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Exploiting Linked Data to Create Rich Human Digital Memories

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Abstract

Memories are an important aspect of a person's life and experiences. The area of human digital memories focuses on encapsulating this phenomenon, in a digital format, over a lifetime. Through the proliferation of ubiquitous devices, both people and the surrounding environment are generating a phenomenal amount of data. With all of this disjointed information available, successfully searching it and bringing it together, to form a human digital memory, is a challenge. This is especially true when a lifetime of data is being examined. Linked Data provides an ideal, and novel, solution for overcoming this challenge, where a variety of data sources can be drawn upon to capture detailed information surrounding a given event. Memories, created in this way, contain vivid structures and varied data sources, which emerge through the semantic clustering of content and other memories. This paper presents DigMem, a platform for creating human digital memories, based on device-specific services and the user's current environment. In this way, information is semantically structured to create temporal "memory boxes" for human experiences. A working prototype has been successfully developed, which demonstrates the approach. In order to evaluate the applicability of the system a number of experiments have been undertaken. These have been successful in creating human digital memories and illustrating how a user can be monitored in both indoor and outdoor environments. Furthermore, the user's heartbeat information is analysed to determine his or her heart rate. This has been achieved with the development of a QRS Complex detection algorithm and heart rate calculation method. These methods process collected electrocardiography (ECG) information to discern the heart rate of the user. This information is essential in illustrating how certain situations can make the user feel.

Keywords: Human Digital Memory; Linked Data; Semantic Web; Resource Description Framework; Lifelogging

1. Introduction

Remembering the past helps people in re-examining their life, recalling previous activities and accomplishments, pursuing remote memories, and seeking personal validation [1]. As such, retaining information and reconstructing past experiences is one of the most important ways by which a person's histories animate their current actions and experiences [2]. Retaining every aspect of daily life, for example, how we felt or what we did on a specific day is virtually impossible, especially when recollecting events from 10 years ago. As people get older, the ability to remember this type of information declines [3]. However, as technology advances, devices are, nowadays, capable of storing a lifetime's worth of data and capturing our every move, interactions and physiological signals. These machines now fit seamlessly into our world, instead of forcing users to enter the machine's environment, a concept first envisioned by Weiser [4]. An entire lifetime can be reconstructed from collected digital artefacts, and thus a Human Digital Memory (HDM) can be created. These personal archives are constructed from a wide range of data sources, across various media types [5]. This idea is echoed by Kelly [6], who states that "*We have now reached the point where all of a person's personal life experiences can be stored digitally – everything from items read, written, or downloaded; to footage from life experiences, e.g. photographs taken, videos seen, music heard, details of places visited, details of people met, etc.*" However, reasoning over a lifetime's worth of data, to construct a HDM is a challenge. The task of managing, and using, digital memories, over this extensive period of time, has led to *Memories for Life: managing information over a human lifetime* being declared a computing grand challenge [7].

A consequence of living in the digital age is the abundance of information that is available. In today's society, it is common practice to capture, store, upload and share almost every moment of daily life. Sensors, embedded in everyday objects, are also capable of connecting to the network and providing useful information, without user intervention; thus resulting in "information overload". This vast amount of data is growing every day, and inadvertently significant mementos are, undoubtedly, being lost and forgotten. Providing an intelligent way of searching this data has led to the development of the Semantic Web, Web 3.0 applications and linked data. The Semantic Web, also known as "Web 3.0", simplifies human-computer interfaces by attaching machine-readable metadata (information about information) to web content to enable computers to 'understand' the actual/intended significance of this content, as they process it [8]. Information, from distributed data sources, can be linked, in order to add more "meaning" to the data. It is this mash-up at the data level, rather than the application level, that has led to the phrase "*Web 3.0*" being coined [9]. Creating these links between objects is fundamental to these applications. This is achieved using the Resource Description Framework (RDF), which provides a means to link data from multiple websites or databases together, and is the basis of Web 3.0 applications [9]. This collection of interrelated datasets can also be referred to as Linked Data [10]. Bizer *et al.* [11] summarizes linked data as being, "*simply about using the Web to create typed links between data from different sources*". It is this idea that is fundamental to current work, as distributed sources of information are brought together, searched and linked, to create a HDM.

The idea of storing all of ones accumulated digital items was first proposed in 1945, by Vannevar Bush [12], with the concept of the *Memex*. This idea is described as being, "*a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility. It is an enlarged intimate supplement to memory*". Since that time, the notion of storing all of ones accumulated digital items has been a topic of interest, for many researchers. HDMs are comprised of many items, and as stated by Kelly [6] are, "*typically a combination of many types of media, audio, video, images, and many texts of textual content*". This outlet allows us to capture, from a variety of data sources, rich information about our surrounding environment and ourselves. A HDM is comprised of many items; however, successfully bringing together these fragmented pieces of information is a challenge. The use of linked data, semantic web principles and RDF is seen as a way to alleviate this problem. RDF enables data to be incorporated into a memory, irrespective of its format. This feature is especially useful because, as Fitzgibbon and Reiter [7] question, in their report *Memories for Life: managing information over a human lifetime*, "*How can we ensure that data is still accessible in 50 years time, despite inevitable changes in software, hardware and formats?*". By using linked data and RDF, as time goes on and new devices and formats emerge; the original data can still be incorporated into a HDM. This is reiterated by The World Wide Web Consortium (W3C) [13], who comment that, "*RDF has features that facilitate data merging even if the underlying schemas differ, and it specifically supports the evolution of schemas over time without requiring all the data consumers to be changed*". Linked Data provides a way to fuse data, about entities from different sources, together and to crawl the data space, as the data is connected by links [14]. It is these ideas that are particularly interesting and ones that will be incorporated into the work of building HDMs. The memories that are created contain vivid structures and varied information sources, which emerge through the semantic clustering of content and other memories.

