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The CLARITY Modular Ambient Health and Wellness Measurement Platform

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***Abstract* — Emerging healthcare applications can benefit enormously from recent advances in pervasive technology and computing. This paper introduces the CLARITY Modular Ambient Health and Wellness Measurement Platform, which is a heterogeneous and robust pervasive healthcare solution currently under development at the CLARITY Center for Sensor Web Technologies. This intelligent and context-aware platform comprises the Tyndall Wireless Sensor Network prototyping system, augmented with an agent-based middleware and front-end computing architecture. The key contribution of this work is to highlight how interoperability, expandability, reusability and robustness can be manifested in the modular design of the constituent nodes and the inherently distributed nature of the controlling software architecture.**

Keywords-heterogeneous wireless sensor networks; pervasive healthcare; agent based intellegence; interoperability.

I. INTRODUCTION AND MOTIVATION

New emerging demographic trends toward an aging population has highlighted the need for next generation cost effective pervasive healthcare technology [1]. These medical domains will consist of large numbers of autonomous, processing, communicating and sensing devices. Research has striven to develop these wireless devices, all the while adhering fervently to the requirements of the medical professional while also considering the needs of the end user [2-4]. However, the ad-hoc nature of many of the solutions available today can be found wanting from an interoperability, expandability, reusability and robustness perspective [5, 6].

While the standardization of wireless technology has alleviated some of the interoperability shortcomings, in order to truly overcome this barrier to heterogeneity, the employed wireless technology should be easily interchangeable whilst retaining the system's background functionality. An example of this would be an IEEE 802.15.4 pervasive monitoring service [7], operating in a topographically clustered indoor environment and suffering from extensive channel degradation. Ideally, the goal would be to retain the sensing functions, energy source and packaging of the device while the communication technology is replaced with a solution more robust to multipath effects, for instance IEEE 802.15.4a Ultra-Wide Band. This in turn would reduce the cost in materials and time spent redesigning the entire device - reliability would be improved and sensor recalibration would not be required.

Another advantage of this modular approach is the ease at which the state of the art in sensor devices may be harnessed and incorporated in the system again removing the need to design an entirely new wireless sensor node in order to house the emerging sensor. In this manner new, technology can be incorporated seamlessly with existing architectures.

The synergy between the underlying hardware and the computational infrastructure is also an important factor when provisioning for reliable context-aware pervasive healthcare services [8, 9]. Making intelligent decisions throughout the software stack is key to this arrangement and in itself is a major component of pervasive computing. Many implementations to date, due to the limited computational resources available at mote level, have contained much of the system's intelligence in the upper layers of the network architecture, focused mainly at a singular or a small number of computational hubs [10, 11]. With recent advances in agent-based mote technology it is now possible to fulfill the fundamental requirement that the network is intelligent and contextually-aware by enabling intelligence throughout the system rather than at a central point in the upper layers [12]. This distributed approach inherently improves the robustness of the system to faults and removes any over-dependence on centralized information processing hubs.

This paper introduces the CLARITY Modular Ambient Health and Wellness Measurement Platform, the goal of which is to provide easily interoperable, expandable, reusable and robust solutions for the pervasive healthcare environment in a manner that is intelligent, seamless and context-aware. The paper is organized as follows: Section II will begin with a description of CLARITY and how end-to-end wireless sensor research is conducted at the centre. An outline of the CLARITY Ambient Assisted Living platform is then provided in Section III. This is followed in the same section by a detailed look at the CLARITY Sensor Platform highlighting its adaptive modular nature and expansion capabilities in the pervasive healthcare context. The section concludes with a discussion on the intelligent agent based approach employed. Finally future work is outlined and conclusions are drawn in Sections IV and V respectively.

II. CLARITY: CENTRE FOR SENSOR WEB TECHNOLOGIES

The CLARITY Centre for Sensor Web Technologies [13] focuses on the intersection between two important research areas - Adaptive Sensing and Information Discovery. A differentiating factor of CLARITY's approach to the development of realistic pervasive scenarios is the coherent amalgamation of its various research programs in an end-to-end solution.

