A Multi-agent Approach to Smart Home Sensors for the Elderly based on an Open Hardware Architecture: A Model for Participatory Evaluation

Katsumi Wasaki[1], Masaaki Niimura[1] and Nobuhiro Shimoi[2]
[1]*Faculty of Engineering, Shinshu University, Nagano, 380-8553, Japan*
[2]*Faculty of Systems Science and Technology, Akita Prefectural University, Akita, 015-0055, Japan*

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Abstract: In this position paper, we present the design and implementation of an in-home sensor agent as an Internet of Things (IoT) smart device system based on an open hardware architecture. This sensor agent is designed to be connected to a wireless network in the target individual's home where it collects trigger information from various switches, motion detection sensors in the room, along with the pillow and bed. We began our study by conducting a complete requirement analysis to determine the functions required for the home sensors. Next, we examined the proposed system terms of its hardware and software requirements and fabricated working prototypes. Here, it should be noted that the hardware and software were designed to aggregate connections with various composite sensor devices in order to allow trigger collection and processing. Finally, we reviewed visualization techniques for displaying the analytical results of the monitoring under normal conditions and emergency situations.

1 INTRODUCTION

Numerous application domains exist that involve tracking and monitoring tools for the elderly. One such domain, in which the main purpose is to guarantee the safety of elderly individuals when they are alone at home, is home monitoring (Jian et al., 2010)(Gaddam et al., 2011)(Yan et al., 2010). Other proposals focus on a specific part of the house, such as the bedroom (Schikhof and Mulder, 2008) or bathroom (Chen et al., 2005). However, unsurprisingly, there are numerous privacy issues involved in using active sensors such as cameras or microphones. Alternatively, applications have also been developed with a focus on monitoring the health conditions of elderly individuals, such as in (Wtorek et al., 2010)(Coronato et al., 2010)(Arcelus et al., 2007), which evaluate physiological and/or physical activities. These observation methods have a high level of accuracy in terms of detecting various behaviors of the target individual via the use of indirect sensors, even though there is still the possibility of more invasive watch-over capabilities when other sensors detect high levels of stress.

Key points for watch-over activities include the early awareness of something unusual happening with the target individual, automatically contacting specialized institutions, and appropriately handling such situations. Unfortunately, in the case of solitary elderly persons, it can be difficult to quickly notice the occurrence of something unusual (such as a porch light remaining on during the daytime, newspapers piling up in a newspaper box, or the person not showing up to meetings) via indirect observations alone. Therefore, it is necessary to construct an automated mechanism that will make it possible to observe the inside of a residence regardless of the time of day or night with a high level of accuracy through a gradual reduction of psychological barriers.

Solitary elderly are typically unemployed persons that spend most of their time at home, often with little communication with the outside world. Despite this, since the daily pattern of everyday lives normally remain constant, it is possible to monitor situations and ascertain the condition of a target individual at home via the operation of his or her electrical appliances and home equipment, and, in doing so, maintain an awareness of possible hazards to the individual.

For example, an elderly individual might habitually wake up at approximately six in the morning, open and close the refrigerator at various times during the day to prepare breakfast, lunch, and dinner, spend the evening watching television, and go to bed

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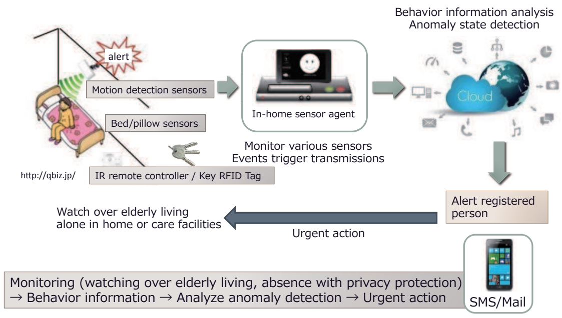

Figure 1: Overview of our elderly monitoring network, which uses multi-fusion sensors and an in-home agent.

at ten at night. He or she might also habitually participate in group activities on Friday afternoons. These examples present typical patterns of a normal lifestyle that many elderly individuals share.