This paper explores how HDMs can be created in both indoor and outdoor environments, how semantic web technologies can be applied into the creation of these memories and how collected heartbeat information can be processed. In achieving this, the DigMem system is presented, which creates rich and interactive HDMs. In order to create these dynamic memories, a new method is being proposed. The approach takes data, from ubiquitous devices, and, using linked data combines these various pieces of information together, to form a HDM. These collected data sets, are not very useful in representing a memory on their own and need to be transformed into a smaller amount of more meaningful information. In this context, memory boxes have been created by semantically linking all of the related data together and turning it into visual items of events. In order to demonstrate the applicability of the design a prototype has been developed to demonstrate the design. To validate and evaluate the implementation, various experiments were also undertaken that use the system for several periods of time. These studies evaluate the system in both indoor and outdoor environments. Furthermore, collected heartbeat information has been examined to illustrate how it can be processed to discern the heart rate of the user. This has been achieved using a developed *QRS Complex* detection algorithm and heart rate calculation method.

The remainder of the paper is structured as follows. Section 2 provides a brief overview of related work, within the field of lifelogging and linked data. Section 3 describes the design of the DigMem system and provides an overview of how the system functions. This section also includes a brief discussion about how the user is monitored indoors and how heartbeat data is analysed. Section 4 discusses the implementation of the DigMem system and illustrates the creation of a memory box. Section 5 evaluates the system posited in this paper. As well as evaluating DigMem, this section also evaluates the use of the created indoor localisation system, which is capable of tracking the user inside. It also evaluates the developed *QRS Complex* detection algorithm, and heart rate calculation method, that are used to illustrate how heartbeat data is processed. This information is essential for inferring feelings and moods from events. Section 6 provides a discussion of the paper, whilst Section 7 provides a summary and the direction of future work.

2. Related Work

Research into capturing and creating HDMs has received a great deal of attention, from researchers, over the last few decades. Since the *Memex* [12], in 1945, research into how aspects of our lives can be captured and organised, have been investigated. Over time, this vision of storing accumulated items has evolved into lifelogging, the process of automatically recording aspects of one's life in digital form [15]. The culmination of this practise has been to continually capture content, with the aid of wearable systems. Obtaining data in this way produces a phenomenal amount of information. The way in which this information is being searched and accessed is also changing. The Semantic Web provides an intelligent way of searching this data. Information is given well-defined meaning, better enabling computers and people to work in cooperation [16]. The following provides an overview of the research efforts into capturing HDM data and how this information can be brought together, using the principles of the semantic web and linked data.

2.1 Capturing Human Digital Memory Data

Lifelogging has been revolutionised by Microsoft's *SenseCam* [17]. This device is designed to capture a digital record of the wearer's day by recording a series of images and capturing a log of sensor data [17]. The device contains a digital camera, with a fisheye lens, and multiple sensors. On-board there are sensors to detect changes in light levels, an accelerometer, a thermometer, and a passive infrared sensor to detect the presence of people [17]. It has been used in various studies [1], [15], [18–23] to capture and display memories and to monitor behaviour. One such approach is Doherty *et al.*'s [18] *SenseCam browser*. Their work applies a series of automatic content analysis techniques to structure the *SenseCam* images into "events" [18]. Lee *et al.* [24] also use the technology as a memory aid to capture the user's daily routine. The images recorded are then presented in a timeline format, similar to the approach used in Microsoft's *MyLifeBits* [25] project. In contrast, the device has also been used within the area of travel research and to monitor sedentary behaviour. Kelly *et al.*'s [22] study used the technology to determine that it was a useful tool in successfully and accurately investigating the mode and duration of travel behaviour. Without the device, it was common that self–reported journeys were often over–reported. Taking an opposing view, Belimpasakis *et al.* [26] have used mobile devices in order to implement a "*client–server platform that enables life logging, via mobile context collection, and processes the data so that meaningful higher-level context can be derived*". However, this system focuses on enhancing social connections rather than lifelogging.

As well as recording images of a user's daily life, recording biological signals offers a new insight into how our bodies are functioning. Sensor–based systems are also quickly emerging as a new way to capture a user's every move and to monitor their health and wellbeing [27]. The development of smaller sensing devices and wireless communications is revolutionising the way in which a subject can be monitored, ubiquitously [28]. Recent research into the area of affective computing has demonstrated that emotional states of people can be recognized from their physiological signals [29–31]. This data is highly personalized and unique to every individual. Its incorporation into a HDM allows us to reflect on how we were feeling at any stage of our lives. The development of smaller sensing devices, and wireless communications, is revolutionising the way in which this data can be obtained [28]. However, these devices are primarily used within Wearable Health-Monitoring Systems (WHMS). As Pantelopoulos and Bourbakis [32] observe, "*These systems represent the new generation of healthcare by providing real-time,*

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unobtrusive, monitoring of patients' physiological parameters, through the deployment of several on-body and even intra-body biosensors". As well as monitoring our health and wellbeing, the data generated from WHMS can also be used to enhance a HDM, by providing us with physiological data, which can be reasoned upon. WHMS, composed of a number of different sensors, can measure a variety of parameters, including electrocardiogram (ECG), blood pressure, respiration, body and/or skin temperature etc. [28]. Incorporating this multitude of data, into a HDM, allows memories to become more dynamic and personal to the user. It also enables a richer understanding about our health, level of activity and wellbeing to emerge. Physiological data, obtained through the use of wearable sensors, provides a wealth of information about affective, cognitive and physical state and is able to record long-term trends [33]. In order to add more depth and detail, about ourselves, into HDMs, incorporating this technology is essential.

One such sensing device is the *activPAL* system, which uses a single–axis accelerometer [34] to identify sitting or lying, standing, and walking transitions. The *activPAL* accelerometer has also been used to determine habitual behaviour, whilst also determining the interplay between sedentary behaviour and periods of physical activity [35]. However, the limitation of this system is its inability to recognise slow steps, due to the small amount of amplitudes that are produced. In terms of creating memories, this system can be used to illustrate the movements of a user throughout the day. Nevertheless, the context in which those movements occurred is unknown, without the use of a visual aid.