Molecular level basic research is carried out contributing to the next generation of sensing devices. In parallel state of the art wireless sensor nodes and embedded software are developed and research issues arising from the prototype deployment and harmonizing of heterogeneous, resource bounded sensor networks are explored. Further up the stack contextual content analysis is employed to filter out interesting information relevant to the end user and research into how this information should be retrieved, indexed and accessed is seen as critical to this process. Finally and to ensure the content management technologies are harnessed to expose the true potential of the underlying architectures, the needs, preferences, behavioral patterns and activities of the individual and/or group are used to make proactive recommendations of relevant content.

CLARITY envisions personalized health and pervasive monitoring both remotely and on-body as key areas where its research can impact positively on 'Quality of Life'. An Ambient Assisted Living (AAL) scenario has been coined to demonstrate where these contributions can be made.

A. The Ambient Assited Living Platform

The CLARITY AAL platform focuses on helping people to more effectively monitor and manage their personal health and well-being which in itself is an important social and economic goal that has significant fiscal implications for the healthcare sector and the quality of life of individuals.

1) CLARITY AAL Phase 1 Deployment

The CLARITY AAL network incorporates a suite of sensors that enables occupant activity to be modeled to an adequate level of detail for deriving behavior patterns. In essence, this meant identifying the minimum configuration of sensors that, in combination, would enable the construction of a range of models all pertinent to select aspects of occupant behavior. Thus, a tradeoff is required between the number of sensors required for the task at hand, ensuring that the environment is not saturated with sensing technologies as well as ensuring there is sufficient redundancy in the configuration to support fault tolerance.

It must be acknowledged that the ultimate location where AAL is deployed influence all of these factors. To date the CLARITY configuration incorporates a number of sensors types packaged so as blend seamlessly into the environment. Devices currently deployed have the following sensing capabilities:

- PIR - Passive InfraRed (PIR) - are used at room level. Such sensors indicate whether there is activity in a room suggesting the presence of an occupant. In many, but not all cases, they can be used as a ground truth to establish occupancy.



Figure 2. CLARITY Ambient Assited Living

- Embedded motion sensors - incorporate a 3 axis accelerometer to indicate motion of the item the sensor is attached to. In this deployment, it is attached to doors and windows, indicating the opening and closing of each of these objects. It could also be deployed on fridges and other items with doors, should this level of information be required.
- Pressure mats - a number of pressure mats allow the position of the occupant be detected quite accurately if required. The strategic location of these mats allows select behaviors be examined. For example, such mats are frequently placed beside beds so that an alarm can be raised when the occupant leaves the bed. This is particularly important when the person suffers from dementia and is prone to episodes of wandering behavior. Such mats can also indicate how long a person is standing on them, should such information be required.

The deployment of each sensor explicitly identifies a physician activity and implicitly identifies an action, usually occupant related, that occurs. All sensors are programmed to report any activity to a base station.

III. THE CLARITY SENSOR PLATFORM

The building block used in the AAL platform is the CLARITY Sensor Platform consisting of heterogeneous modular hardware and embedded software developed at the Tyndall National Institute and an agent and component-based intelligent, robust computing architecture developed at University College Dublin.

A. The Modular Tyndall Mote WSN prototyping system

The Tyndall prototyping system has been developed to address a wide array of scenarios in the Wireless Sensor Network (WSN) application space. A highly modular approach to design has been adopted negating the need to

replace the mote infrastructure should a change in wireless technology, sensing capabilities or power supply be required [14, 15]. The platform implementation consists of a variable number of layers that are stacked on top of each other in order to satisfy application requirements.

