A Smart Monitoring System for Assisted Living Support Using Adaptive Lifestyle Pattern Analysis

A Vision for the Future

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Abstract. In recent years there has been a rapidly increasing intensity of work going into investigating various methods of facilitating assisted living for the benefit of the elderly and those with difficulties in mobility. This chapter describes one such effort which distinguishes itself from the rest by considering and describing a system with true commercial potential and thus significant social impact. Promising efforts in investigating and identifying the requirements for a system of smart monitoring and adaptive lifestyle pattern detection and analysis are described. An initial proposal for a system relying on remote monitoring using persistent communications technology and a centralized data gathering, analysis and decision making is presented. During the initial development stage requirements for sensor placements, efficient sensor data formats and transmission protocols became apparent; unit testing and system validation demanded generation of large amounts of suitable sensor data. Here we also describe a simulator we developed in order to support these requirements; the rationale behind the simulator, its main functions and usage and the positive contribution it has made during the initial stages and the prototyping phases of the above system are explained. Finally a prototype developed in facilitating initial investigations is described and the vision for future developments is articulated.

Keywords: assisted living, pattern recognition, remote sensors, communications protocols, simulation, rule-based inference.

1 Introduction

Advancements in technology have significantly changed the way we think and act. Banking, travel, science, education and health are some of the areas that have seen huge improvements as a result of recent innovations in technology. This is especially true in the case of the health services. Leveraging modern computing power, communications technology and advancements in software developments for the benefit of those who suffer disabilities and health problems and are in need of regular supervision and personal caring have become essential for providing the best support in affordable, enhanced and caring social services. This support is aimed at providing two

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main benefits: enhancing independent living of the individuals affected and making significant savings in the cost of support to individuals provided by the social services and the local authorities.

Our motivation for pursuing this research project initially stems from several important considerations often associated with ageing: rapidly increasing numbers of aged people, correspondingly increasing old-age related chronic illnesses and disabilities and increasing rate of life-threatening injuries. Fig 1(left) illustrates that in UK the number of people aged sixty and over is projected to increase from 12 million in 2001 to 18.6 million in 2031 [1]. At the same time according to Fig 1(right) chronic diseases and disabilities are projected to increase twofold to threefold [1] for people aged 65 or over. Mental illnesses like feeling alone, fear of falling, feeling weak and depression often lead to excessive intake of alcohol that further increases the risk of falling, poor mental and physical health. The following statistics on falls in UK represent some sobering facts. About a third of all people aged over 65 fall each year (which is equivalent to over 3 million); falls represent over half of hospital admissions for accidental injury and the combined cost of hospitalisation and social care for hip fractures (most of which are due to falls) is £2 billion a year or £6 million a day [2].

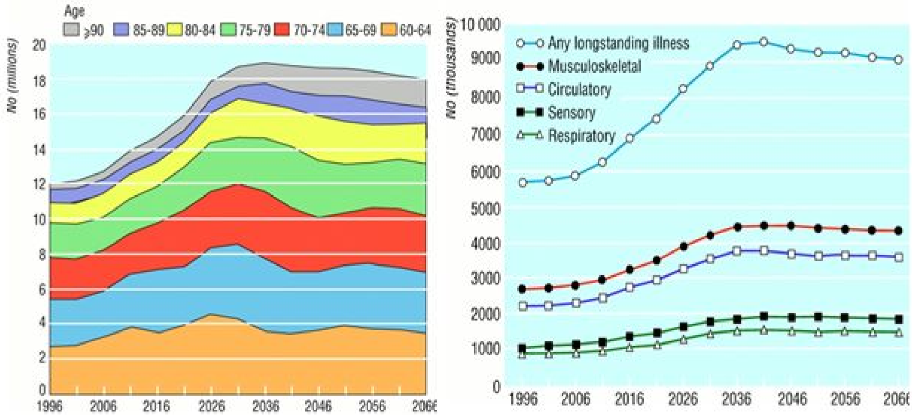

Fig. 1. (Left) Projected numbers of people aged 60 years and over in the UK; (Right) Projected numbers of people aged 65 or over with chronic illness in UK [2]

Most humans naturally prefer independent living but with advancing age or disabilities this becomes risky when living alone; elderly or people with disabilities often end up living in sheltered housing where nursing and care facilities are available at a price. This imposes increasing pressure on the resources of social services and local authorities to provide efficient and cost effective carer services especially during the current economic climate in which the stringent austerity measures are likely to become more severe.

It is in these settings that we at the Department of Computing got together with a local high-tech commercial security systems company Securecom Ltd. based in Rochdale, UK. Securecom design and develop specialist remote monitoring systems for the security industry and work closely with local authorities to provide secure housing for a large number of local authority tenants. The collaborative work is on the initial definition of the requirements for and the subsequent development of a scalable assisted living support system based on the extensive experiences of Securecom on remote monitoring and the application of this to software based adaptive lifestyle pattern recognition technology. The requirements have resulted in a number of challenges for us to face and find solutions for. We elaborate on these challenges later on.

2 Remote 'Smart Monitoring' for Assisted-Living

Fig 2 depicts the general setup for remote home monitoring system designed to provide assisted-living support. Sensors placed in a property are used to track various aspects of the monitored person's daily activities. Sensor data are gathered by the transmitter installed in the property that is responsible for sending the sensor data to a central station via a permanent Internet connection available in the same property. This transmitter also functions as a security alarm panel protecting the occupants from hazards like intrusion or fire.

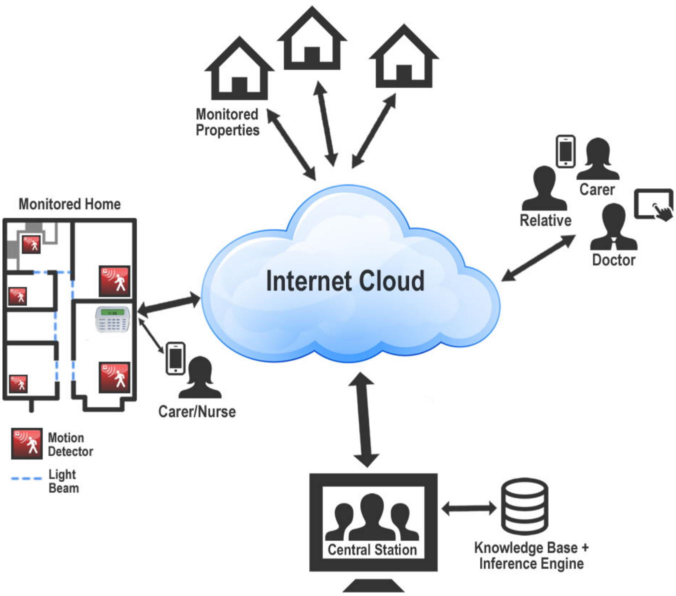

Fig. 2. Outline of remote 'smart' monitoring system

The central station constantly monitors and evaluates the incoming sensor and security alarm data and stores the information in customer database while at the same time analyzing the sensor data in order to detect any anomalies in a person's daily activities and life-style patterns; on detection of such anomalies the central station can alert the nominated person(s). The system is highly scalable and is designed to handle monitoring a large number of properties.