Armbands have also been developed that house several sensors, within the device, so that a variety of physiological data can be collected. The *SenseWear Armband (SWA)* collects data from a bi-axial accelerometer, galvanic skin resistance (sweat rates), heat flux (heat dissipated from the body), and skin and near body temperature, to estimate energy expenditure and step count [36]. The device has been used within Dwyer *et al.*'s [36] work to determine its accuracy for estimating energy expenditure and step count during treadmill walking in cystic fibrosis (CF) patients, compared to healthy adults. In this instance, the *SWA* provided a reasonably accurate measure of step count compared to manual counting during tread mill walking and diagnosis of CF didn't affect its accuracy [36]. The *SWA* has also been used to monitor adherence in women with rheumatoid arthritis in a similar way to measuring decreases in sedentary behaviour [37]. The results from this study concluded with an 89% adherence rate and that the *SWA* is a viable method of quantifying physical activity and may be useful to monitor effectiveness of interventions to increase activity in people with rheumatoid arthritis [37]. In relation to creating memories, this system can also be

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used to illustrate the movements of a user throughout the day. However, like the *activPAL* system [34], the context in which those movements occurred is unknown, without the use of a visual aid.

Whilst collecting physiological data is relatively straightforward, interpreting this data is more challenging. The electrical activity of the human heart (heartbeat) can be captured with the use of WHMS. This information is recorded as waves, in an ECG reading. The most common waves, in an ECG reading, are the "*P*", "*QRS*", and "*T*" waves (see Fig. 1). Interestingly, the letters "*P*", "*Q*", "*R*", "*S*", and "*T*" are not abbreviations for any actual words but were chosen many years ago for their position in the middle of the alphabet [38].

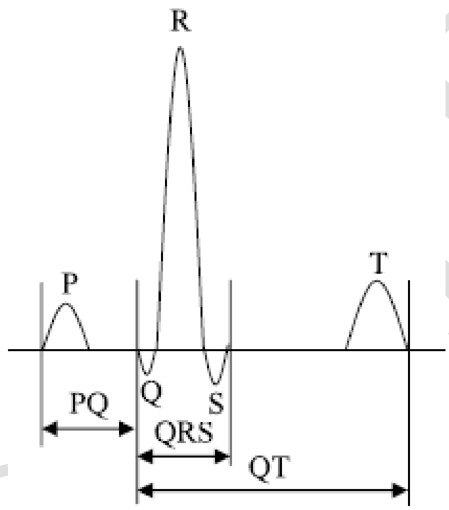

Fig. 1 Different Types of Waves in an ECG Signal [39]

The "*P*" wave illustrates atrial contractions, of the heart, ventricular contractions are known as a series called the "*QRS Complex*", whilst the third is the "*T*" wave, which illustrates the electrical activity produced when the ventricles are recharging for the next contraction (repolarizing) [38]. The *QRS Complex* is a major wave in any normal ECG beat [39]. By detecting the *QRS Complex*, and then measuring the interval between the "*R*" wave types, the user's heart rate can be determined. The distance between the "*R*" waves is known as the R-R Interval (*RRI*). If this distance is closer together, then this indicates a higher heart rate, than if they are further apart. This information, along with location and photo data, for example, can be used to infer how the user was feeling, at any given time.

Whilst the technologies and methods discussed are a useful starting point, within the area of lifelogging, novel solutions are needed that include much richer data capturing capabilities and require a less obtrusive and expensive, approach. Although the *SenseCam* has been hailed as a "*revolutionary pervasive device*" [40] it has its limitations. One drawback is in relation to the access of data. Images have to be manually downloaded, periodically, which can

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be very time-consuming and mundane for the user. The device is also very costly. Exploiting the services of devices, already present within our environment, is a far less expensive approach. Another limitation, of current systems, is that they record only a restricted amount of information, either visual or physiological data. In order to form a better rounded snapshot of our lives these technologies need to work together. So that not only can a visual representation of experiences be recapped, but also the feelings and changes our bodies were experiencing when those experiences were occurring. Another drawback is that physiological data can be ambiguous and can require extensive data analysis. Automatic analysis of this data would have to be performed, in order to discern meaningful information to enhance memories. Subsequently, incorporating environmental factors, such as temperature and humidity, would reduce ambiguity further and add more information to a memory. For example, a higher heart rate, than normal, and an increase in sweat production could be attributed to many things. Presenting only this information, as a memory, is insufficient. However, if it was known that it was a hot day, by incorporating a temperature reading and that a photo of the user doing physical activity was also obtained, then the context of the physiological data is known. Bringing together data, from separate sources, enables a finer level of detail to be achieved.

Current research is aimed at incorporating a multitude of data, from distributed sources and pervasive devices, to form a memory box. In this context, a memory box contains visual items, i.e. photos, as well as several sensor readings, ranging from location to changes in physiological data. However, constructing and linking these data items presents a significant problem. To address these problems semantic web technologies offer an ideal solution, as it shall be seen in the following section.

2.2 Using Linked Data to Create Human Digital Memories

Linked Data (also known as the Semantic Web) provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries [41]. It enables intelligent search instead of keyword matching, query answering instead of information retrieval, document exchange between departments via ontology mappings, and definition of views on documents [42]. The heart of the Semantic Web lies in linking data together from different sources. The term "Linked Data" refers to a set of best practices for publishing and connecting structured data on the Web [11] and is essential in connecting data across the semantic web [43]. Linked Data relies on documents that are in the RDF format [11], a model for describing resources [44]. The following is a brief overview of this area.