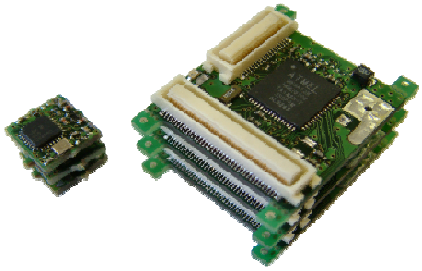


Figure 3. Tyndall mote – 25mm and 10mm systems

There are a number of benefits in adopting this modular approach to node design namely the platform is far more interoperable with a wider range of wireless technologies and should there be a need to change technology the background functionality of the network is retained and the need for sensor recalibration is removed [16, 17]. In addition the embedded intelligence within the system can provide the necessary filtering and processing algorithms to enable autonomous operation, adaptive sampling regimes based on sensory input and data filtering using readily available embedded C or TinyOS code libraries. The modular platform has been built in two form factors – the more mature 25mm form factor technology and an associated 10mm form factor implementation as illustrated in Figure 3.

To date upwards of 30 system layers have been developed [18]. From a wireless ISM band perspective the platform is Zigbee/802.5.4, and Bluetooth compliant. An Ultra Wide Band (UWB) 802.15.4a layer is also under development. Additional wireless transceiver layers available operate at 433, 868 and 915 MHz. The Atmel ATmega128 micro-controller is employed for onboard processing. Over 20 modular sensor layers have been developed some of which are intended for use in the pervasive healthcare space and are described in more detail in further sections. There are also a number of interchangeable power supply and energy harvesting options [19, 20].

1) "Agent ready" Smart Pervasive Sensor platform

To augment the sensor platform with a smart and intelligent software platform, a smart pervasive system layer was developed. This comprises a powerful Java compatible processing platform supporting a SQUAWK virtual machine enabling the deployment of certain Java-based agent frameworks.

The system is designed to be compatible with the 25mm family of devices available from Tyndall (sensors, transceivers etc) but with a high end processing capability. The envisaged operation and modularity of the system is outlined in the block diagram in Figure 4

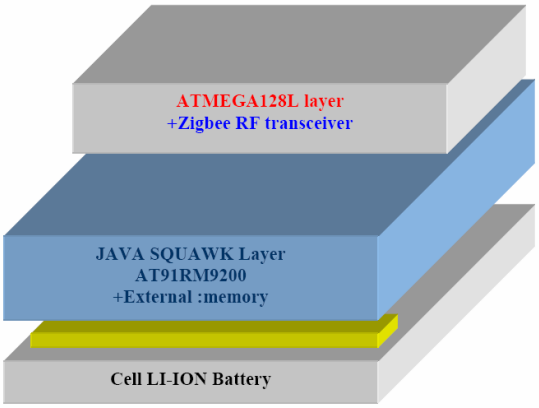


Figure 4. Agent Ready System Block diagram

The required system functionality is provided by the main Processor – the ATMEL AT91RM9200, in conjunction with external memory – the Spansion S71GL032N40, 32MB NOR Flash memory and 4MB pseudo-static random access memory (pSRAM) along with the CC2420 interface compatibility. This enables the device to combine the versatility of the original low power consumption reduced functionality device based on the Atmega 128 microcontroller with the processing power and Java based interface of the ATMEL AT91RM9200 to enable agent-based operation in an assisted living implementation using Java.

2) Sensor Layer 1 – Pervasive Monitoring Layer

This sensor layer is built around the various sensor interfaces provided by the Atmel microcontroller in conjunction with a multi-sensor interface layer (ref. Figure 5). This sensor layer is fully compatible with the Tyndall mote 25mm "family" of devices and sensor layers and includes a variety of typical sensors on board which provide useful data within the AAL environment including temperature, humidity, light levels, vibration, orientation and presence. There are, in addition to this standard set of onboard sensors incorporated in the system, a variety of sensor interfaces such as I2C, USART, RS485 and analogue I/O capability for additional "non standard" sensor interfacing.



