to continuously monitor the video feed in order to ensure that crucial events are not missed in the image analysis process. Moreover, image analysis is a costly approach both computationally and financially.

Ultrasonic sensors are a low-cost, light weight alternative which are computationally inexpensive; particularly in comparison to vision and laser sensors [15]. For this reason it was decided to investigate their viability as a sensor substitute for the determination of door state.

An internal door within our laboratory was selected as the target door in the experiments carried out within this study. The area surrounding the door was divided into six regions. The rationale for this approach stemmed from the varying effects of sensor placement on the accuracy of state detection. By dividing the area surrounding the door into six regions, an optimal placement for the robot could then be determined based on the most accurate detection of the door state in relation to its position at the door. The accurate relocation of the robot to the optimal position at the door is dependent on effective navigation within the environment. The area of robot navigation in indoor environments is a broad research area that is vastly populated with a range of approaches to accurate navigation. As a result, the specific method of navigation to the optimal robot position is out of the scope of this piece of work.

In this initial study it was determined that the experiments would be carried out in an environment in which sources of interference were strictly limited. As a result the experiments were carried out without the involvement of human participants at this stage in order to initially verify that the ultrasonic array could determine two basic door states; opened and closed. In addition to the determination of these states, we then attempted to establish if the ultrasonic array could detect the presence of an object in the doorway whilst the door was in the open state.

B. *Hardware Set-Up*

The hardware used in the experiments carried out in this study consists of a Pioneer 3DX research robot [16] equipped with an array of eight ultrasonic piezoelectric sensors, a pressure mat and a magnetic contact sensor. The ultrasonic sensors in the array together form a range of coverage of 180°. The sensors are placed at fixed positions within the array; one is placed on either side of the array, while the remaining six face outwards at 20° intervals. The variations of the angles at which the ultrasonic sensors sit provide maximum area coverage and minimize the risk of interference from conflicting echoes. The placement of the sensors within the array is depicted in Fig. 1.

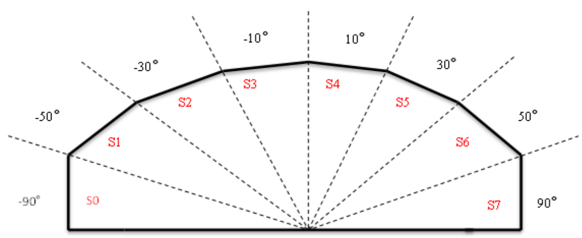

Figure 1. The arrangement of the ultrasonic sensors in the array.

The ranging rate of the ultrasonic sensors was set to 25Hz with a sampling rate of 40ms. Each sensor in the array fires simultaneously every 40ms. Therefore, a full cycle of the sensor array is completed in 320ms. The sensors in the array fire in a specified pattern; in Fig. 1 the sensors are labeled S0 to S7: the firing sequence of the sensors begins in a left-to-right pattern beginning with the sensor labeled S0. Fig. 2 shows the real-life positioning of the ultrasonic sensors in the array; sensors S1-S6 are clearly visible.

Figure 2. The real-life positioning of the ultrasonic sensors in the array. Sensors S1-S6 are clearly visible as the forward facing sensors on the Pioneer 3DX; sensors S0 and S7 are positioned to the left and right of the array respectively.

C. *Experiments*

The experiment stage of this study was divided into two experiments that aimed to establish the accuracy with which the ultrasonic array mounted on the Pioneer 3DX was capable of determining two states: door-closed and door-opened. The experiments were executed based on the failure of the contact sensor to activate.

1) Door-Closed State: In the first experiment carried out in this study we initially sought to establish if the ultrasonic sensor array could determine definitively that the door was in the closed state. The six regions devised from the door area acted as the markers for the placement of the robot. The regions were clearly defined using markings placed on the floor of the laboratory environment in order to enable accurate repeatability of the experiments at each position throughout each stage of the experiment process. The placements of the robot in relation to the door area are depicted in Fig. 3.

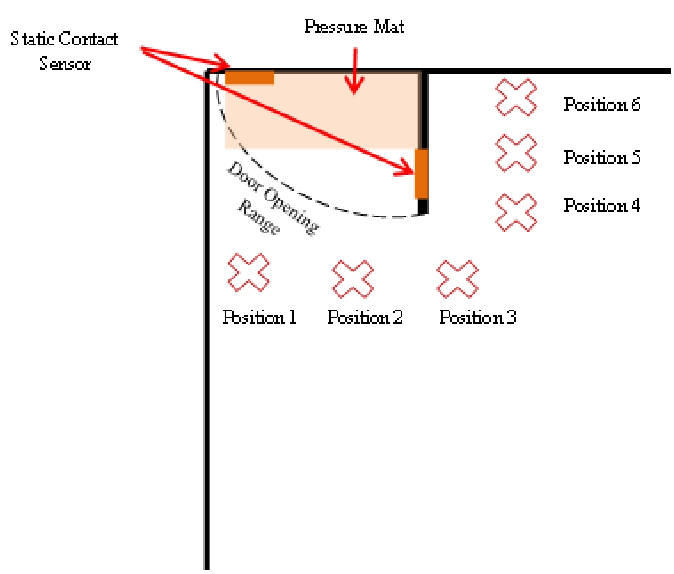

Figure 3. The six robot placement positions in the door region utilized within each of the three experimental stages of this study. The placements of the pressure mat and contact sensor are also depicted.