The Linking Open Data community project [45] is the most noticeable example of the implementation of the semantic web. The project's aim is to bootstrap the Web of Data, by identifying existing data sets that are available, and publishing them on the Web [11]. The data sets are distributed as RDF and RDF links are set between data items from different data sources [45]. This project has been incredibly successful. As of September 2011 there were, collectively, 295 data sets, consisting of over 31 billion RDF triples, interlinked by approximately 504 million RDF links [45].

One such application that has come out of the Linking Open Data community project has been *DBpedia* [46]. This project "*focuses on the task of converting Wikipedia content into structured knowledge, such that Semantic Web techniques can be employed against it*". *DBpedia* has been very successful, with 4.7 billion interlinked RDF triples residing [47]. This project has also been extended with the implementation of *DBpedia Mobile* [48]. The mobile version "*allows users to access information about DBpedia resources located in their physical vicinity, from where they can explore links to other resources on the Semantic Web*" [48]. This work has been very successful in linking data together from a variety of resources. Furthermore, it illustrates how a variety of information can be connected in this way. The mobile version is also particularly interesting due to the integration of location information.

Meanwhile, Smith *et al.*'s work focuses on using open linked data to annotate the life logs of a user [49]. Their project, *Imouto*, collects and organises lifelogs and life annotations, as well as combining them with both external contextual data and open linked data from the web [49]. This work is of particular interest due to the similar nature of present research. However, current research aims to improve on this idea by using linked data to connect data from distributed data sources together, instead of obtaining the information from the internet and to provide intelligent searching of this data.

In comparison, Araújo and Houben's [50] work takes the idea of building digital memories in a different direction, by envisioning the web as a "*living system*". The use of Semantic Web technology and Information Extraction is used for weaving the users' personal data into a web of concepts [50]. This work is closely related to current research, however it is only limited to linking data from the web and from online social communities. For a true representation of a memory to be built data also needs to be incorporated from real–world devices, e.g. sensors. Current research is focussing on the idea of building a memory that is composed of linked data from a number of distributed devices.

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In contrast, *SPITFIRE* [51], takes the idea of the semantic web further. In this work, Pfisterer *et al.* [51] describe their vision of a "*Semantic Web of Things*". This idea is focused on integrating Internet–connected sensors into the Semantic Web [51]. Their work, "*Provides abstractions for things, fundamental services for search and annotation, as well as integrating sensors and things into the linked open data cloud*" [51]. In this context "things" refers to real-world entities, such as meeting rooms and parking spots [51]. This work is of significant importance because, when building a memory, incorporating as much data from the surrounding environment and smart objects, is vital. Sensor data tends to be ambiguous; therefore overcoming this challenge is a big step into integrating data from a variety of sources into HDMs. Incorporating this type of data would produce richer HDMs, as the level of detail is increased.

There are many systems that exist that capture data and that can create HDMs and there are many approaches that are used within the Semantic Web; however very little work exists that brings together these two areas. In order for a better representation of our lives to be digitally encapsulated enabling these separate disciplines to work together is fundamental so that a variety of data can be linked. As well as linking information together, the data itself needs to also be processed. Physiological data can be ambiguous and can require extensive data analysis. Combining this data with visual items enhances the level of context associated with a memory. Another issue is that memories are not isolated static events, but rather a continuous sequence of experiences contextually linked and created within and across different geographical areas within the environments we occupy. Therefore their digital counterparts should be the same.

A limitation to current systems is that, as the user moves through different environments, their devices have to be adjusted. For instance, due to the limitations of Global Positioning System (GPS) sensors, recording location information, using this technology, is not feasible indoors. GPS is a popular location estimation system for use in outdoor environments. However, it does not work indoors because it uses signals from GPS satellites, which are blocked when the user is inside a building [52]. Any system that uses this method of data collection would be rendered useless in an indoor environment. As the user moves between outside and inside settings, the devices and services that are accessible change. In this sense, the memories that are being created will never be the same. Therefore, as the user moves through these different environments, the data that is accessible varies and this will be reflected in the memories that are created. In order to achieve the goal of creating an accurate representation of a human digital memory, in both indoor and outdoor environments, the DigMem system is presented. This system links a variety of information together and visualises these items as a memory box, as it shall be seen in the following section.

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3. DigMem System Design

The DigMem system has been designed to create a HDM, based on the services available at the time, in a variety of environments. The system is composed of a number of layers and three components – Mobile DigMem (MoDM), DigMem Server and DigMem Web application (see Fig. 2). The mobile aspect of the system [53] is used to gather information, from a variety of pervasive devices. The server side stores the collected data and enables this information to be semantically searched, so that links between items from different data sets can be made. The web application then provides an interface to input search queries and enables a memory box to be created and displayed. A more detailed description of each layer is presented below.