Figure 5. 25mm BEM Standard Sensor Layer



Figure 6. The Multisensor Layer in the modular stack

The system also includes dual actuation capabilities for any AC/DC system using an external high power relay as well as an onboard low power switch to enable a low current actuation facility without external infrastructure if required. This Pervasive Sensor layer also incorporates external flash memory (Atmel AT45DB041). The layer features a 4-Mbit serial flash for storing data, measurements, and other user-defined information.

3) Sensor Layer 2 - The Multisensor Layer

The Multisensor Layer comprises of a light dependant resistor to measure ambient lighting levels, a thermistor to highlight changes in temperature, relative temperature and humidity sensors, a 3 axis accelerometer to monitor movement and a microphone to detect sound. The Multisensor layer is illustrated in Figure 6 as part of the modular stack.

4) Sensor Layer3 - Generic Sensor Interface Layer

The Generic Sensor Interface layer can be interfaced to as many as eight different sensors/devices. In addition to enabling connections, the layer has onboard signal conditioning designed to remove noise. In the context of the AAL platform, this layer has been employed to gather pressure mat readings to detect presence and mobility. The pressure mat configuration is shown below in Figure 7.

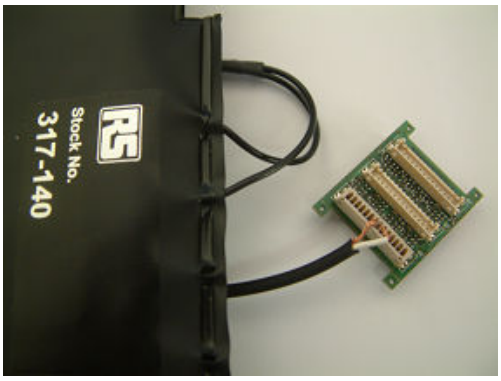


Figure 7. 25mm Generic Sensor Interface Layer connected to a pressure mat

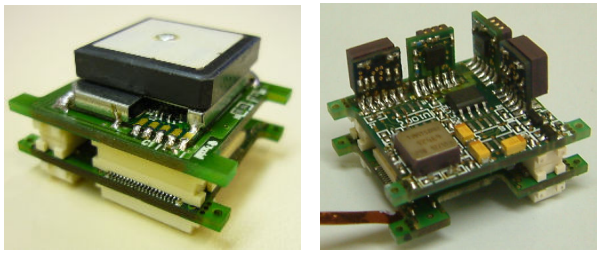


Figure 8. 25mm GPS Layer (left) and the IMU Layer (right)

5) Additional Layers available for future AAL deployment

In addition to the platform layers outlined above, a number of other layers have been developed that will be considered in further deployment phases of the platform.

The vision for the "virtual presence era", which can be described as a geographically distributed home, is of particular interest in the pervasive healthcare context where the location and wellbeing of an individual is of key importance [21]. The Global Positioning Satellite (GPS) 25 mm layer has been developed with this in mind and this low power module is useful in the pervasive AAL framework where geolocation is required and where the move from indoor to outdoor environment has taken place. The 25mm GPS Layer is shown in Figure 8.

As injury is the fifth leading cause of death in older people, where most of these fatal injuries are related to falls [22], detecting falls and monitoring body position accurately has become an important aspect of pervasive health research. The Inertial Measurement Unit (IMU) has been developed for such applications. Incorporating 6 degrees of freedom the IMU module consists of an array of inertial sensors including three single axis gyroscopes, two dual axis accelerometers and two dual axis magnetometers, coupled with a high resolution Analog to Digital converter (ADC). The 25mm WIMU is illustrated in Figure 8 can be employed as part of a Body Area Network (BAN) configuration in conjunction with the electrocardiogram (ECG), pulse oximeter, temperature and accelerometer on-body sensors that have been developed for this purpose.

B. Information Fusion

The wide range of sensed modalities that this architecture potentially gives rise to ranges issues of information management, and situation recognition. In the first case, a mixed component/stream integration framework is harvested; in the second, an agent based approach is adopted.