The information gathered can be presented in many different forms that can represent a ‘picture’ of a person’s life-style and highlight any significant anomalies or deviations from the ‘norm’. It can also identify any gradual and subtle changes in behavioural patterns that may be indicative of possible onset of an illness, e.g. loss of weight (if measured), increasing visits to toilet, increasing instability in movements, etc. This information can then be made available to interested relatives, carers and doctors via their mobile equipment such as mobile phones and tablet computers.

3 Related Work

Research in assisted living has been an area of rapidly increasing interest involving both the academics and the health industry for some time under various names such as Ambient Assisted Living (AAL), Tele-Health Systems, Smart Home Environments, E-Health Services, etc. and covers a very wide area generally involving assistance to enhance the quality of life of elderly and the disabled. The common theme is based on the acknowledgement of the power of modern computing and communications technologies that can drive and facilitate these systems and schemes. The published number of research is too numerous to review here. However, we can classify the work done under some general groups that distinguish their contributions:

- Sensor networks and activity detection devices: The research work in this group describe sensor networks, sensor devices, use of Internet for sensor data transmissions, wireless sensors and devices that can be remotely controlled for robotic assistance [3, 4, 5].
- Pattern recognition and analysis: Behavioural pattern recognition is an area that is attracting much attention. Advancements in ways of analysing patterns of daily activities are central to assisted living support [6, 7].
- Complete monitoring systems: These are systems that include sensor networks, communications methods and pattern recognition algorithms and form total systems for wide range of assisted living support [8-11].
- Simulation support: Tools to help create innovative products by usability engineers, to model living spaces, movements and locations of monitored persons, to design supporting hardware and software products [12-17].

Our work described in this paper has one important theme in common with the above related work: assisting in the definition and development of safe, efficient, affordable and meaningful assistive technology using targeted modeling and testing of different aspects of this technology. Beyond this our work significantly differs from the work of others and covers areas not covered by other similar work as far as we are aware. For example, we have not come across any simulation models that study and explore specific areas such as sensor data formats and protocols, sensor device selection and placements, local sensor data buffering and efficient transmission to remote central monitoring centers. Most of the work carried out has been theoretical and experimental with several systems proposed and frameworks developed. However, to our knowledge, there has not been any significant system developed and demonstrated at a commercial level and scale. Therefore we claim in this paper that what sets our work apart from most of the others is that our work has primarily been driven by the desire to realize the results of our research in commercial settings.

4 The Challenges

Our research work was prompted by a need for a new comprehensive and tightly integrated technology within security industry involving ‘intelligent’ remote monitoring for assisted living support. The challenges faced are multifaceted:

- Collection of multitude of data using a wide range of remote sensors.
- Transmission of sensor data to a remote central station
- Storage, analysis and visual presentation of the collected sensor data.
- Determination and prediction of state-of-health of monitored persons.

We investigated each of the above challenges through preliminary test cases which involved software prototyping and simulations of sensor data collection, transmission and analysis. Below we consider our initial responses to each of the above challenges.

4.1 Collection of Multitude of Data Using a Wide Range of Remote Sensors

In order to be able to provide support for assisted living regular collection of data on location is a necessity. The challenge in this case is to determine what sensor data to gather, what the optimal placements of the sensors are and how frequently the sensor data should be gathered. In order to be able to investigate this challenge a unique software simulator was designed and developed. This simulator served three purposes: a) to investigate sensor requirements and placements, b) to assist in the development of new transmission protocols and c) to serve as a test data generator for the analysis software based at a central monitoring station.

4.2 Transmission of Sensor Data to a Remote Central Station

The challenges here are a) the economy of the format of sensor data packets, i.e. the minimum content required that can be efficiently (in terms of frequency, priority and size) transmitted and stored and b) the storage and pre-processing of data by the local data-logger and transmitter. The sensor data is sent wirelessly across the property to the data logging device which will transmit blocks of sensor data to the central monitoring station at suitable intervals. The transmission method is persistent and will rely on the transmitter’s ability to use any one of the progressively lower quality transmission routes: Internet using TCP/IP connection, GPRS, telephone line using DTMF signaling and SMS text messaging.

4.3 Storage, Analysis and Visual Presentation of the Collected Sensor Data

The sensor data received at the remote central station will be stored in the most suitable and efficient manner which should enhance the accuracy and speed up the analysis phase. The central station should be able to receive and store sensor data from many remote locations often at the same time. The main challenges here are a) formatting of sensor data which may be stored in compressed form, b) the real-time analysis of sensor data and c) the presentation of the results of the analysis. The digital receivers at central station will be capable of communicating with many remote digital transmitters using proprietary protocol that will be independent of the chosen transmission route. This protocol will rely on high-level handshaking and error detection/correction methods for maximum reliability. The biggest challenge is the analysis phase. The project proposed and investigated the use of 'Adaptive Life-style Pattern Recognition and Analysis' (ALsPRA) process as the linchpin of the project and the system being investigated. The life-style pattern of a person being monitored is developed over a period of time and is central to the detection of any significant or trending deviations from a baseline, i.e. the most recent 'norm'.

4.4 Determination and Prediction of State-of-Health of Monitored Persons

This part of the investigation looks into the future. It is expected that ALsPRA method will have the potential for short-term predictive capability. This is most appropriate in the case of health and behavioural monitoring. Any deviation from norm over certain period of time may be indicative of impending health problem(s) which if treated on time may save lives or improve quality of life.

5 Simulating Assisted-Living

Our collaborative effort first needed to develop a prototype system in order to a) assist us in our initial feasibility study in exploring the potential of the proposed system including its commercial viability, b) identify any unique supporting features needed in the new generation of digital transmitters currently being developed by our collaborating company partner and c) serve as a demonstrator for the company to attract interest from its existing and future customer base. We therefore resorted to developing our own unique purpose built simulator to support our initial effort.