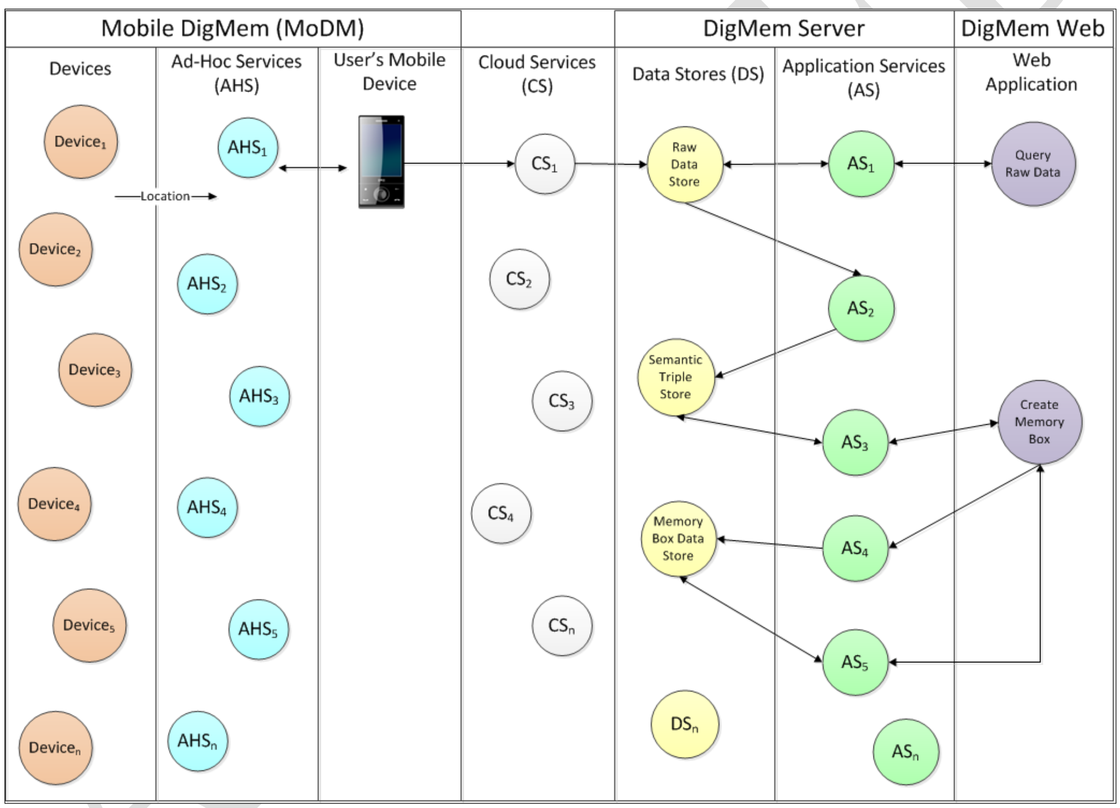

Fig. 2 DigMem System Design

The first three layers of the system represent MoDM, the mobile aspect of DigMem. Firstly, all pervasive devices, within the user's vicinity, which are running the MoDM middleware [53], are connected, via a peer-to-peer (P2P) network. The Ad-Hoc Services and Mobile Device layers then work in conjunction with each other to extract information from the devices, in the previous layer. The Ad-Hoc Services layer enables any service, which a device has to offer, to become available for use, within a memory. In the previous layer, the MoDM middleware connected all devices together, via a P2P network. In this layer, MoDM is also used to advertise the services that each device has to offer and enables the mobile device (that is used in the Mobile Device layer) to request the use of that service. For example, if the user walks into a room, all devices (e.g. cameras, temperature sensors, location sensors, and body sensors), within that room, would be connected, via the P2P network. In order to make a memory, of that specific time, the user's mobile device then lists all the available services. When a service(s) is chosen, a request is made to all the peers on the network, to find that service(s). Once a response is received, a command for data is sent, to the responding device(s), and the data is obtained. This method allows for any number of Ad-Hoc Services (AHS_1, AHS_2, AHS_3….AHS_n) to become available. This method provides adequate flexibility in a number of environments, as the services that are accessed will change, in any situation. Since the capacity of mobile devices is limited, the retrieved information is periodically transferred to the cloud. This enables more data to be collected and more complex processing to occur, at a later time.

Once the mobile device starts to collect data, this information is then transferred to the Cloud Service layer. This layer also offers a number of Cloud Services (CS_1, CS_2, CS_3....CS_n), which can be tailored to the user's specific needs. Once the data is in the cloud it can be accessed from anywhere in the world. This layer is flexible enough to allow data to be transferred to any device, at any time.

From the cloud, the data is periodically transferred to the DigMem Server aspect of the system. This part of the system is composed of the Data Store and Application Services layers. Various Data Stores (DS_1, DS_2, DS_3…DS_n) are located within this layer. Once the data is initially transferred, it is stored in its raw form, within the Raw Data Store. Storing the data in this way allows it to be manipulated and transformed into any other format, at a later time. This layer will also contain a number of other stores, which can save other instances of the data. For example, the Semantic Data Store would store the raw data as tuples and the Memory Box Data Store would store the memory queries. However, transforming the raw data into this format, so that it can be queried and these queries can be saved, is the responsibility of the Application Services layer.

From the Data Store layer, the information is transferred to the Application Services layer. This layer provides an interface to the Web Application and provides a means of communication. This layer contains a number of Application Services (AS_1, AS_2, AS_3…AS_n) and allows the raw data to be transformed into any format. This method provides the user with the flexibility to choose the format that they want their data to be stored and accessed in. If the user wants to query the raw data, the Application Services layer provides a link between the Raw Data Store and the Application layer. However, querying the raw data does not provide a sufficient level of detail. For example, querying the user's raw location data would only retrieve a list of coordinates. This is not sufficient for a memory; a plotted map of their movements would be more useful. In order to visualise the memory data, the Application Services layer checks the Raw Data store, for data, every *x* minutes. Any new data is transformed into a metadata model. This model is then transported back to the Data Store layer and stored within the Semantic Data Store.

The DigMem Web aspect of the system consists of a web interface, where the user can log in and create memory boxes. Once logged in, the user can query their information, either in its raw form or semantically. Querying the data semantically means that, after the data is retrieved, it is visualised as a "memory box" of that query. A memory box displays all information, as visual items, and links data, from distributed sources together, in one place. In this context, for example, all photos, physiological information, temperature and location information are presented in a graphical manner. This is opposed to just listing the raw information (e.g. location coordinates, file locations of photos or physiological readings). Memory boxes are temporal; therefore, the queries that are used to produce them are the items that are saved. When a query has been executed, it will be saved, within the Data Store layer, in another data store. Another Application Service is required that takes the query and saves it in the Memory Box Data Store. Using another Application Service, the interface should also retrieve previous queries, from this store. Once a query is retrieved is should be displayed, again, as a memory box. Queries can also be enhanced and an augmented memory, of the original memory, can be created and saved. In this instance, similar memories would need to be clustered together. The system should also allow multiple users to log on and share their memories, via a public folder. In this way, group memories can be created, and personal memories can be augmented with even more information.

