Ambient Health Monitoring System for Solitary Elderly

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***Abstract*—In this paper, we propose a sensor-based monitoring system that evaluates the health status of solitary elderly based on daily living activities, and provides signs of declining health to a local nursing center without explicit user interaction. We focus on three daily living activities: urination, kitchen work, and practices for good personal hygiene, because these activities are closely involved in maintaining a healthy lifestyle. These activities are usually accompanied by water use. There are some regularities in the water use during these activities, and the resident's health status is correlated with the regularities. Therefore, the proposed system monitors health status by using water flow sensors which are attached to faucets in the kitchen, washroom and to the toilet. An advantage of this method is that the system can be readily installed in any type of housing at low cost. In addition, this system does not require personal data to be saved or transmitted. The monitoring systems have been installed in three volunteer's housing and some results from this experimental use will be presented.**

***Keywords*–Health monitoring system; Solitary elderly; Water flow sensor; Active RFID tag; Vibration sensor; Quotidian activity.**

I. Introduction

We are confronted with an increasing population of solitary elderly, many of whom live in their own homes and for whom dangerous situations that may require medical attention are ubiquitous. However, the number of caregivers available for frequent home visits is limited. Thus, new care services, such as those that use monitoring systems, are needed to cut costs in health care while still providing security and adequate medical treatment for people who live alone.

There are a number of compact wearable sensors used for the detection of emergencies, such as sensors for the observations of vital signs [1]. This kind of emergency sensor has one disadvantage: it has to be worn constantly and operated actively, making it highly limited in regards to functionality and comfort. Recently, research into this aspect of health care has focused on capturing the activities of daily living by using non-contact monitoring systems. Such monitoring systems can be divided into two categories: to identify a situation that the resident requires immediate medical assistance, or a situation that the resident's health conditions deteriorates at slow rate. One typical example of the first case is a broken bone due to a fall and the second case is caused by hidden diseases, such as a diabetes or by malnutrition. In this paper, we focus on deteriorating health at slow rate, in other words, a sensor-based monitoring system that evaluates the health status of an elderly person based on his/her daily living activities and reports his/her health condition to a local nursing center without explicit user interaction.

One method for the early detection of deteriorating health is monitoring systems that use position sensors. The best-known representatives of position sensors are infrared-ray sensors, which are installed in the living room, bedroom, corridors, and so on [2], [3]. Positional information for the person is acquired from the detection of body heat as he/she moves through the house. A model of the normal day-to-day behavior patterns is created based on the individual's at-home habits, such as their movements, living room use frequency and living room use time, which are derived from positional data [4], [5]. Problems with the individual's physical condition can be detected when there is a major variation between the model behavior and actual behavior patterns. The development with this kind of day-to-day behavior models using machine learning methods is that they require a solid database with a substantial number of cases in order to achieve reasonable results. In addition, a unique model must be made for each and every person. Therefore, the installation of such technologies takes a great deal of time.

Moreover, these position sensors provide only indirect information on health status. In other words, positional information does not always correspond to vital activities related to health status. From the viewpoint of reliability, it is desirable to directly specify normal daily activities and then to detect variations which may be signs of a dangerous situation. TV cameras can observe daily activities and detect dangerous situations, but privacy concerns make their introduction into private homes limited. A smart meter, which is used for the billing of electricity, can also be used for activity recognition [6]. Momentary variations in power consumption are recorded in the smart meter, and use of household appliances, such as a vacuum cleaner and a toaster oven, can be ascertained from the variations, allowing the inference of daily living activities. However, it is very difficult to analyze the variations in power consumption.

We focus attention on three quotidian activities: urination, kitchen work, and practices for good personal hygiene, because these activities are closely involved in maintaining a healthy lifestyle. These quotidian activities are usually accompanied by the regular use of tap water, and an individual's health status can be correlated with this regularity. Therefore, we propose a health monitoring system that uses the water flow sensors that are attached to faucets in housing. An advantage of this method is that rule-based methods can be used for analysis and interpretation of the sensor data [7], [8]. The

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rules can be derived from experiential knowledge of water use during urination, kitchen work, and practices for good personal hygiene. In addition, these sensors are available at a reasonable cost. The system can be installed easily in any type of housing, and no interaction by the user is required. No personal data, such as photographs or video recording are saved in the system or transmitted.