In order to be able to study the requirements for sensor selection and placements as well as the requirements for the essential communications parameters such as higher level protocols, data formats and frequency of transmissions we designed and implemented a simulator with two-dimensional graphical interface. Fig 3 shows the main screen of the simulator. Using colour-coded design objects the floor plan of a property can be interactively defined. This allows the placement of the walls and the internal doors guided by the grids. Different rooms are identified and furniture such as the chairs and the beds are positioned. Next various sensors are placed in selected locations within the property. For example, there are sensors for detecting entry and exit through the doors using light beams or pressure pads at doorways; there are sensors that can sense pressure exerted in beds, in chairs and on toilet seats. Each sensor is designated a unique identity number that is used to identify the type of the sensor. The monitored person is identified as a colour-coded solid circle and can move within available spaces along the grids simulating day-to-day activities of the occupant of the property. As the person enters and exits rooms, climbs into and out of the bed and occupies and vacates the toilet seat relevant sensor data are generated and displayed at bottom right of the screen.

The simulated movements of the person being monitored can be manually captured as a series of scenarios in a library of activity scenarios. Various sequences of activities can then be constructed from this library and played back at selectable speeds. This method can be used to generate a large series of sensor data in a relatively short period of time reflecting a person's life-style al be it in a much accelerated manner thus simulating a time period that represents a much longer time in reality. Fig 4 shows the screen used to capture and play back the scenarios.

5.1 The Implementation Details

In this section we describe the design goals and the implementation behind the simulations we developed in order to assist us in the development of the proposed assisted living system based on remote monitoring of the daily activities of persons.

The 2-D graphical simulator is developed in order to mimic the daily living activities of persons in their homes. As a person's activities are simulated virtual sensor data is generated in a manner dictated by the currently defined configuration. In order to define a configuration the necessary steps are the design of the layout of floor plan across the floor grid, the placement of the furniture and the sensors and finally the activation of sensors within this layout. The configuration is manually constructed by using pre-defined color-coded design objects such as wall object, door object, chair object, etc.

The first action is the design of the floor plan using the wall and door design objects; the floor plan defines the configuration of the rooms. Next the furniture is placed in rooms using the design objects such as the bed object and the chair object. Once the floor plan is completed various sensor objects can be 'installed' and 'activated'. The 'installation' of sensor objects implicitly associates them with objects such as beds, chairs, doors, etc. For example, a sensor object associated with a wall object is able to monitor motion, a sensor object associated with a bed or a chair object is able to detect changes in pressure and a sensor associated with a door is able to detect entry and exit through the door. The intention here is to simulate actions such as movements within rooms, persons going to bed, sitting in chairs and entering and exiting rooms. Each sensor object is given a unique id number so that they can be easily differentiated. A color-coded person object is used to simulate movements and other common human activities such as lying in bed, sitting in a chair or on the toilet and going in and out of rooms. For example as the person object enters the floor grid occupied by the bed object this is regarded as the person going to bed and as the person exits this grid this is regarded as the person getting out of bed. Each of such actions will generate unique sensor data making identification of actions possible. This way the simulator enabled us to study the requirements for sensor type selection and placement options as well as the requirements for the essential communications parameters such as higher level protocols and data formats.

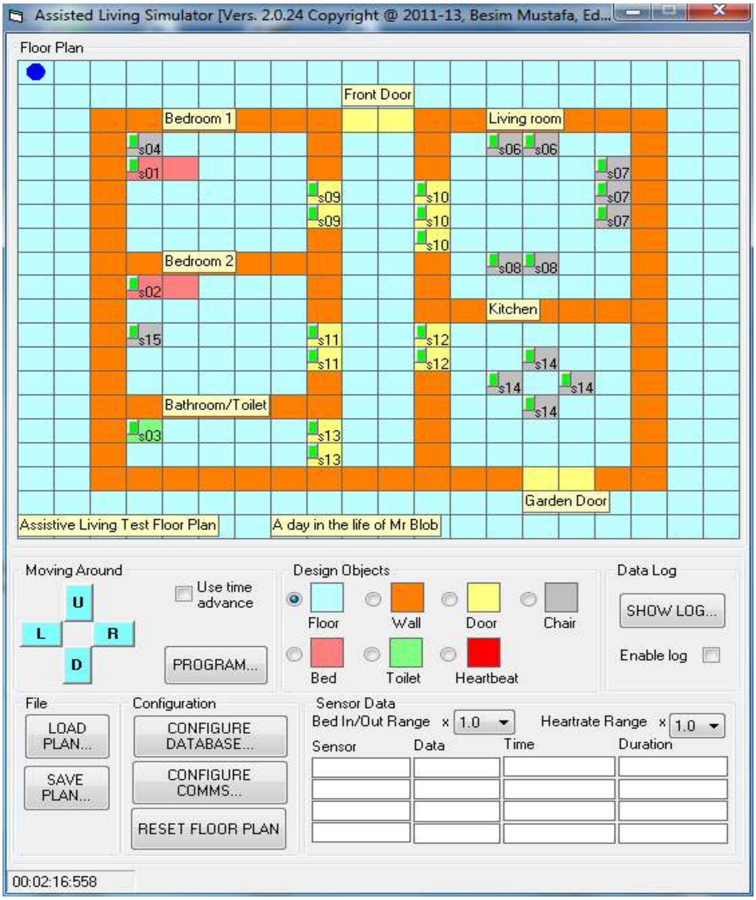

Fig. 3. Main simulator window

A feature of our simulator is its ability to capture and store the simulations of a person's activities in a library of 'activity scenarios' and to play back these scenarios at different speeds, frequency, order and combinations. Fig 4 shows the library containing sample list of scenarios. On the left is the list of captured activity scenarios and on the right is the list of scenarios selected to be played back in the order listed. The sensor data are re-generated while the captured actions are replayed. The sensor data is used to establish a person's lifestyle pattern over time as the 'norm'. The simulator can then be instructed to generate sensor data with statistically variable degrees of deviations from the established 'norm' in order to simulate exception conditions that should be detected by the sensor data analysis software thus testing and validating detection and analysis algorithms without the availability of real person subjects and physical locations.