An overview of the process of creating a HDM is described below. Figure 3 represents these steps and is based on the system design from Figure 2.

1. Mobile device (laptop, tablet, smartphone, etc.) sends a request for data, from devices within their environment (temperature sensors, body sensors, cameras etc.).
2. The data obtained gets automatically transferred to a data store within the cloud.
3. It is then, periodically, transferred to a Raw Data Store.
4. From the Raw Data Store the data is then transferred to the Application Services layer. Here the data can be transformed and manipulated into another format or transported to the application's interface.
    4a. If the user wants to query the raw data then the data is transferred directly to the applications front-end. At this point a sequel query can be performed on the data.

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4b. However, if the user wants to transform the data into another format, another application service checks the Raw Data Store, every *x* minutes, and converts the data into the new format.

5. Once the data is transformed, it is then transferred back to the Data Store layer and stored within a, separate, Semantic Data Store.

6. The Application Services layer provides a link between the semantic data store and the applications interface. The user can perform "smart" queries on this semantic data (memory box).

7. Once a memory box has been created, the query, which was used to create it, is saved. In this instance another application service is required that will take the query and save it into another data store, Memory Box Data Store.

8. When a query is saved, it can then be retrieved again from the DigMem interface, via another application service, and displayed as the original memory box.

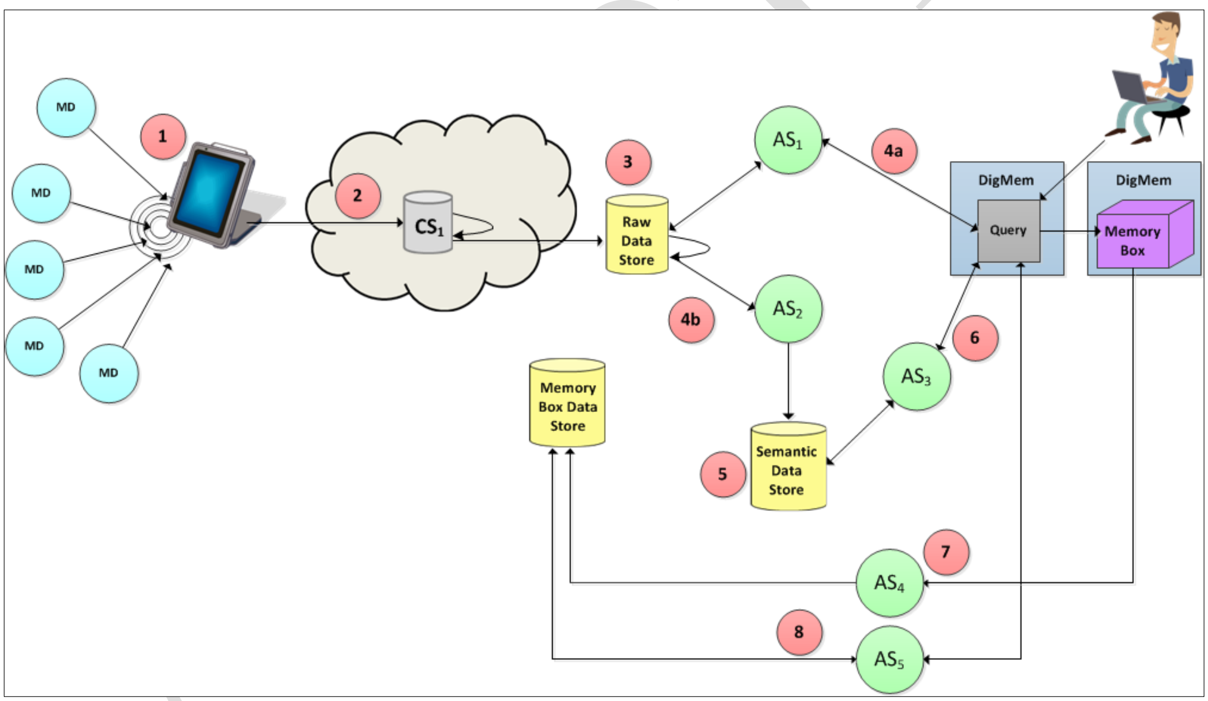


Fig. 3 Process of Creating a HDM Using DigMem

Whilst MoDM is capable of collecting data in an outdoor environment, another means of collection is needed whilst the user is indoors. In this sense, "memory black spots" can be alleviated. These occurrences happen when there is a gap in the HDM. Previous work [53] focused on only collecting outdoor information; therefore, when the user went inside the HDM stopped and there were significant gaps in their day. To overcome this challenge a wireless sensor network, and custom-built sensors, have been developed that are capable of tracking the user indoors, in this case in their home [54]. By incorporating this platform into DigMem, lifelogging can occur in both indoor and outdoor environments. Now that it is possible to collect lifelogging data, almost continuously, processing that data presents another problem. Information from location and photographic data can easily be discerned. A map tells the user exactly where they were, whilst pictures illustrate the context of those movements. However, physiological information, such as the user's heartbeat, is more complicated to understand. In order to process this information, a new algorithm and calculation method are also presented. These methods are capable of filtering any captured heartbeat signal in order to detect the *QRS Complex* and calculate the *RRI*. By calculating the *RRI*, the user's heart rate is able to be determined.

Linking all of these components together forms the complete lifelogging system. The MoDM application provides services to access the hardware of ubiquitous devices and to process the data streams that they provide. This aspect of the system is used to gather information in an outside environment. Physiological data will be gathered using our custom built sensor system [54]. This system works indoors and, using sensor networks, is able to track the location of people inside of their home and to determine specific body positions. Once the data is collected it is then transferred, using the Internet and Cloud Computing services, to the DigMem system. Any physiological information can also be process using the *QRS Complex* detection algorithm and *RRI* calculation method. It is envisioned that the system will provide users with an outlet to capture, share and interact with their memories, in a number of different environments.