In our present study, we seek to enable the automatic detection of abnormal changes of a target individual at an early stage using a non-invasive collection of triggers that originate from life patterns or cyclic events, while simultaneously considering reduced psychological barriers, by installing sensors in the individual's home. To achieve this, as illustrated in Figure 1, our study proposes the "Solitary Senior Citizens Life Support System of Depopulated Region Area", which requires the installation of sensor agents in an individual's home in order to ascertain normal life patterns and gather information on event triggers. Then, in cases involving changes that deviate widely from these patterns (i.e., anomalies), our system can rapidly detect these variations and immediately report them to a predefined individual in charge of the observation network.

The remainder of this paper is organized as follows. First, we review and analyze the requirements for our system in conjunction with the bed monitor and pillow sensors. Then, based on results of an overall requirement analysis, we consider the functions necessary for sensors in the home. Next, we place our sensor agent, *MaMoRu-Kun* which means "to defend and save" in Japanese, within the home as an embedded system, after which we examine its requirements in terms of hardware and software specifications. Here, it should be noted that the hardware and software were designed to aggregate connections with various composite sensor devices in order to collect and process trigger data. We then examine the specifications in terms of the sending protocol and format for all data collection servers connected using a wide-area long-term evolution (LTE) wireless network. Finally, we review visualization techniques for displaying the analytical results of the monitoring under normal conditions and during an emergency situation.

2 REQUIREMENT ANALYSIS OF OUR WATCH-OVER NETWORK

The most important point for watch-over activities is alerting to abnormalities regarding the target individual as early as possible. Here, it is necessary to identify a threshold level that requires an urgent response via a combination of exterior and interior observations. An increased observation period makes it possible to collect and judge information with higher levels of accuracy, even though there are concerns that the psychological barriers and/or stress related to watch-over systems will be heightened, and that the target individuals could be exposed to privacy invasion risks via the system.

Given these constraints, we performed a detailed requirement analysis regarding an actual implementation of the selected watch-over network observation items, as well as the feasibility of urgent response actions. Each of these areas are described below and labeled [A] and [B], respectively.

[A] *Observation items:* This area governs the ability to observe a target individual's behavior and living conditions under certain situations. Specifically, the equipment must be completely non-invasive. Individual observation items are as follows: (A1) Going to bed as opposed to getting up. (A2) Being at home as opposed to being away from home. (A3) The operation and usage of television(s), air conditioner(s), and other appliances. (A4) The frequency of movements within the home. (A5) Ongoing confirmation that the individual is not bedridden. (A6) The presence or absence of urgent notifications.

[B] *Urgent response items:* This area governs the setting and detection of threshold values regarding whether the present conditions are within or deviating widely from the normal range, as compared with the ordinary life patterns exhibited by the target individual. Urgent response items are as follows: (B1) Data collection and learning during normal situations. (B2) Providing a warning. (B3) Automatically notifying urgent responders (such as relatives, social welfare workers, administrative officers, and retirement home managers). (B4) Real-time alert dispatch to the target individual in the case of an emergency. (B5) The priority of an urgent response. (B6) Using anonymized gathered data, in practice, as big data.

3 COLLABORATION WITH A BED MONITOR AND PILLOW SENSOR

Research is currently underway by Shimoi and Madokoro at Akita Prefectural University regarding bed monitoring and pillow sensors designed to watch over solitary elderly persons while they are sleeping (Shimoi and Madokoro, 2013). Their efforts have focused on detecting situations in which the target individual is sleeping and then changes his or her position when waking up. Such detections are accomplished via a piezo load sensor. Furthermore, as shown in (Madokoro et al., 2013), Madokoro et al. investigate the possibility of making multiple observations of a sleeping individual by installing a three-axis accelerometer within a urethane pillow.

After the system is emplaced and operating, individually observed data are transmitted to a monitor terminal via a ZigBee wireless serial line, which makes it possible to directly gather and store both sensor load and acceleration sensor values in real time.

In this monitoring system, which has already been set up in nursing facilities and similar facilities, it is assumed that a manager located within the same building can visually observe the target individuals. Since the radio wave signals within reach of the target individual's bedroom must be transmitted to a central ZigBee receiver, the transmission range is roughly limited to within a residence. This factor makes it difficult to obtain observation data from outside the individual's home or current location (such as a nursing facility).