This paper is extended in some ways from our previous paper [9]. The former system was just a prototype to see whether the sensor system can acquire correctly the time and frequency of water use from the quotidian activities. The present system has been redesigned and improved at the points of reliability and energy consumption in order to keep functioning for a long time in real environments. The monitoring system has been installed in three volunteer's housing and some results from this experimental use will be presented. This paper is organized as follows. In Section 2 we give a brief outline of the proposed method and monitoring system. Section 3 describes the technical aspect of the monitoring system. Section 4 describes the implementation of the monitoring system and experimental results. Concluding remarks and future goals are given in Section 5.

II. Overview of the Proposed Monitoring System

In our system, we focus on three quotidian activities, that is, urination, kitchen work, and practices for good personal hygiene. As mentioned below, there are some regularities in the water use during these activities, and the resident's health status is correlated with the regularities.

We know that humans urinate an average of six to eight times a day; thus, if an individual makes much less or much more frequent use of the toilet, then some illness or problem can be suspected. If one wakes two or more times before dawn to urinate, this can also be a sign of poor health state. Common causes of such symptoms are a urinary tract infection, diabetes, stroke or other neurological diseases, chronic kidney disease, and so on [10], [11]. Therefore, the number of times and the time of day that an individual urinates are important signs of health status. It is possible to infer the health status by checking the flow of water at the toilet's flush tank in the bathroom.

Cooking is also a fundamental human activity. It is not only connected with the joy of eating but also deeply affects various aspects of human life, such as health. Needless to say, healthy eating habits improve quality of life and help the elderly maintain good health. It is said that changes of appetite occur in conjunction with diseases of the digestive system, taste disorder, dementia, and so on [12]. Therefore, daily kitchen work also includes an important sign of health status. At mealtimes people use a large volume of water in the kitchen for cooking and washing dishes. Time periods when the use frequency of tap water in a kitchen is high appear in the distribution graph of water use, and are very likely to be observed in the morning, at around lunchtime, and/or in the evening. Such activities can be inferred based on water flow at the kitchen sink.

If people are healthy, they usually wash their faces and rinse their mouths when they get up in the morning and go to bed at night. They sometimes perform activities, such as hand-washing to keep themselves clean. It is said that poor personal hygiene occurs in conjunction with depression, dementia as a result of Alzheimer's disease, Parkinson's disease, and so on [13]. Such activities as maintain personal hygiene show important signs of health status. Although the volume of water use at a washroom sink is not large and the water use is scattered sparsely in the distribution graph of use frequency, such activities can be inferred based on water use at a washroom sink.

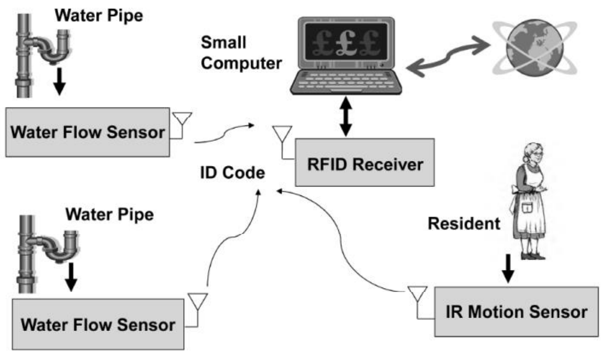

Figure 1. Functional block diagram of the monitoring system.

Therefore, monitoring the duration of tap water use at kitchen and washroom faucets and at toilet at particular times of day, makes these three activities (urination, kitchen work, and hygienic activities) directly recognizable, and signs of ill health in the elderly can be deduced. Figure 1 provides the functional block diagram of the proposed monitoring system. The monitoring system consists of three main components: water flow sensors with active radio frequency identification (RFID) tags, an infrared (IR) motion sensor with an active RFID tag, and a small computer with an RFID reader. The water flow sensors are attached to a water pipe near faucets on the kitchen and washroom sinks, and to the water pipe to the flush tank of the toilet in the bathroom. These sensors transmit a radio frequency (RF) signal with an ID code, at one-second intervals while water is flowing through the faucet. The IR motion sensor is installed in a place where the resident comes and goes frequently, such as the living room, a bedroom, or corridors. It sends an RF signal with its ID code when the resident passes the sensor. The monitoring system can acquire information about whether the resident remains indoors based on the time stamp of the ID codes from the motion sensors. The computer is placed in the house of the resident and is wirelessly linked with the sensors through the RFID reader. The computer records the receipt time of the ID code sent from each sensor, judges the health status, and sends a report to the nursing center via the Internet.