4. Implementation

The prototype that has been developed, for this work, relates to the DigMem Server and Web application side of the system. This element is used to demonstrate the core aspect of the research, using linked data to build a HDM, which is composed of information from multiple sources. In previous work [53], the MoDM middleware platform was developed, in order to connect and access the hardware and services that distributed devices had to offer. MoDM is capable of tracking a user's outside movements by using location and camera services. However, for indoor localisation, a sensor network has also been developed [54] that provides location tracking to room precision. The purpose of this was so that data, for the memory boxes, could start being collected in both indoor and outdoor situations. Current research takes this variety of collected information and semantically searches and links it together, using linked data. The information is then presented as a memory box, of a specific time in the user's life.

So far, the ways in which memory data can be captured and how linked data can be used to connect all of this data together, have been discussed. Additionally, the design of the DigMem system has been presented. Currently, systems, such as *SenseCam* and the *SWA*, have been used to capture an explicit set of results. *SenseCam* captures photos and limited physiological data, whilst the *SWA* captures biological data, such as sweat rates and energy expenditure. Whilst these systems are useful, within their specific areas, they are not a practical solution in creating human digital memories, over a lifetime. Buying expensive, specialist, equipment and using such closed systems are not a viable option. A new system is required, which can be deployed on everyday devices, and can be adapted to the surrounding environment. In the next section, the DigMem implementation is presented, which moves towards the goal of creating rich human digital memories, using linked data and pervasive devices.

4.1 Technical Description

The prototype uses a variety of hardware devices to collect a range of information. A *Samsung Galaxy* tablet is used to collect location (GPS) and photo data. Physiological (ECG) information is collected, using *NeXus-10* body sensors [55], and *TelosB* sensors are used to gather indoor localisation information. For demonstration purposes, in an outdoor situation, photos are taken, automatically, every 30 seconds. GPS data (time, latitude and longitude positions of the user), is also recorded every time a new position is reached, whilst ECG data is recorded using the body sensors. However, whilst the user is indoors, for example in the home, *TelosB* sensors are fitted to them and at fixed points in the environment. These are used to transmit information between each other and to calculate the signal strength between the static sensor nodes, and the mobile node (the user). The sensors are capable of detecting behaviours, such as sitting, standing or lying down, whilst the sensor network provides location tracking, to room precision.

Once the information has been obtained it is transferred to the user's Dropbox folder [56]. From this location, a number of developed python scripts are executed. These scripts process the data and transfer it to the separate Raw Data Store. This store is a MySQL database, which is located on a server, within Liverpool John Moores University (LJMU). Once the raw data has been saved, a memory box can be created. In order to create a memory box the raw data needs to be transformed into RDF tuples, so that items, from different data sources, can be queried and linked together. In order to query these documents, a SPARQL Protocol and RDF Query Language (SPARQL) endpoint, has been implemented using *ARC2* [57]. Using the SPARQL [58] query language, the RDF documents are then searched. In order to demonstrate the system, the query, "Where was I on 17th July 2012, what was I doing and how was I feeling?" has been executed. The SPARQL endpoint enables the results to be displayed in a number of formats. In order to create a memory box, the results need to be serialised in the JavaScript Object Notation (JSON) format so that they can be displayed as visual objects, within the web browser. Once this file type is chosen, the data is transformed into a memory box (see Fig. 4).