Technically, it is easy to consolidate observation data of an individual directly in the server in remote locations via a Wi-Fi wireless local area network (WLAN) or wide-area LTE wireless network. However, from the standpoint of psychological barriers and privacy protection, we must avoid directly recording and sending the target individual's real-time behavior to remote places while he or she is sleeping. This raises a conflicting issue, because emergency reports using the pillow sensors and other such devices around the bed require high levels of real-time information to be useful.

4 FUNCTIONS AND SPECIFICATIONS OF AN IN-HOME SENSOR AGENT

In this section, we describe *MaMoRu-Kun*, a sensor agent for the home. In brief, this agent is a system

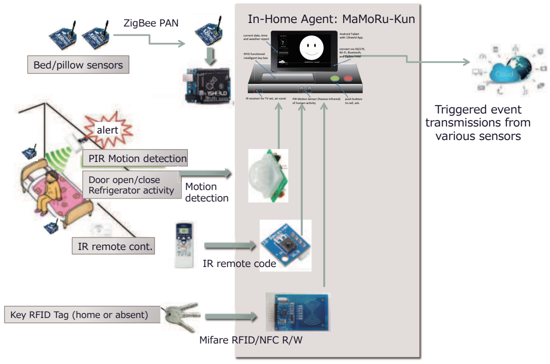

Figure 2: Multi-fusion sensors and detection function using an in-home agent.

embedded with a communication function in such a way that it can operate in cooperation with various sensors installed in the home of the watched-over target individual.

As shown in Figure 2, the most important function of the in-home agent its ability to detect trigger information from various composite sensors, including physical switches, infrared motion sensors, remote control sensors, and radio frequency identification (RFID) key tags (MIFARE, 2001), as well as the bed monitor and pillow sensors mentioned above. The detected trigger information is then transmitted to a local server installed separately within the home that gathers and stores information on the target individual's normal life patterns.

During the day, when the target individual is not in bed, the system is obviously unable to perform behavioral observations with only the bed-based sensors. Therefore, we incorporated the combined use of infrared motion detection sensors, consumer electronics remote control sensors, and other similar sensors to make it possible to observe other behavioral patterns throughout the day (e.g., opening and closing doors, refrigerator access frequency, and household electric appliance use). Furthermore, the system determines whether the target individual is at home by identifying whenever an RFID key tag is detected on a tag interface connected with the agent. More specifically, the system automatically determines that the target individual is not at home when this RFID key tag is not detected within the home for a given length of time.

As part of an entire watch-over network, the sensor agent functions to send life-pattern data under normal conditions and emergency alert notifications to all data-gathering and monitoring servers for use on external networks.

The above functions make it possible to implement requirements (A2), (A3), and (A4) for observation [A] items of the watch-over network. They also make it possible to implement requirements (B1) and

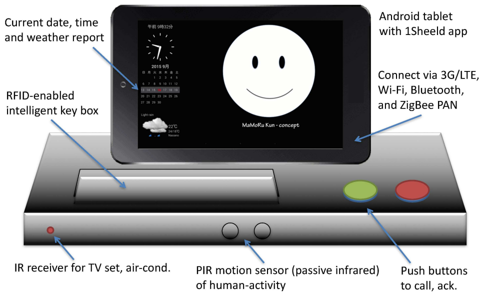

Figure 3: Concept diagram for our in-home agent: *MaMoRu-Kun*'s base station.

(B2) for the [B items] via the combined use of the server in the home. In addition, it is possible to implement requirement (B4) via the emergency reporting transmission function noted above.

5 DESIGN AND IMPLEMENTATION OF THE HOME SENSOR AGENT

We designed and implemented our home sensor agent using peripheral hardware composed of various physical switches, firmware on a microprocessor-embedded Arduino, an interface connected via Bluetooth to the 1Sheeld App (1Sheeld, 2017) multipurpose connection application installed on an Android terminal, and the N2TTS text-to-speech voice synthesis application.