The reasoning program installed in the computer derives the time and duration of tap water use from the time stamps of the received ID codes from each faucet. In addition, it estimates the at-home time of the resident from the IR motion sensors. This at-home time is used to reinforce reasoning of health status based on data from the water flow sensors. A model for normal water usage is created based on experiential regularity, as mentioned above. When there are major variations between the model and actual usage patterns, it is assumed that there is something wrong with the resident's physical condition, and the reasoning program reports signs of declining health to a local nursing center. Then, a caregiver will visit the resident to verify his/her condition.

III. Equipment for the Monitoring System

This section describes the technical aspect of the functional blocks shown in Figure 1. We considered the following thing for the system redesign. The sensor system should be reliable and low power consumption for long time operation, because it is not expected that the monitoring system is maintained or managed by the user.

Figure 2 illustrates the latest prototype of the water flow sensor. A water flow sensor consists of a vibration sensor, a sound-activated switch and an active RFID tag. Mechanical vibration in the range of 0.5 to 10 KHz occurs at the water pipe near the faucet while tap water is running. The vibration sensor is designed to be attached to the water pipe near a faucet to pick up the mechanical vibrations. A ready-made vibration microphone used for tuning musical instruments, such as guitars can be applied to the vibration sensor, which is available for less than 5 euros in the market. The microphone is clip-on and the point of a clip is machined to fit the shape of a water pipe. Figure 3 shows an example of the vibration microphone clipped to the water pipe to the flush tank of a toilet. The active RFID tag has a unique ID code (8 characters), which provides information about its location in the house. When the microphone detects mechanical vibrations from the faucet, the sound-activated switch turns on the active RFID tag. Consequently, the tag sends a radio frequency signal (2.4 GHz) with its ID code. The signal is transmitted at one-second intervals while the water continues to flow through the faucet. The monitoring system measures the time of running water from each faucet to obtain the use frequency and duration of tap water use in everyday life. The tags can send signals indoors to a range of up to about 15 m, which is sufficient in a normal house. The sensors have a rechargeable lithium polymer (Li-Po) battery (6600 mAh) built-in and can keep functioning for about 13 months.

Figure 4 shows the prototype of the IR motion sensor. The motion sensor consists of a pyroelectric infrared sensor with a Fresnel lens and an electronic circuit to form the module, and an active RFID tag. The motion sensor is installed at a location in the house where the resident comes and goes frequently. The motion sensor detects motion by checking for a sudden change in the surrounding infrared levels, which is caused by the resident's body heat as he/she passes the sensor. The sensitivity of the sensor is limited to detecting a person up to 4.5 meters away. When the infrared sensor module detects such changes of the infrared levels, the module turns on the active RFID tag for 2 seconds. Consequently, the tag sends an RF signal with its ID code twice (once per second). The monitoring program records the time when an ID code was transmitted in order to estimate how many hours the resident was at home that day. The sensors have a Li-Po battery (6600 mAh) built-in and can keep functioning for about 7 years.

Figure 5 illustrates a small computer (Raspberry Pi B+) with an RFID reader. The RFID reader receives the RF signal from the tags, obtains the ID code and reports it to the computer through a USB port. A reasoning program is installed on this computer, which is written in C and runs on the Pidora (a kind of the Linux for the Raspberry Pi).

The number of times that ID codes were transmitted from the faucets indicates the amount of time that there is running tap water, and this is proportional to the amount of water

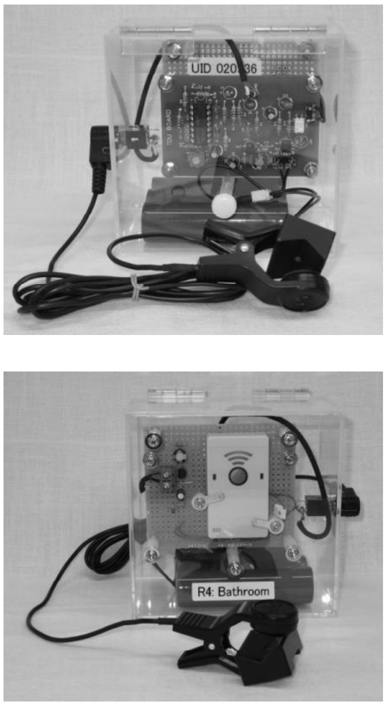

Figure 2. Prototype of the water flow sensor which consists of a vibration microphone, a sound-activated switch (the upper image), an active RFID tag (the lower image), and a battery.