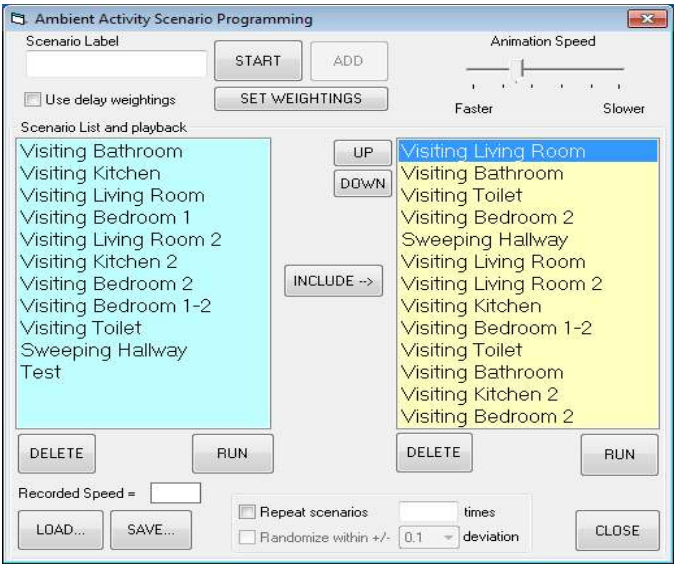

Fig. 4. Life-style scenario capture and playback showing list of scenarios

Fig 5 shows simulator's log of sample sensor data. The log records include sensor identities, activity events, activity start and end times as well as the durations of the activities thus capturing the three important parameters on which the lifestyle patterns are established. The simulator's behaviour is in fact indistinguishable from the physical transmitter/data-logger device as far as the pattern analysis software is concerned; the pattern analysis software simply receives the sensor data and is not concerned with the source of the data. Therefore the simulator can play the important and central role of helping identify any new features required in transmitter hardware and firmware in order to provide unique specialist support for assisted living at the same time as providing large amounts of realistic sensor data for the pattern analysis software testing thus making possible parallel developments of these two key areas thus speeding up the development process. The captured data can also be used as off-line test data for the analysis software. The simulator enabled us to experiment with the format of the sensor data, the storage requirements at the local transmitter and the manner in which this data is pre-processed and transmitted to the central station (frequency, size, etc.).

As the sensors are potentially capable of generating a large number of data, e.g. motion sensor data and door entry/exit data, we envisage a mechanism whereby a local buffer memory will be reserved to temporarily store blocks of non-urgent, i.e. low priority, sensor data. In order to minimise communications bandwidth requirement the buffered sensor data will be sent to the central monitoring station under certain conditions, e.g. when buffer full or at pre-configured intervals. The simulator is designed to include features to enable us to study the requirements for the size of sensor data buffer responsible for temporarily holding sensor data and to explore conditions under which the buffered data is to be sent to the central station. The simulator therefore enabled us to experiment with the optimum buffer size requirements and to explore different configurations for transmission intervals, e.g. after every N number of sensor events or after every T minutes, etc. Provisions for these facilities can be seen in Fig 5 at the bottom of the window.

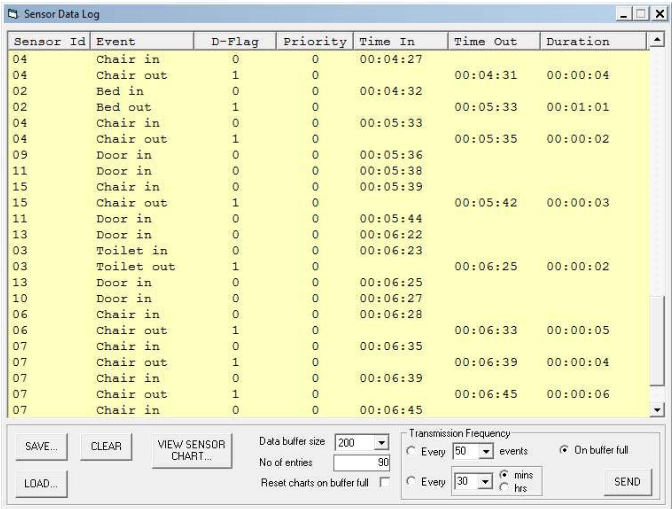

Fig. 5. Sensor data log showing a list of sensor detections

The sensor detected data can provide basic information used to construct a ‘view’ of a person’s way of life that is characterized by three specific attributes making pattern recognition and analysis possible: frequency of events, time of events and duration of events. For example, the frequency of events can be attributed to the number of times a person visits the toilet; the time of an event can be attributed to the time a person goes to bed; the duration of an event can be attributed to the time a person spends in bed. All this information forms part of a person’s lifestyle pattern in which there may be some embedded activity data that is indicative of possible underlying health related problems that have been gradually developing over the time. The simulator can generate this kind of data relatively easily and rapidly with suitably modulated temporal information for more realistic data. Fig 6 shows the simulated sensor data patterns represented by the two charts where the frequency of events detected (y-axis) is plotted as a line graph against each of the ‘installed’ sensors (x-axis) and the duration of certain events (y-axis) is also plotted as a bar chart against each of the installed sensors (x-axis) relevant to those events. For example, the events to do with going to bed and getting out of bed will be associated with the durations in bed, i.e. how long a person spends in bed presumably sleeping or resting; associating events such as entering and exiting rooms with durations can be less meaningful in certain cases depending on the context, i.e. time, location and any associations with other events, of the activity that is taking place. The area under the activity frequency line graph represents one aspect or ‘dimension’ of a person’s daily activity pattern; the duration bar chart representing another; a third ‘dimension’ is the representation of the activity start times not shown here.

The buffering of the sensor data prior to transmission gives us the possibility to do initial pre-processing of the sensor data. The data logger incorporates moderately powerful processing capability as described in section 8 making pre-processing possible. For example, motion detectors are likely to send their data much more frequently than any other type of sensors. This will therefore generate large amounts of sensor data all of which may neither be sensible nor necessary to transmit to the central station. It may then be possible for the data logger software to identify transitions from room to room, i.e. when a person leaves one room and enters another where there is a motion detector is fitted. This will make possible the detection of ‘in and out of room’ events. It can also make possible estimation of the speed of movements of the monitored persons as they move about in their homes giving some indication of their degree of mobility and may even, together with some other relevant data, contribute to the prediction of their state of health in some cases. The simulator is designed to pre-process this data giving us the ability to experiment with various algorithms for pre-processing the sensor data prior to transmission. These algorithms can then be implemented in the real data logger’s firmware.

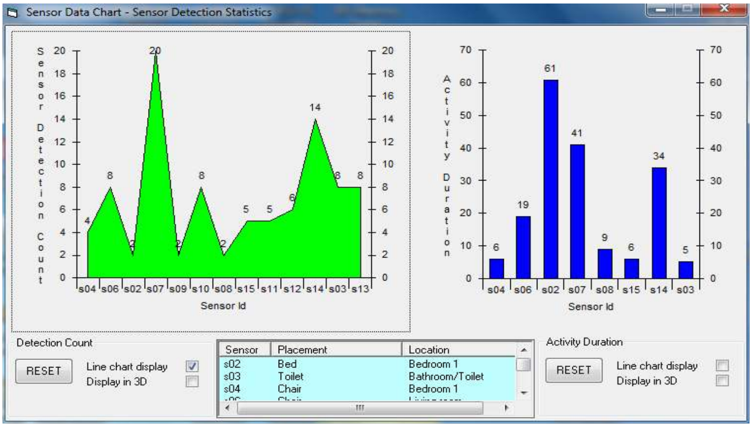

Fig. 6. Sensor data statistics: detection counts and detection durations.