Our system comprises the following components: (1) A base station (new). (2) An Android terminal for communication (existing). (3) A server to gather data within the home (new). (4) An LTE wireless router (existing). Here, component (1) is described in the subsections below, while detailed specifications for components (2), (3), and (4) are omitted due to space limitations.

Figure 3 shows a concept diagram for our in-home agent: *MaMoRu-Kun*'s base station. Figure 4 shows the hardware and software composition of each functional module of the base station.

5.1 Hardware Design and Implementation

(H1) Two physical switches and each passive-infrared (PIR) motion sensor, an RFID-RC522 tag module, an infrared remote-control receiver module, and a motion sensor LED are arranged on a peripheral external board. These devices are connected using the Arduino

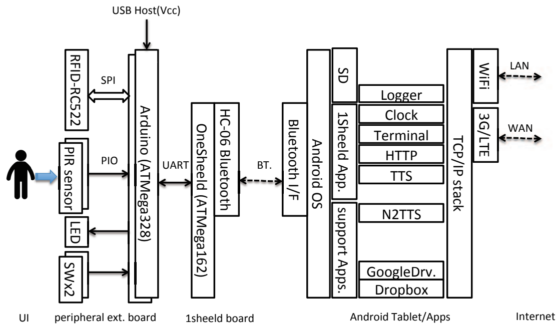

Figure 4: Functional block diagram of our in-home agent, *MaMoRu-Kun*.

(ATMega328) microprocessor via the SPI/PIO interface.

(H2) After processed by the firmware (as described below), trigger information on the processor is transferred to the Bluetooth-connected 1Sheeld app via the UART serial bus.

(H3) After being transferred, trigger information is further transmitted to the Bluetooth paired Android terminal of the other party. The information is designed to be forwarded to the network via the HTTP/TCP/IP stack of the Android terminal.

5.2 Software Design and Implementation

(S1) The Arduino processor firmware, which uses multiple finite state machines (FSMs), was designed and implemented in a way that permits it to format edge triggers via high/low level detection from various sensors and RFID tag modules, as well as conduct tag detection and remote judgment. Two physical switches transmit *"Manual Absent mode"* and *"Manual Home mode"* at the right and left, respectively.

The PIR motion sensor conducts accumulation counts of approaches and departures, transmitting count values when the trigger disconnects from the sensor. The RFID tag module detects approaches and departures of the Mifare tag given to the key (bunch), and after the module remains in a specific state for more than a specific time period, transmits *"Manual Absent mode"* and *"Manual Home mode"*, respectively.

For the infrared remote-control data received, the encoding maker code results and a portion of the 32-bit data are transmitted in the data communication. Motion sensor LEDs blink when physically switched off and when the PIR sensor and RFID tag detect approaches.

(S2) The multipurpose connection application, i.e., 1Sheeld, implemented on an Android terminal, receives trigger information sent from the Arduino firmware and executes processing according to the base station's functional differences (such as logger, clock, terminal, HTTP, and TTS).

(S3) Trigger information was implemented in such a way that it is sent to the network via Wi-Fi using the HTTP/TCP/IP stack. When shifting to home or absent mode manually or automatically, the utterance is implemented via the text-to-speech synthesis application N2TTS for feedback to the target individual.

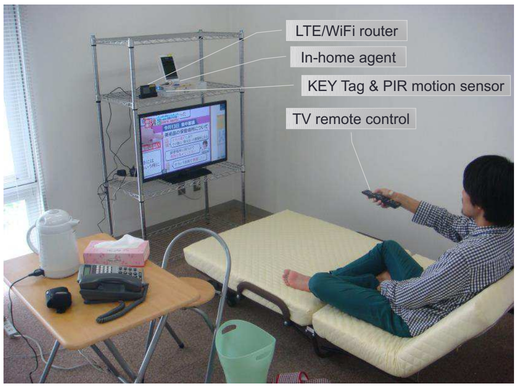

Figure 5: Model room demonstration setup.