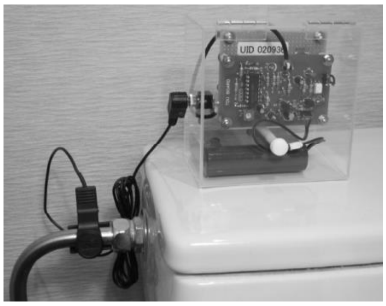

Figure 3. Vibration microphone clipped to the water pipe to the flush tank of a toilet.

used because ID codes are transmitted steadily at one-second intervals while the water is running. The received ID codes are accumulated at one-hour intervals to obtain a distribution of the duration of tap water use for each faucet. On the other hand, the time when the ID code was transmitted from the motion sensor indicates the resident's stay in the house. The received ID codes are also accumulated at one-hour intervals to obtain the frequency distribution of access to the sensor, in order to estimate how many hours the resident was at home by the hour. The reasoning program judges the health condition of the resident based on the distributions of the duration of tap water use for each faucet and the frequency distribution of access to the motion sensor.

IV. Implementation and Experimental Results

The monitoring system was installed in a real housing environment and an experiment was conducted to see whether the sensor system can acquire the time and frequency of water

Figure 4. Front side of the IR motion sensor (an IR sensor module with a Fresnel lens and an active RFID tag at the back side).

Figure 5. Small computer with an RFID reader inserted in its USB port.

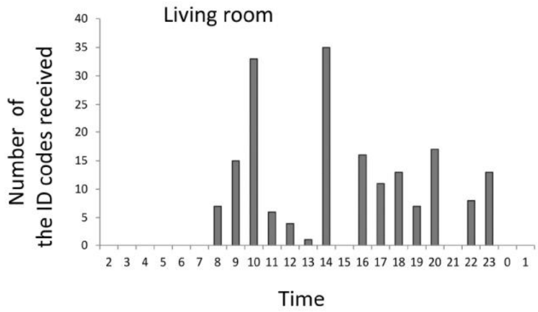

Figure 6. Frequency distribution of the resident's access to the living room.

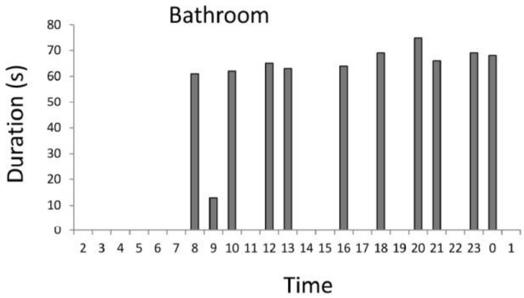

Figure 7. Distribution of the duration of water flow at the toilet's flush tank.

use from the resident's quotidian activities. The house had a living area of 108 square meters (roughly 15 m by 8 m) and the resident was a 68-year-old man. The IR motion sensors were placed on a cabinet in the living room. The water flow sensors were set at the kitchen sink, the washroom sink and the toilet's flush tank. The maximum distance between the RFID reader and the sensors was 8 m. First, the sensitivity and reliability of the water flow sensors were checked. The sensors could detect gently running water, such as would be poured into a glass.

Figure 6 illustrates the frequency distribution of the resident's access to the living room. The horizontal axis of the graph denotes the time at one-hour intervals, starting at 2 a.m. The vertical axis shows the number of times ID codes were received from the IR motion sensor. The sensor was placed on a cabinet in the corner of the living room connected to the corridor; thus, the motion sensor was activated only when the resident went in and out of the living room along the corridor. The sensor transmitted its ID code twice at one-second intervals, each time the resident passed it. The number is proportional to the frequency of access to the living room. Based on the time stamp of the received ID codes from the motion sensor, it can be seen that the resident got up at around 8 a.m. and went to bed at around 1 a.m. During the day, he was in the house and followed his daily routine. From the frequency distribution, the time zone when the resident went out can be estimated, and is used to reduce uncertainty in deducing health status based on data from the water flow sensors.

Figure 7 illustrates the distribution of the duration of water flow at the toilet. The horizontal axis of the graph denotes the time at one-hour intervals starting at 2 a.m. The vertical axis shows the duration of water use in seconds. The water flow sensor was set on the water pipe connected to the toilet's flush tank in the bathroom. The flow sensor transmitted its ID code at one-second intervals while water was flowing into the flush tank; it took about 60 seconds to fill the tank. The graph shows that the resident urinated 10 times on this day, at an average interval of 1.7 hours.