2) Door-Opened State: The second experiment was set up in a manner identical to that of the first experiment. In contrast to the detection of the door-closed state, the door was opened fully in this instance and readings were obtained from the ultrasonic array from each of the six positions identified in the door area.

IV. RESULTS

The results obtained from the experiments completed within this study showed that ultrasonic sensors provide a viable way for the determination of door state. The variations in the thresholds of the sensor readings were stable. However it was also established that the placement of the ultrasonic array is a contributing factor in the effective detection of door state.

A. Door-Closed State

The robot was placed at the six different positions identified in Fig. 3 in the region of the door and a total of ten samples were taken for each placement of the robot. Each sample taken consisted of fifty sensor readings for each of the eight sensors on the ultrasonic array. A sample size of ten was selected in order to establish the repeatability of the results. The experiment began with cold sensors. The samples were progressively obtained from the sensors as their running time was extended. This facilitated the verification of the consistency of the readings.

The results obtained showed that Position 2 was the most promising placement for the obtainment of consistent readings that could accurately monitor the door-closed state. However, an issue was encountered with the readings from S1; the ultrasonic readings consistently gave a reading of 5000 when the door was in the closed state. Investigation into this issue established that the sensor itself was not faulty as the readings from that sensor altered in their value when placed in the alternative five positions. It was then determined that the consistent reading of 5000 - which denotes that no return echo has been obtained or that an object is closer than 120 millimeters to the array – was a product of sensor noise from the refraction of the ultrasonic signal on the nearby wall.

Position 1 was eliminated owing to its close proximity to the wall alongside the door which produced readings of 5000 from both S0 and S1. These readings compromised the usefulness of those sensors in the later determination of the door-opened state. Positions 3, 4, 5 and 6 failed to produce stable readings that would consistently depict the door state as closed. The rationale for the selection of Position 2 as the optimal placement was derived from the useful vantage point from which the robot could then determine a change in door state from the closed to the opened state as it was directly in the line of the door opening with a good range for the detection of the surface area beyond the door itself which would be present upon the opening of the door.

The data obtained from the ultrasonic array is depicted in Fig. 5. The data are displayed as averages of the sensor readings obtained from the ten samples taken whilst the robot was placed in Position 2. Each sample contains sixty rows of sensor data.

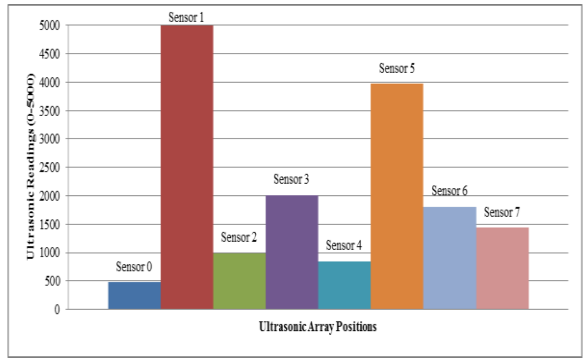

Figure 5. Ultrasonic array sensor data for the determination of the door-closed state.

Table I contains an excerpt of four samples of the sensor readings obtained for each ultrasonic sensor in the array placed on the robot. The data obtained from the sensors show that the readings are stable with only minor variation in their values.

TABLE I. DOOR-CLOSED STATE SENSOR DATA

	Ultrasonic Sonar Array Positions							
	S0	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*
Sensor Readings	478	5000	991	2139	851	3971	1810	1439
	478	5000	991	2139	851	3973	1810	1439
	478	5000	991	2139	851	3973	1810	1439
	478	5000	991	2140	851	3973	1810	1439

B. Door-Opened State

In the second experiment an identical approach was taken to that adopted in establishing the door-closed state. The robot was placed in each of the six positions identified in the door region. The primary focus in this experiment was on the readings obtained from the robot whilst it was in Position 2. As expected based upon the findings in the first experiment, the readings obtained from the robot upon placement in Position 2 were the most accurate values which maintained their consistency across the ten samples. The variation in the new thresholds of the sensor values was minimal when the door state was changed to the opened state. The average readings obtained in the determination of the door-opened state are portrayed in Fig. 6. The sensors that showed the greatest changes in their readings were S1, S3, S4, S5 and S6.