6 PROTOTYPING AND PARTICIPATORY EVALUATION

6.1 Prototyping and Load Testing

We produced a prototype based on the above design and specifications. As of September 5, 2016, we had manufactured a total of nine prototype devices ranging from the breadboard to mass production models. The production costs consisting of a newly developed base station were less than $100 USD, while the Android terminal, LTE router, and local server (all of which were commercial off-the-shelf products) were purchased for approximately $900 USD. Thus, each set cost a total of approximately $1,000 USD. We invested approximately 40 person-days into the development of the hardware and firmware, with the size of the firmware being slightly less than 500 lines of code (LOC).

To evaluate the system's actual data-collection abilities, we set up the mass production model in a small-scale test model room at Shinshu University. Figure 5 shows the installation of the tester in the model room, which consisted of a mockup living room and a bedroom of a target individual's home. The model room was furnished with a collapsible cot, an infrared remote control, and various other furniture and fixtures (e.g., a refrigerator, electric pot, desk, chair, and telephone).

The continuous operational test period started on May 18, 2016 for all produced testers (i.e., from the breadboard model to the mass production model), with all testers gathering trigger information from various sensors in the course of normal operations. At one point during the testing, an error occurred in which a library or function involving the key-waiting portion of the RFID tag module stopped working due to noise (i.e., an erroneous stop). Therefore, we devised a method to automatically recover from such a firmware stop by monitoring for malfunctions via a watch dog timer (WDT) inserted into the loop-processing portion of the firmware.

6.2 Collection and Analysis of Multi-fusion Sensors and Trigger Information

We then attempted to apply visualization to each device using a D3.js visualization engine. Figure 6 shows examples visually displayed with the same equipment ID and various parts of the daily trigger information. The displayed examples were obtained by plotting trigger information (i.e., SW1, SW2, KEY, PIR, and RMO) from a home agent with a certain ID between the hours of 6:00 and 20:00 for five consecutive days. When the PIR motion sensor was detected continuously, it was judged that the target individual was actually *at home*, watching television, or moving around the house. In addition, the RMO, which is a receiver for the infrared remote control system, provided evidence to help determine the target individual's *wellness state*, because it switches the television on or off as well as changes the channel. At one point in the data, when the KEY and SW triggers, as well as the PIR and RMO triggers, were missing for as long as two days, it was determined that the target individual was *not at home* during this time period.

7 CONCLUSIONS

In this paper, we described our home sensor agent, *MaMoRu-Kun*, which was developed under the "Research and development of the regional/solitary elderly life support system using multi-fusion sensors" project. Our intent was to construct a network to watch over elderly persons living alone. The hardware and software were designed to establish con-

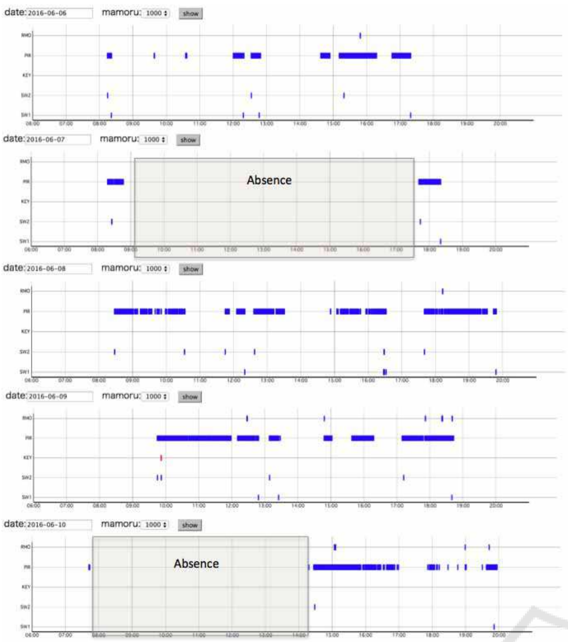

Figure 6: Example trial of device-specific visualization (device ID = 1000),

nections with various composite sensor devices in order to achieve trigger collection and processing. The items added for additional review included visualizing analytical results of the monitoring system under usual conditions, as well as emergency reporting under abnormal circumstances.

With the aim of evaluating the advantages of our proposed system configuration, we created a mockup of a house's living room and bedroom, and configured the system to collect actual data by performing a small-scale demonstration experiment. More specifically, the trigger information for various switches and motion detection sensors was collected by actually activating prototype sensors in our long-term study.

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