1) Component and Stream Framework

The applications targeted in the AAL domain are data intensive, as they must implicitly rely on contextual data, both system and user originated, to construct and maintain sophisticated behaviour models driving system-user interaction.

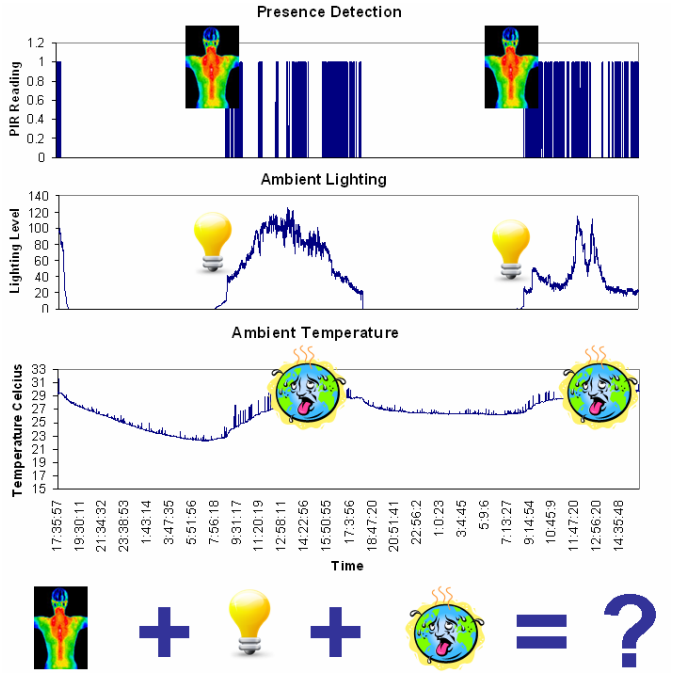


Figure 8. Event capturing capabilities of the Tyndall Mote WSN system. Events are flagged in real-time and the situation or context is determined by an intelligent agent based approach.

We also advocate the development of heterogeneous and dynamic wireless sensor network applications capable of self-organization in order to offer fault-tolerance, adaptation to varying environmental circumstances, and graceful degradation of their sensing and acting capabilities.

On one side, we support this vision by imbuing intelligence within the network, for instance, by using agent techniques to opportunistically drive the adaptation of aggregation functionalities, sensing and sleeping patterns, routing and other network parameters, and also human-system interaction. In this way, much of the decision making and intelligence can occur at run-time and at the leaf nodes rather than the trunk of the sensing & acting network. On the other side, we need to support the integration of more sophisticated functionalities which cannot rely solely on in-network processing over computational constrained nodes. To this end, and in order to address both the interoperability and the extensibility requirements set for the overall framework, our initial solution is based on the integration between a stream-based middleware, the Global Sensor Network (GSN) [23], and a component based framework, the Java Modular Component Framework (JMCF) [24].

GSN is one example of a large number of complimentary works on query processing in sensor networks, Aurora [REF], STREAM, TelegraphCQ, and Cougar being the most prominent ones, which can be used in this sense. Compared to those systems, GSN takes a more general view and use only small set of powerful abstractions to provide, not only APIs and a set of readily available drivers (called *wrappers* in GSN) to connect to existing sensor networks, databases and web resources (e.g. services), but a complete query processing and management infrastructure with a declarative (SQL-based) language.

GSN provides a *logical view* on sensor networks based on the *virtual sensor* abstraction. Virtual sensors abstract from the implementation details to access sensor data and model sensor data as temporal streams of relational data. Virtual sensors can also represent derived views on sensor data streams, resulting from post-processing and combination of sensor data from different sources.

However, GSN suffers from a number of limitations, namely:

1) It only supports data type communication (streaming)
2) A virtual sensor can have any number of input streams but produces only one output stream.
3) It does not support dynamic load-balancing.
4) It supports well data collection but it does not facilitate control interventions on the sensor layer.