Figure 8 is a graph of the duration of tap water use at the kitchen. The water flow sensor was set on the water pipe connected to the sink's faucet. High-use periods were observed three times on this day. This implies that the resident used tap water for preparing meals in the morning, at around lunch time, and in the evening. The total time of water use was relatively short because the house is equipped with a dishwasher.

Figure 9 is a graph of the duration of tap water use at the washroom sink. The water flow sensor was set on the water pipe connected to the sink's faucet. This sensor is intended to detect quotidian activities for maintaining physical cleanliness. In other words, this sensor detects activities such as face washing, and brushing of teeth. The volume of water used at the washroom sink was not large because washing a face does not require so much water. The graph shows the washroom sink was used at around 9 in the morning. This implies that the resident used tap water for activities such as brushing his teeth and washing his face. It also illustrates that he performed activities, such as hand washing during the day and rinsing his mouth around midnight.

The reasoning program regards the duration of water use at each interval as one activity if the duration is above a fixed

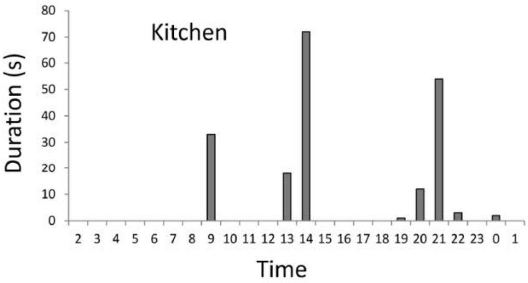

Figure 8. Distribution of the duration of tap water use at the kitchen.

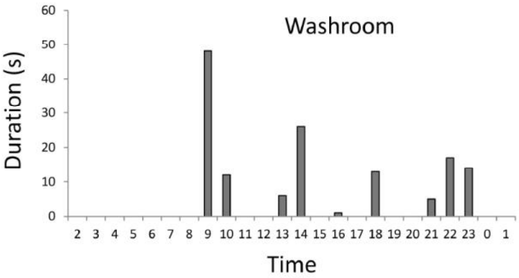

Figure 9. Distribution of the duration of tap water use at the washroom.

threshold of time. When the number of quotidian activities coincides with given criteria, it is assumed that there is some problem with the resident's physical condition. The criteria for judgment were created based on the model of normal water use, which was derived from the medical knowledge and regularity of daily living activities, as mentioned in Section 2.

In order to confirm the criteria for reasoning, we asked three solitary elders to use the monitoring system. The two of them (denoted as A and B, in Table I, II, and III, respectively) are 86 and 91 year-old women in good health conditions. By good health conditions we mean these elders are not under a doctor's care. Although they are living alone, their relatives visit their homes sometimes. The third elder (denoted as C) is a 92 years-old man with the early stage of dementia, and hypertensive condition. He takes an anti-hypertensive drug. There is no relative to visit him and the care giver visit him regularly. In the case of the two women (A and B), the monitoring system has been set in their housing for nearly one year, and the man (C) for three months.

It is said that humans urinate an average of six to eight times a day; thus, if an individual makes much less or much more frequent use of the toilet, then some illness or problem can be suspected. If one wakes two or more times before dawn to urinate it can also be a sign of a poor state of health. Therefore, Table I shows the average frequency of the water use per day at the bathroom in each housing and the average frequency is based on the latest one month measurement. The average frequency of the bathroom use for A was 8.71 times with standard deviation (STD) 2.23. The average frequency before dawn (from 2 a.m. to 5 a.m.) was 1.54 with STD 0.85. In the second elder's case (B) the average frequency was 6.93 with standard deviation 1.75. The average frequency before dawn was 0.72 with STD 0.53. In the case of the

TABLE I. Frequency of water use at the bathroom.

	All day		Mid night	
ID	Average	STD	average	STD
A	8.71	2.23	1.54	0.85
B	7.03	1.93	0.72	0.53
C	13.5	2.29	1.84	1.18

TABLE II. Peak time of water use at the kitchen.

ID	Breakfast	Lunch	Supper	Percentage of the day
A	7.6	13.2	18.2	74
B	9.0	11.8	18.7	100
C	8.8	12.3	18.4	63

man (C), the average frequency was 13.5 with STD 2.29. The average frequency before dawn was 1.84 with STD 0.85. These numbers suggest that his micturition is affected by some disease.