The sensor detection count, the event start time and the event duration together constitute the monitored person’s 3D lifestyle pattern. It is this 3D information that the inference engine (described in section 9) processes. Looking at Fig 6 we can get glimpses of the monitored person’s lifestyle. For example, from the sensor detection frequency graph that the event detected by sensor 2 (going to bed) does not occur frequently; from the corresponding activity duration chart we can see that this activity is of the longest duration which is expected. On the other hand the event detected by sensor 7 (sitting in chair) does occur frequently and the duration of this occurrence is moderately high. From this information we can deduce that this person appears to sleep well and that spends a lot of time sitting which are indications of little activity.

6 Initial Results and Findings

Using the simulator we have been able to experiment and conduct our initial investigations into the various aspects of sensor data generation and transmission that included

- Type and placement of sensors
- Definition of sensor data formats
- Specification of sensor data transmission protocol
- Determination of optimum frequency of sensor data
- We elaborate further on the above in the following sub-sections.

6.1 Definition of Sensor Data Formats

Each sensor data gathered will be formatted in such a way that it conveys all the essential information to the analysis software in the most economical manner as potentially large number of sensor data can be generated in a relatively short period of time. We investigated properties of sensor data and the following represent some of the essential components of sensor data

- Sensor id: used to identify individual sensors.
- Time stamp(s): can be multiple time stamps, e.g. bed-in time and bed-out time or toilet-in time and toilet-out time.
- Priority indicator: determines the urgency of sensor data, e.g. fall detected or raised blood pressure, etc.

The sensor id and time-stamps are needed in order to be able to track the matching activities of the individual sensors. For example, a sensor can be responsible for detecting the person going to bed and the same sensor detecting the person coming out of the bed. These sensor data can be used to determine three important pieces of information: the fact that the person went to bed (presumably for sleeping), the time the person spent in bed, the fact that the person came out of the bed (presumably woken up from sleep). From these several inferences can be made: if the person sleeps; if the person sleeps long enough; if the person is able to come out of bed. Still further inferences can be made from this information such as the person is or is not sleeping, or the person is or is not sleeping well or the person is unable or unwilling to come out of bed which in turn can be further connected to the ambient temperature of the bedroom or to the count of visits to the kitchen and the toilet; it may be that an elderly person is unable to come out of bed due to lack of heating in the bedroom or it may be that the person is possibly too weak to climb out of the bed and walk. The sensor data can be used to determine the frequency of activities such as how often a person visits the toilet or the kitchen that can be used to infer any potential health problems (i.e. not eating well or regularly or changing toilet habit indicated).

The sensor data priority is required to determine if the sensor data needs to be immediately transmitted to the central monitoring station or that it can be delayed in order to minimise communications traffic when several sensor data can be collectively transmitted at pre-determined intervals as a block. For example, if an elderly or a disabled person has fallen the data sent by the accelerometer sensor needs to be urgently transmitted so that help can be provided for the fallen person as fast as possible; the vibrations detected in a child's cot by a sensor possibly due to an epileptic episode needs to be acted upon as soon as possible. On the other hand sensor data on going to bed and coming out of bed do not need to be sent immediately but can be stored for later transmission. The priority is implied by the type of sensor as identified by its id or channel number and is facilitated by a look-up table maintained for this purpose.

6.2 Specification of Sensor Data Transmission Protocol

One of the aims of this investigation has been about identifying any new supporting features that are needed to be designed into Securecom's new breed of advanced commercial digital transmitters in order to provide efficient support for the assisted living system we are proposing. These advanced transmitters are designed specifically for remote monitoring of properties for security purposes. As a result of our collaborative work we have been able to identify and specify an extension to the existing protocol used for providing assisted living support at an early stage of product development. We describe the digital transmitter further later on.

The transmission protocol the digital transmitter uses is based on the standard used by the security industry. In order to be more flexible Securecom decided to define and use an extended proprietary version which is not publicly made available. Due to non-disclosure agreement we are unable to reveal this information in detail. However, it suffices to say that the basic elements include a means of identifying the property, the identification of the alarm trigger condition(s) and the device status. Depending on the mode of transmission each data transmitted may require acknowledgement along the same path of connection, e.g. acknowledgement packets on Internet connection (TCP/IP) or audio frequency signalling on land-line and mobile audio (GSM) connections.

6.3 Determination of Optimum Frequency of Sensor Data Generation

Monitoring persons' life styles in terms of their daily activities will require handling of a relatively large number of sensor data and the number generated in a single day can be in hundreds in the case of an active person. The sensor data generated can provide three types of information: 1) frequency of activities, 2) times of activities and 3) durations of activities. These can be used to make inferences such as that an activity is taking place (e.g. moving, sleeping, eating, going to toilet, etc.), that an activity is taking place at expected or during normal times (e.g. having breakfast in the morning, taking the pill in the morning, going to toilet at night, etc.) and that an activity is taking as long as expected or normal (e.g. sleeping around six hours, spending no more than ten minutes in the toilet, staying in kitchen for at least half an hour, etc.). The words expected and normal are used in relative sense and can be interpreted differently for different people; what is expected and what is normal will be established on a per person basis after a period of monitoring.

The challenge here is the determination of the number of activities to monitor and how often to monitor. It is quite possible that not all activities will be necessary to monitor and monitoring only the targeted activities that reflect a person's particular nature of disability or age will be meaningful. Nevertheless monitoring of the daily activities of thousands of individuals can put a large demand on the communications devices and networks.

7 Sensors, Sensors and Biometrics

The proposed system heavily relies on activity sensors in order to be able to gather information on persons' life styles. Therefore it is important that the correct sensor technology is used and that the sensors are optimally positioned and configured.

The system proposed can be configured to use any number of sensors although this will be restricted in reality to a few strategically placed sensors. The sensors used can be off-the-shelf inexpensive devices. However, for practical reasons we propose to use sensors with wireless capabilities. For this reason the digital transmitter we use is able to handle wireless sensors as we are adopting a system that already accepts wireless detection devices for security alarms, e.g. fire, intrusion, etc. Table I lists types of typical low cost sensors that can be used in order to help establish persons' life style patterns over time. The table includes information on types of data the sensors can provide and whether the frequency and durations of data are relevant or not.