The information provided by the ultrasonic array confirms that the difference between the sensor readings from our initial experiment and those of the second experiment are significantly different. The change in sensor readings can then be used as a sufficient means by which to alert the central server to a change in the topology of the door.

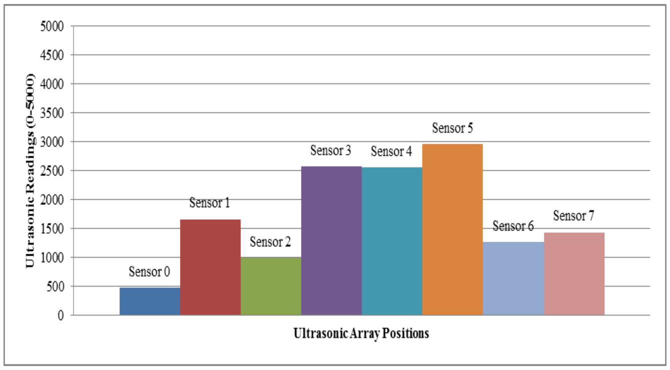

Figure 6. Ultrasonic array sensor data for the determination of the door-opened state.

The data represented in Table II provides an example of the sensor readings obtained with the door in the opened state. The data obtained from the ultrasonic array show a marked difference from those readings obtained when the door was in the closed state.

TABLE II. DOOR-OPENED STATE SENSOR DATA

	Ultrasonic Sonar Array Positions							
	S0	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*
Sensor Readings	478	1662	992	2570	2559	2959	1265	1440
	478	1662	992	2570	2559	2959	1265	1440
	478	1662	992	2574	2559	2958	1265	1440
	478	1662	992	2574	2559	2958	1265	1440

C. Limitations of the Study

The results of this study validate the hypothesis that a mobile ultrasonic array is a viable approach to the substitution of sensors around an external door in an intelligent environment. The results presented have evidenced that the variation in the range of ultrasonic sensor readings are sufficient to differentiate a change in the topology of a door in order to determine one of two states: door-closed, and door-opened.

Whilst the results of this study are promising they are not without limitations. The placement of the robot in Position 2 has the ability to provide accurate and consistent sensor readings; however, Position 2 is not a sustainable position to adopt in the introduction of a human into the further work that will be pursued in this research. The placement of the robot in Position 2 presents an obstruction to the traversal of the door. This would be particularly problematic in an environment occupied by elderly persons suffering from dementia. This is a limitation that will be addressed in future work through variation in the distance from the door at which the robot is placed.

A second limitation of this approach is the inability of the robot to determine the profile of the person traversing the door through the use of ultrasonic sensors alone. The determination of the door state alone is not enough to inform the central server if it is appropriate to send an alert to a care home worker. Whilst the ultrasonic sensors are capable of establishing door state and have the potential to determine a human occupying the region of interest at the door, it cannot clarify: if the person has traversed the door, pacing behaviour or if the door has been propped open.

In order to address these limitations the future work in this research will develop an investigation into the effectiveness of correlating the data obtained from the sensors based in the intelligent environment with those placed on the robot. The aim of this approach is to collectively establish the door state, user profile and the degree to which the door is opened by utilising the available sensing resources rather than relying on one sensing modality. The results of this study have provided a foundation for the progression of this piece of research through the clarification of the capability of the ultrasonic array and the thresholds that are produced when the door is in one of the two states investigated in this study.

V. CONCLUSION

The results of the experiments indicate that the utilization of ultrasonic sensors in the event of the detection of anomalous sensor behavior is a viable option for effective sensor substitution. The data produced by the ultrasonic array show significant variation in the thresholds of the readings to be sufficient to differentiate between a door-opened and a door-closed state. The variation in the ultrasonic sensor readings is not only distinctive, it is also consistent and the results are repeatable when the robot is navigated to the same position. The ultrasonic sensor can determine the door state and provide supplementary information to a central server for effective monitoring of the environment. The results validate a cheaper means of delivering sensor substitution at a low cost both financially and computationally. The safety of intelligent environment occupants can be improved through the substitution of faulty or failed door sensors with an ultrasonic array placed on a mobile robot.

VI. FUTURE WORK

Future work within this research program will seek to build upon the results obtained from this study. In the first instance we will investigate the ability of the ultrasonic array to determine the degree to which the door is open. This will be accomplished by the division of the door opening into six sectors at 15° intervals and the analysis of the subsequent sensor readings. These measurements have been derived from the door opening at a standard 90° angle. The effectiveness of variations in the placement of the robot in relation to the door will then be investigated in order to address the concern of the robot becoming a trip hazard. We will then introduce the human into the scenario and establish the effectiveness of the ultrasonic array when it is subjected to the greater range of variation that it is anticipated the human participant will introduce.