All these issues are addressed in the CLARITY platform by employing GSN for data streaming within our JMCF component framework. JMCF is a minimal component framework for interfacing with different component-enabling technologies, such as OSGi and Java Beans. For AAL applications, JMCF: (i) wraps resources (e.g. databases) and sensors, (ii) enables the reification of particular services and functions offered by the smart environment (e.g. activity recognition modules), and (iii) provides a consistent interface to interact with functional layers to components and services organized in component contexts based on standard component technologies. Crucially for this integration, JMCF supports procedural interfaces, variable number of components' input & output interfaces, and self-configuration and load-balancing capabilities that can be driven via a well-defined interface, such as that provided by the deployed agents.

To illustrate the integration of GSN with the AAL platform (Figure 9), a simple example, where data from a sensor network consisting of a number of heterogeneous Tyndall nodes is now considered. Each node in the example depicted in Figure 9 sends different data packets reporting the data sampled by its specific sensing hardware. Data packets are relayed to the base station, where they are read by the Serial Forwarder (SF) application provided in TinyOS. The Serial Forwarder uses a publish-subscribe TCP/IP communication protocol to distribute these data packets to a number of GSN virtual sensors in the GSN node, each of which is concerned only with packets of a specific type. Finally, these GSN virtual sensors acts as bridge between the GSN and the JMCF context, by themselves operating a publish-subscribe protocol. These virtual sensors use TCP/IP to extract data packets from specific sensors and to offer the corresponding data to the components loaded in the component framework.

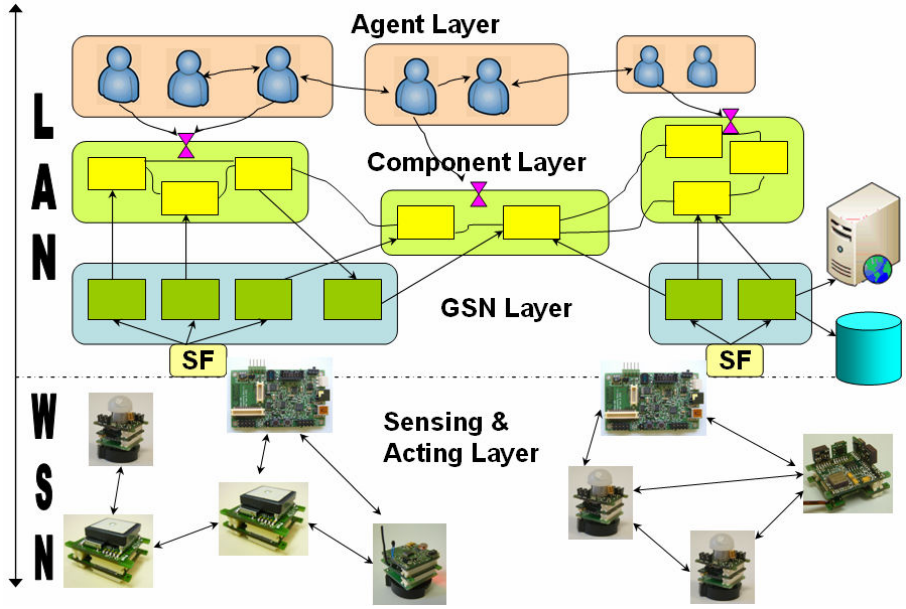


Figure 9. AAL System Diagram

2) Agent Layer

Having harnessed various types of sensor data, the key question that arises is how to make sense of it or how to apply some meaningful semantics to it. Agents offer one paradigm for achieving this. Their distributed nature augmented with their social ability allows them to collaborate in ascribing meaning to a context. Two methods are supported and the choice of method depends on the configuration deployed in any given AAL deployment. This configuration will in turn be influenced by the nature of the physical environment in which it is deployed but more importantly, the circumstances of the occupant in the AAL environment will determine the most appropriate combination of sensors.