The sensor triggers will be detected by the digital transmitter using the standard wireless communications protocol. This is likely to be similar to or same as the ZigBee communications protocol offering low power requirements, good range, low price and low susceptibility to interference [21]. Although ZigBee has low data rate (20 to 250 Kbps) this is nevertheless more than adequate for short bursts of sensor data transmissions. It is decided to use the lower frequency band of 868 MHz for sensor transmissions. This band offers better penetration characteristics through brick walls as most of the older properties tend to be brick built inside. This frequency band is restricted to a single channel necessitating the transmission of sensor id numbers; each sensor is given a unique id number for this purpose. The id will then be transmitted to the local digital transmitter/data logger. The low priority events will be logged by the transmitter in its buffer in 5-byte blocks of information: 7- bit sensor id, 1-bit sequence number and 4-byte time stamp. This format will allow a maximum of 128 sensors; the sequence bit will be used to identify two-state matching events from the same sensor (e.g. in and out, on and off, etc.) and time stamp will be used to indicate the time of occurrence of the event. If the event is of high priority then this will be immediately transmitted to the central monitoring station in the same format as above without being buffered first. The buffer size will be determined by the frequency with which the buffered data will be transmitted and can be configurable depending on the circumstances of the monitored subject.

Table 1. Attributes of some common sensors

Sensor	Priority	Placement	Information	Duration	Frequency
Motion detector	Low	Rooms, other spaces in property	Motion, paths of movements	Not relevant	Not relevant
Pressure pad	Low	Doorways, beds, chairs, toilet seats	In and out of rooms, on and off chairs and toilet seats, in and out of beds	May be relevant	May be relevant
Light beam	Low	Doorways (may require two to detect direction)	In and out of rooms or property	May be relevant	May be relevant
Accelerometer	High	Worn on person	Orientation, degree of instability in movements	Not relevant	Relevant
Thermometer	Low	Rooms, outside the property	Temperature (above or below threshold)	Not relevant	May be relevant

Although the sensors in Table 1 are capable of providing data from which current state of health can be indirectly inferred to a certain extent they are nevertheless not able to directly provide biometric data that can be further relied upon for real-time supportive evidence of state of health. For example blood-pressure sensor data can be used in conjunction with the data from accelerometer sensor in order to reasonably conclude that a fainting episode is a strong possibility and together with the spatial and the temporal information gathered over time the subject's future state of health can be projected; data from pulse rate sensor, data from blood-pressure sensor, data from accelerometer sensor and a microphone can be combined to infer a possible onset of a stroke demanding immediate attention and more aggressive follow-up monitoring. One of the uses of biometric information is that it can be used to authenticate the monitored subjects through 'liveness' detection [18, 19].

By taking full advantage of biometric data capture, both authentication and medical data can be captured and correlated within a system in a secure environment [20]. As with all system implementations involving persons and health data the security concern is always present, and biometric devices are no exception. There are a number of biometric security concerns that must be addressed, especially if the systems are going to contain data about vulnerable users such as those our system is designed for the benefit of. We are closely allaying with the research work of one of the authors of this paper on the definition of a security related framework on biometrics which we believe our work can benefit from [23]. There are various security related issues that need tackling; use of encryption is particularly useful in resolving few of these issues.

We envisage primarily two ways of collecting biometric data: 1) automatically using wearable biometric devices and sensors, 2) by a visiting nurse or a carer using mobile devices. The former requires that the monitored person is semi-permanently connected to biometric devices such as blood pressure and pulse rate monitors; the latter is carried out by a nurse or a carer during regular visits who manually enters the data in the mobile device they carry which then gets transmitted to the local digital transmitter at the end of the visit.

8 Digital Transmitter and Remote Data Logger

The digital transmitter we have been working with belongs to a new range of transmitters designed by Securecom specifically for remote monitoring of properties for security purposes. At its heart is the processing power based on a 32-bit power-efficient ARM Cortex-M4 core technology. These microcontrollers are popular high-performance choice in low-power constrained and cost-sensitive signal processing devices offering Ethernet connectivity.

The digital transmitter is designed to be located at the property to be monitored. It is actually integrated into the alarm panel and is responsible for transmitting alarm data whenever an alarm condition such as intrusion, fire or panic button is triggered. Each property is identified by a unique site code which is also transmitted to a central monitoring station capable of monitoring hundreds of properties fitted with the same transmitter. Fig 7 shows the general components of the digital transmitter. The alarm sensors communicate with the transmitter using a wireless protocol on 868 MHz band using a single channel and employs a contention based protocol where if a sensor needs to send data it establishes a connection with the transmitter and all other sensors are prevented from transmitting their data while this connection is present. The transmitter acknowledges all sensor data. Once the current connection is removed, the transmitter polls all other sensors for data. When no more sensor data is available both the transmitter and the sensors go into sleep mode. This method affords low duty cycle for the sensors thus minimizing their power requirement.

The alarm data is normally transmitted to the central monitoring station immediately using a proprietary format conveying enough information for the central station to act upon in consultation with the user data stored in a customer database. The transmission uses a persistent mode of establishing connection depending on how it is configured. This mode has a sequence of priorities for establishing the transmission path and in order of preference these are: TCP/IP connection via Ethernet interface, GPRS connection via 3G/4G mobile data services, GSM audio with DTMF signaling and finally SMS. In all but the SMS method acknowledgments are possible.

The digital transmitter is capable of supporting enhanced system integrity and reliability using three main methods: 1) embedded MCU watchdog mechanism, 2) application level error detection and correction, and 3) periodic or on demand test signaling. The watchdog method is a standard mechanism for resetting MCU whenever it fails to respond to independent watchdog commands. This method attempts to mitigate mainly obscure embedded software related problems. Test signaling can be done at two levels: central station sends test data to remote digital transmitter and expects an acknowledgement; the digital transmitter sends each remote sensor test data and expects acknowledgements. This can either be done regularly, say once a day or it can be done at times when sensor activity is deemed to be lower than expected.