Further work will also be pursued in order to determine if the mobile sensor array can distinguish between a door-opened and door-closed state with the presence of an obstacle in the doorway. It is anticipated that the presence of an object could cause the static environment sensors to produce anomalous data. For example, a pressure sensor may be constantly sending sensing information whilst the door-frame mounted sensor may be indicating the door is closed. A degree of correlation between these two static sensors may be expected – where the pressure sensor is activated, followed shortly afterwards by the door-frame sensor activating – indicating that someone has moved to the door and opened it. We endeavor to resolve this by then correlating the sensor data obtained from the robot with the data obtained from the static sensing technology within the intelligent environment for the purpose of the verification of sensor activity and to assist the central server in decision making.

Finally, we will investigate the robot's ability to test the pressure mat at the door in order to establish if is working correctly through autonomic testing of the pressure sensor. The robot will accomplish this by driving onto the area covered by the mat and obtaining information on its activation or the absence thereof from the central server.

REFERENCES

[1] D. J. Cook, J. C. Augusto and V. R. Jakkula, "Ambient intelligence: Technologies, applications, and opportunities," Pervasive and Mobile Computing, vol. 5, pp. 277-298, 8, 2009.

[2] C. D. Nugent, Xin Hong, J. Hallberg, D. Finlay and K. Synnes, "Assessing the impact of individual sensor reliability within smart living environments," in Automation Science and Engineering, 2008. CASE 2008. IEEE International Conference on, 2008, pp. 685-690.

[3] A. Dohr, R. Modre-Opsrian, M. Drobics, D. Hayn and G. Schreier, "The internet of things for ambient assisted living," in Information Technology: New Generations (ITNG), 2010 Seventh International Conference on, 2010, pp. 804-809.

[4] Research Councils UK. (2011, November 01). Lifelong health and wellbeing. [Online]. Available: http://www.rcuk.ac.uk/research/xrcprogrammes/Pages/Ageing.aspx

[5] D. G. Harwood, W. W. Barker, R. L. Ownby and R. Duara, "Relationship of behavioral and psychological symptoms to cognitive impairment and functional status in Alzheimer's disease," Int. J. Geriatr. Psychiatry, vol. 15, pp. 393-400, 2000.

[6] C. K. Y. Lai and D. G. Arthur, "Wandering behaviour in people with dementia," J. Adv. Nurs., vol. 44, pp. 173-182, 2003.

[7] H. de Quetteville. (2008, June 03). Fake bus stop keeps Alzheimer's patients from wandering off [Online]. Available: http://www.telegraph.co.uk

[8] Alzheimer's Society. (2012, June). Moving and walking about [Online]. Available: http://www.alzheimers.org.uk/site/scripts/documents_info.php?documentID=152

[9] R. Preece. (2012, Oct. 7). Dementia sufferer died after being locked out of care home when he was able to wander outside in middle of the night [Online]. Available: http://www.dailymail.co.uk

[10] R. Sterritt and C. Nugent, "Autonomic computing and ambient assisted living - extended abstract," in Engineering of Autonomic and Autonomous Systems (EASe), 2010 Seventh IEEE International Conference and Workshops on, 2010, pp. 149-151.

[11] G. Brady, D. N. Monekosso and R. Sterritt, "Autonomic robot for assisted living: supporting people with mild dementia," in Engineering of Autonomic and Autonomous Systems (EASe), 2012 Ninth IEEE International Conference and Workshops on, 2012.

[12] H. Lee, H. Dong and H. Aghajan, "Robot-assisted localization techniques for wireless image sensor networks," in Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on, 2006, pp. 383-392.

[13] N. Sato, I. Yoda and T. Inoue, "Shoulder gesture interface for operating electric wheelchair," in Computer Vision Workshops (ICCV Workshops), 2009 IEEE 12th International Conference on, 2009, pp. 2048-2055.

[14] Z. Z. Htike, S. Egerton and K. Y. Chow, "A monocular view-invariant fall detection system for the elderly in assisted home environments," in Intelligent Environments (IE), 2011 7th International Conference on, 2011, pp. 40-46.

[15] L. Kleeman and R. Kuc, "Sonar Sensing," in Springer Handbook of Robotics, Berlin, Germany: Springer Berlin Heidelberg, 2008, pp. 491-519.Z. Z. Htike, S. Egerton and K. Y. Chow, "A monocular view-invariant fall detection system for the elderly in assisted home environments," in Intelligent Environments (IE), 2011 7th International Conference on, 2011, pp. 40-46.

[16] Pioneer 3 Operations Manual, 6th ed., Adept MobileRobots LLC., Amherst, NH, 2010