At mealtimes people use a large volume of water at the kitchen for cooking and washing dishes. Time periods when the use of kitchen tap water is high appear in the distribution graph of water use, and are very likely to be observed in the morning, at around lunchtime, and/or in the evening. Table II shows the average peak time of the water use at the kitchen in the three time zones: breakfast time (6 a.m. to 10 a.m.), lunchtime (11 a.m. to 3 p.m.) and suppertime (4 p.m. to 8 p.m.). The fourth column of Table II presents the percentage of the number of the day when a peak time appears in every time zone. If the day when a peak time appears two times is added to the number the percentage gets up to 99 percent. This percentage means people have a strong regularity regarding to meals.

If people are healthy, they usually wash their faces and rinse their mouths when they get up in the morning, or before they go to bed at night. They sometimes perform activities such as hand-washing during the day to keep themselves clean. Table III shows the average amount and frequency of water use by the day at the washroom in each housing, which is based on the latest one month. In the case of A, the frequency of water use was few. In other cases, the frequency was about four time, and the average amount of running time of water was from 200 to 500 seconds. According to interview with the relative of A, she seems to use often the faucet near the bus tub for washing her hands and so on. As you know Japanese bus tubs are in their own spaces separated from the toilet, and are provided with a place and faucet for washing the body. In the case of C, he used much water at the washroom. He seems to have often washed dusters and so on. The amount and frequency of water use at a washroom seems to be dependent on the resident's lifestyle. Regarding to water use at a washroom sink, more observations in various home environments should be conducted to determine subtle criteria for generating automatic

TABLE III. Frequency and amount of water use at the washroom.

ID	Average frequency	STD	Volume (unit: second)
A	0.71	0.79	45
B	4.0	2.38	193
C	4.47	1.83	507

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Report on Daily Living Activities
Client ID : R4M60001 Date : 2/12/2017

- Urination : Normal
  (Time Log of Water Use: 10 12 15 17 18 19 21 22 0)
- Kitchen Work : Normal
  (Time Log of Water Use: 10 11 15 17 18 19 20 21 0)
- Keeping Cleanliness : Normal
  (Time Log of Water Use: 10 11 12 0 1)
- Movement in & out of Living room
  (Time Log of Movement: 9 10 11 12 13 15 16 17 20 21 22 23 0 1)

Figure 10. Example of an e-mail message.

alert messages.

The criteria for judgment were created based on the results from these observations at three elders' homes, the medical knowledge, and the regularity of daily living activities. A brief outline of the criteria is as follows.

- If the frequency of urination is greater than twice in the night (from 2 a.m. to 5 a.m.), there is an assumption of "something wrong".
- If the resident remains indoors during the day time and
  - the frequency of urination is lower than 5 times or greater than 11 times; "something wrong".
  - the peak time of water use at the kitchen is less than twice; "something wrong".
  - the frequency of water use at the washroom is less than once; "something wrong".
- If the resident is out of the house for a long time, then the numerical values for these criteria are reduced in proportion to that time.

Each night at 2 a.m., the program judged the resident's physical condition from the criteria and sent out a daily report to appointed addresses by e-mail. In this experiment, the relatives, the caregiver, and the author were specified as the e-mail addressee. At same time all the data gathered to the monitor system was saved at the data server in the author's office, and was deleted from the monitor system. Figure 10 shows an example of an e-mail message, which consists of four items: "Urination", "Kitchen Work", "Keeping Cleanliness" and "Movements in & out of Living room". The first three items consist of a judgment, and the list of time of major water use on the day. The fourth item includes only the list of time of the resident's movements in the house. If each quotidian activity coincides with the given criteria, the judgment was denoted as "Something Wrong" and otherwise, as "Normal".

V. Concluding Remarks

We proposed a health monitoring system, which evaluates the health status of solitary elderly based on daily living activities. The system monitors three quotidian activities that are closely involved in maintaining a healthy lifestyle: urination, kitchen work, and practices for good personal hygiene. These quotidian activities are usually accompanied by water use, and there are some regularities in water use, which correlate with the health status of the resident. This is the reason why we paid attention to the three quotidian activities.

There is a demand for a reasonably priced, noncontact sensor system that can directly recognize these quotidian activities. In addition, the monitoring system should be affordably installed into any type of housing. To meet these demands we proposed the water flow sensor with a vibration microphone that can be easily clipped to a water pipe leading to a faucet. We made a prototype of the monitoring system from electronic parts that are all available in the market.

The prototypes have been installed in three volunteer's housing in order to confirm the criteria for reasoning. Although useful results were derived from the experimental use, regarding to water use at a washroom, more observations in various home environments should be conducted to determine subtle criteria for generating automatic alert messages.

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