Working in collaboration with Securecom we have experimented with leveraging the existing remote monitoring and communications capabilities of their digital transmitter in order to facilitate our requirements for assisted-living support. We have managed to use the data from our simulations in order to be able to identify additional requirements that can be integrated with the current design of the transmitter in its

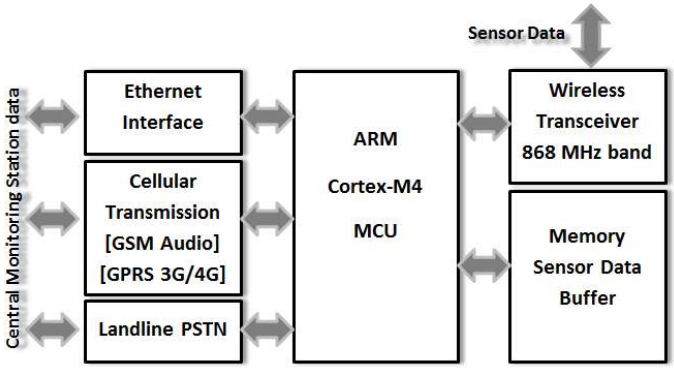

Fig. 7. Digital transmitter block diagram

final stages of development. The following new provisions have been identified for this reason:

- Changes to the proprietary protocol to make allowance for the assisted-living mode of operation
- Changes to transmitter firmware to handle assisted-living protocol requirements
- Changes to transmitter firmware to implement sensor data buffering/logging and periodic transmission of this data

9 Life-style Pattern Recognition and Analysis

The central station software is responsible for various activities that are required to support remote "smart" monitoring and responding on demand to the information it receives. This software is therefore required to offer a range of services; we identified the following essential services:

- Data capture
- Data storage
- Data transformation
- Data analysis
- Identification of exceptions
- Data presentation

We opted for a rule based inference and decision making method of accumulating knowledge and analyzing day-to-day living patterns of persons generated over a period of time. Fig 8 shows an outline of this method. Sensor data are collected in the sensor database in a format that is more compact and amenable to efficient processing than the raw data received. The knowledge base contains sets of rules that are used to facilitate pattern recognition and determination of exception conditions and whether any action should be taken. Initially the basic rules are provided by the domain experts. However some of the sensor data gathered can be transformed into additional sets of rules thus enabling the knowledge base to adapt to the changing living conditions over time. The inference and decision making engine is fed from both the knowledge base and the sensor database. The results of the process of inferring can be fed back to the knowledge base in order to facilitate evolution of existing and adaptation of new rules over time. Similarly a path from the inference engine to the sensor database can be used to assert, retract or modify sensor data. For example, initially, during the learning period, a monitored aspect could be based on the assertion of the rule "for person X it is normal if he goes to bed and comes out of bed within 24 hours". As time passes this rule will adapt to reflect more precisely the reality and may gradually evolve into the new rule "for person X it is normal if he spends between 5 and 8 hours in bed within 24 hours"; a similar rule for person Y may be based on a different set of personal facts. Therefore the knowledge base will accumulate expertise on life-styles of each of the monitored individuals by adaptively generating sets of rules that closely reflect their way of life.

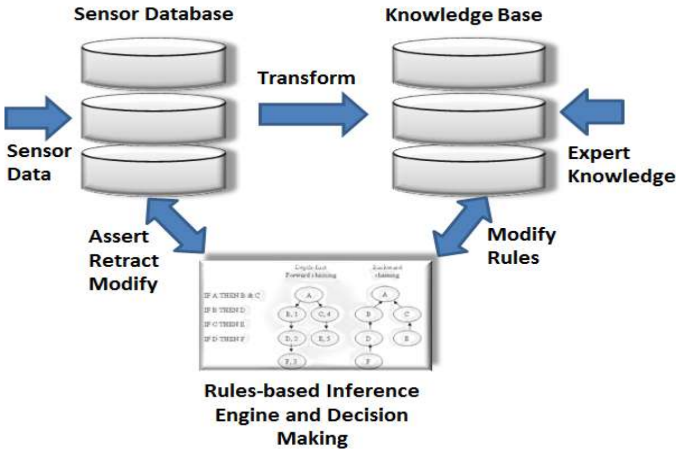

Fig. 8. Adaptive Life-style Pattern Recognition and Analysis System

Over a period of time the monitored sensor data and the knowledge base for each assisted person will grow in size. In order to manage the large amounts of information accumulated it will be necessary to structure the data in a way that makes the time-consuming process of inferring efficient. As the data stored increases the life-style patterns will mature and facilitate increasingly more accurate determination of exception conditions and state-of-health predictions. Fig 9 illustrates a simplified view of data maturity and structuring by base-lining activity 'norms' in order to promote near real-time pattern recognition and analysis. So, instead of ploughing through large amounts of historical data every time sensor data is received the structured base-lining method will enable the inference engine take into account summary of historical data in its reasoning at the same time as considering the most recent data.

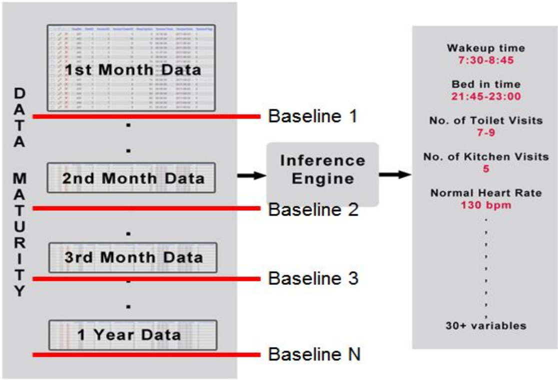

Fig. 9. Sensor data and knowledge base maturity

As always the reality is not as simple as we would like it to be and there are several practical considerations we need to take into account when making inferences if our system is to be workable in practice. We look at three such areas:

- Multiple occupancy
- Accuracy of inferences
- Security of information

9.1 Multiple Occupancy

The proposed system is optimized to work with single occupants in properties. This however presents a dilemma whenever there is more than a single living being in the property. For example, an elderly occupant may be visited by relatives or by a carer; the occupant may have a dog for company. We can identify and authenticate the monitored person or alternatively we can regard the visitors and pets as part of the monitored persons' way of life and hence also part of their life-style pattern. We opted for the latter for two reasons: 1) simpler, cheaper and easier to implement, 2) unusual visits and pet behaviours can also be indicative of exception conditions worth investigating.

9.2 Accuracy of Inferences

In order to enhance the accuracy of decision making the inferences can be based on contextualized sets of actions that take into consideration temporal and spatial indicators. For example, the action of rapidly lowering into a chair needs to be distinguished from falling down. If this takes place in the bathroom or in the hall (as sensed by the motion detectors) this may be construed as a valid fall; if in the living room or bedroom and is followed by pressure sensors triggering then this may indicate actions of sitting in a chair or lying on a bed as opposed to falling down.

We are aware of the potential drawbacks of the proposed rules based inference engine [22]. However we have chosen it as it is relatively easy to implement and is well understood.