In the first instance, data is routed back to a central database. Agents monitor database activity and continuously update a model of occupant activity, according to the activities they are assigned to monitor. In the second instance, agents are hosted on select nodes that enable them monitor all interactions in their vicinity. However, this demands the availability of a sophisticated sensor platform that would support agents. In this case, Agent Factory Micro Edition (AFME) [25] is harnessed. This requires the availability of a J2ME interpreter. Only a few sensor platforms offer this kind of functionality, the Sunspot being one, the Tyndall 'Agent Ready' layer another. In AAL scenarios, assigning agents to monitor activity at room level, for example, is one obvious case where hosting the agent on an individual sensor platform makes sense.

Ultimately, the aim of AAL is assist the occupant in some way. In the current configuration, an interventionist approach is not adopted; rather, the platform operates unobtrusively, assembling a picture of daily activity, enabling carers and health professionals to easily visualize patterns of behavior. Indeed, it is deviations from the daily routine that is of most interest and may indicate a scenario where the person's safety is compromised. For example, should the agents determine that the occupant is spending an inordinate amount of time in their hallway, they might conclude that this merits further investigation. Initially, they may collaborate to verify that the occupant is indeed in the hallway or was last "seen" in the hallway. Should the PIR sensor not detect movement, the agents might activate a different suite of sensing modalities, for example, an embedded microphone, to detect if there are any sounds even if there is no movement. Should the status of the occupant remain undeterminable, the attention of a carer, neighbor or relative must be sought.

From a scalability perspective, the use of agents enables the seamless integration of further sensors into an arbitrary configuration, at least from a software perspective. This is of crucial importance as the needs of the elderly will change over time thereby demanding that the AAL platform can transparently evolve to meet their needs.

IV. FUTURE WORK

The subject of future work will be the extension and expansion of the AAL scenario to the home and outdoor environments where additional hardware modules will be integrated in the scenario, for instance the GPS and wearable modules outlined at the end of Section III. There the mixed component/stream integration framework and the distributed agent based architecture will be developed further to provide the elderly person, their relatives and the medical professionals with context and subject-aware content in an intelligent manner. An event based user interface, of ewhich an initial prototype has been developed (Figure 10), which currently reads XML data from the GSN web-service, will be employed to relay information that is of interest and importance to the stakeholders. The focus here will be placed

on aspects such as the development of the application level, long-term logging, and activity recognition.

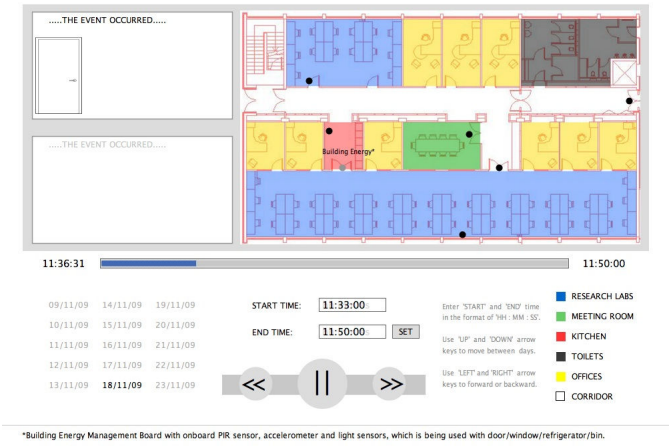


Figure 10. CLARITY AAL Platform Graphical User Interface

V. CONCLUSIONS

This paper has introduced the CLARITY Modular Ambient Health and Wellness Measurement Platform and has highlighted its capabilities as an end-to-end pervasive healthcare solution. Novel heterogeneous wireless sensor network mote technology has been seamlessly deployed in the ambient assisted living environment and the modular nature of this technology makes it cost effective, easily expandable and interoperable with a wide range of sensors and wireless technologies. This unique combination of modular hardware components supported by a distributed component-based intelligent software architecture provides a basis for AAL platforms that exhibit interoperability, scalability, reusability and robustness.

VI. ACKNOWLEDGEMENTS

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