9.3 Security of Information

Security of information has two dimensions: 1) snooping and 2) falsifying. Security is particularly important when biometric data is being gathered. Both of these security concerns can be significantly minimized by encrypting both the sensor data received from the sensors and the data the digital transmitter sends to the central station.

10 Prototyping and Results

In order to test our ideas we resolved to implement a proof-of-concept prototype system. The sensor data was provided by both manual means and from the output of the assisted living simulation scenarios as explained before. We used the manual means in order to inject test cases that simulated abnormal data that deliberately and significantly deviated from norms; we used the simulator output to provide rapid succession of sensor data in order to speedily establish life-style norms. A TCP/IP connection was used in order to establish secure communications between the simulator and the simulated central station monitoring software. In the prototype system we did not implement an adaptive rules-based knowledge base; instead we used relatively simple algorithmic means of processing the sensor data. A web-based graphical user interface was also implemented to communicate with the user and to present sensor data; MySQL was used to create access and manage the sensor knowledge database.

Fig 10 shows two views of the web-based prototype user interface. The background view represents the logging screen for central station personnel as well as for the carers and the family members of the persons being monitored; it is envisaged that different types of observers will be presented with information in formats most appropriate for the type of observer. The foreground view displays the colour-coded graphical representation of sensor data gathered from the daily activities of a person being monitored; normal data (green), data needing close watch (yellow) and data that needs to be acted upon urgently (red). The foreground image in Fig 10 depicts an example visual status of four monitored persons. Each person is identified by a unique site id assigned at the time of the installation of the system in their home. The monitored activities and other related parameters are shown at the top of the image. In this example persons 1 and 2 are showing daily activities within their normal ranges. However, persons 3 and 4 are exhibiting exception conditions highlighted in red with person 3's daily kitchen visits below his established 'norm' and person 4's daily toilet visits below her established 'norm'. Another exception condition for person 4 indicates a significant deviation from her daily routine with respect to her use of the main door, for example she may have exited her home or left her door open at an unusual time of the day. This daily activity information can be made available on daily, weekly or monthly bases in various graphical formats designed to enhance visual impact in the identification of possible exception conditions. This information will also be remotely accessible via mobile devices that will present the information in formats relevant and suitable to the type of users, e.g. doctor, carer or family member.

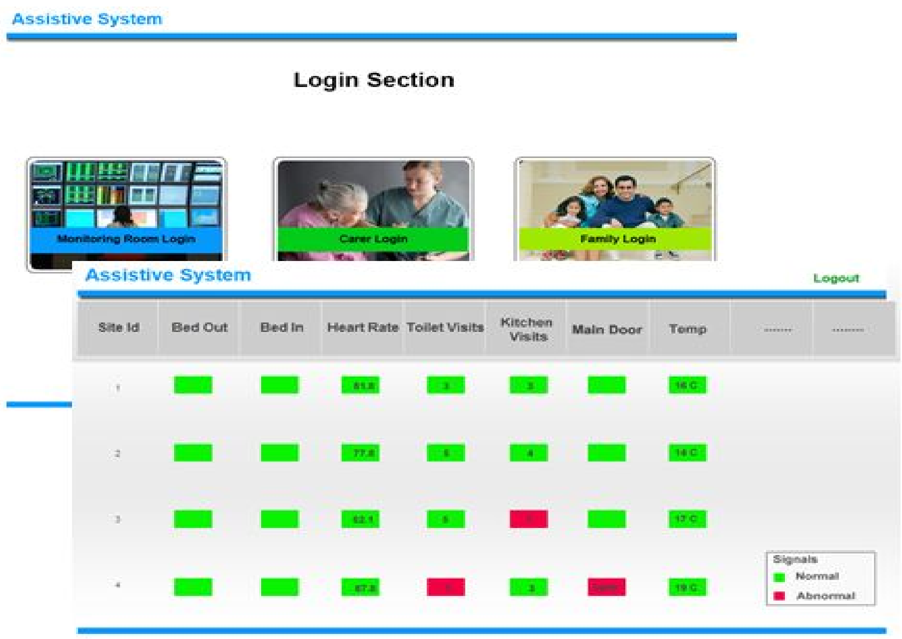

Fig. 10. Central station assisted living support interface

An important reason for developing the prototype was for Securecom to use it as a proof-of-concept to a large housing authority as a potential customer base with a vested interest in the technology. This demonstration was successful and suitably impressed the senior staff of this authority to such an extent that they expressed keen interest in further development work investigating predictive technology where the state of health of persons can be predicted into the future. This is seen to be desirable for facilitating efficient planning and funding of public services such as health care for elderly and disabled. At times of sweeping government cuts in spending on public services this technology is suddenly a welcome prospect.

The full implementation of the monitoring software will be integrated with Securecom's existing central station system normally used to handle monitored alarm incidents. Once this implementation is stable the next stage will be to install sensor devices in several selected properties in order to further evaluate and fine tune it over a period of time before commercially rolling it out. For a larger scale validation we intend to seek the assistance of housing authorities responsible for large numbers of care homes.

11 Looking to the Future

We continue working on the remotely monitored assisted living system described in this paper in collaboration with Securecom Ltd. and expect it to become a commercially viable product in the near future. There is still some work to complete especially in the development of efficient algorithms for life-style pattern recognition and algorithms for inference engine and decision-making that can monitor the daily activities and accurately assess significant deviations from what is regarded as norms as well as detect subtle trends of changes that can point to any future health related problems needing attention sooner than later.

Another area we would like to concentrate on in the future concerns the ability to accurately predict any future health related problems of the monitored subjects. This will require the assistance of biometric devices; our partner company is in the process of developing such devices. The intention here is to be able to use the sensor information from the biometric devices together with the information gathered from other sensors in order to make reasonably accurate extrapolations into the future state of health of the monitored individuals. This process will also help identify gradual degradation in the mobility and health of persons much faster than a human observer can. Local authorities can use the information of this kind in order to better plan and target for future support and funding requirements. Also a more timely medical intervention may be administered enhancing quality of life and improving life expectancy.

12 Conclusions

In this paper we considered a wide spectrum of assisted living issues and technologies. We described our initial and promising investigations into smart remote monitoring using a range of sensors and ubiquitous communications methods for the benefit of elderly and disabled who wish to maintain their independence and dignity as long as possible often living alone. We then went on further and proposed a scalable system that can recognise daily activities as life-style patterns for establishing norms over time and that uses rule-based adaptive knowledge base method in order to detect any alarming deviations from these norms. Working with a commercial partner we aim to help realise the proposed system as a commercial concern thus fulfilling our purpose to support the aging populations. There are many productive and promising research activities in this area and we are hoping that our work will make a modest contribution.

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