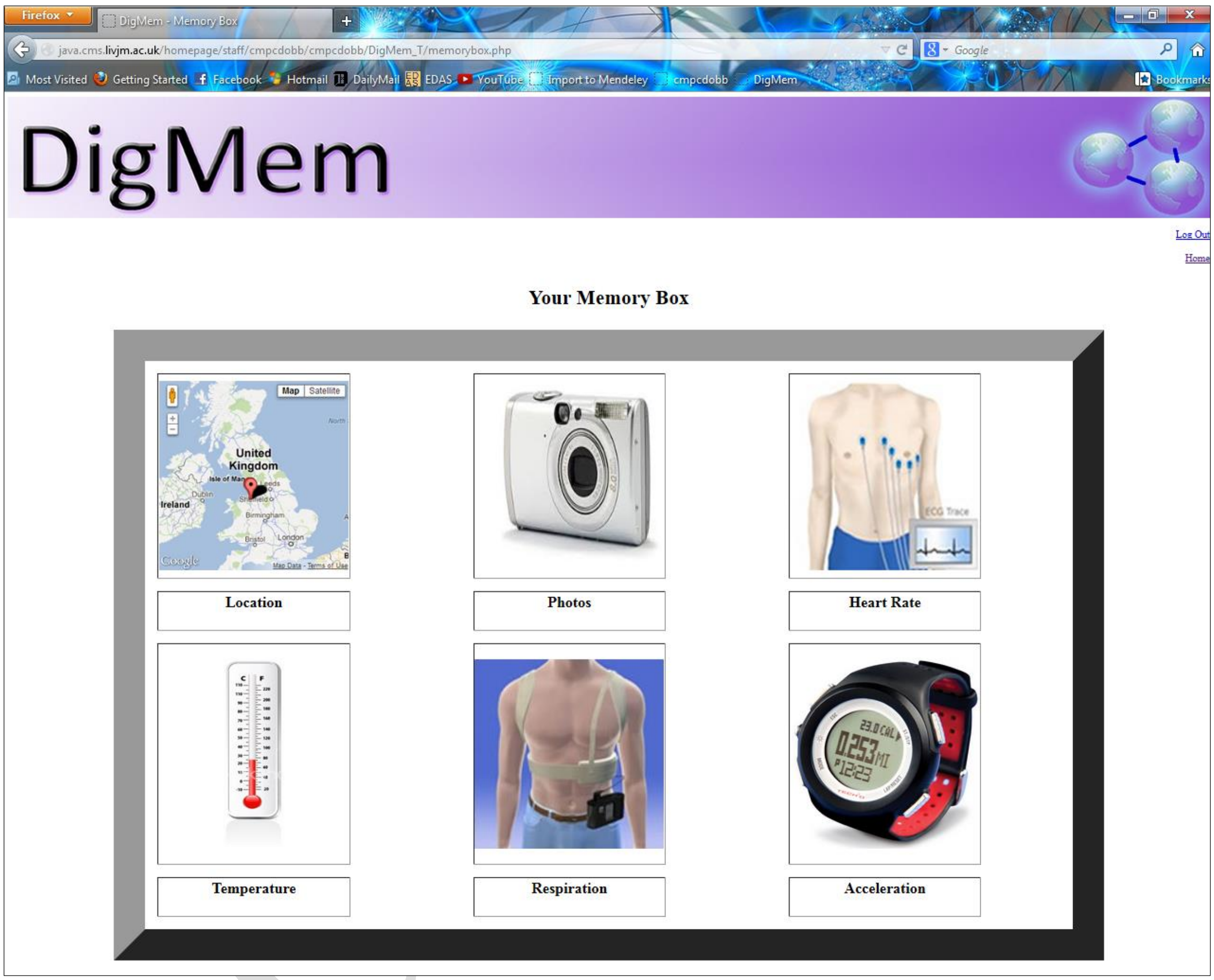
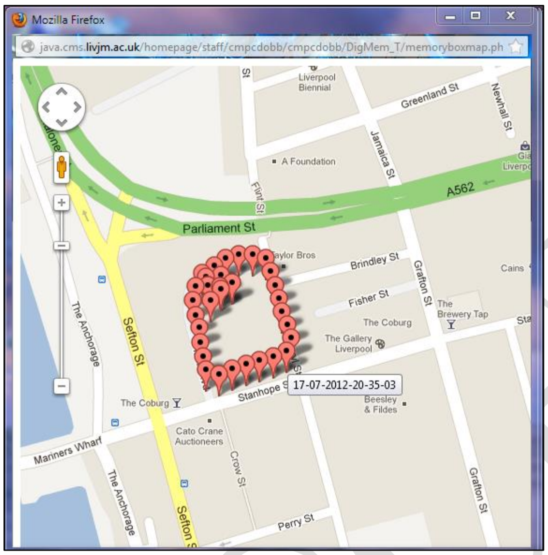
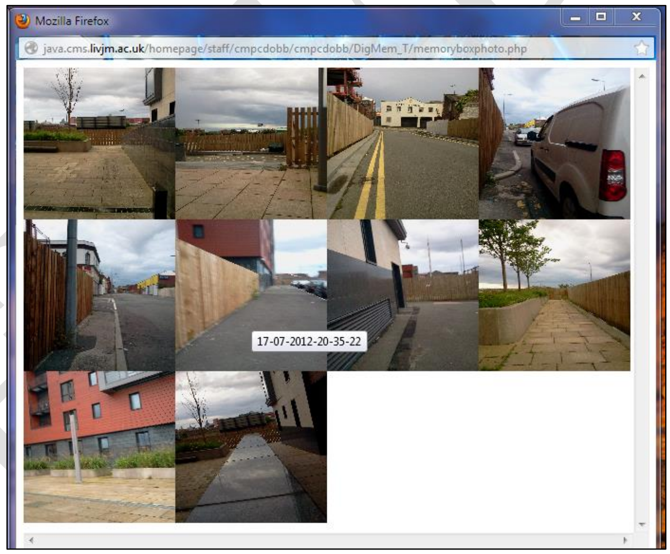


Fig. 4 DigMem Memory Box

The location, photo, and heart rate inputs are displayed, as thumbnails, along with an example of other potential inputs. The range of devices that are accessible will change, depending on the current environment. Nevertheless, for demonstration purposes, this sample selection illustrates the range of information that can be included in a memory box. When the user clicks on a thumbnail, a new window opens and displays the related information. In the case of the memory box above, and query about the user's movements on 17th July 2012, the following information is displayed. When the 'Location' thumbnail is clicked, the serialised GPS JSON results are passed into a jQuery *ajax function()*. The results are then extracted and, using Google's Map Application Programming Interface (API) [59], are plotted (see Fig. 5 a). In order to display the photos, from that time, the same method is used. When the 'Photos' thumbnail is clicked, the photo JSON results are passed into an *ajax function()*. The results are then extracted and the images from that time, along with their timestamp, are displayed (see Fig. 5 b). In order to display the ECG results, the *Flot* API [60] was used. This is a JavaScript graph plotting library for jQuery [61]. In order to plot the information the timestamp data, within the original results, had to be first transformed into JavaScript timestamps, as this is the only time series support that *Flot* uses. In order to overcome this obstacle a Java program was developed, which transformed the timestamp information into the required JavaScript format. After this, the JSON data was then loaded and used to plot the graph (see Fig. 5 c). It should be noted that the graph in Figure 5 c) is not intended to be a representation of an ECG signal, but rather it is illustrating an average reading every 30 seconds.



a)



b)

c)

Fig. 5 DigMem a) GPS, b) Photo and c) ECG Memory Box Data from 17th July 2012

As it can be seen, in Figure 5, the data is displayed as visual items, within the memory box. The results from this demonstration indicate that on 17th July 2012, the user was walking around. Since their heart rate dropped slightly, could indicate that they took a break. The map depicts their exact location, whilst the ECG data illustrates that, as their heart rate was higher they were walking (this is verified from the photos and map). Then, as it drops slightly, they might have taken a break. As their heart rate increases this illustrates that they started walking again. The accompanying photos support this. This method can be used to recall any part of our lives and what our bodies were experiencing at the time. This information could then be used to illustrate how we have changed over time. For example, if we have become more sedentary, over time, factors contributing to this behaviour can be identified. From here, action can be taken to prevent this behaviour. In this demonstration, GPS and photo and ECG information has been used to illustrate how a memory can be made. This approach is flexible enough to incorporate any number of devices and different types of data.

The idea of creating a "box" for a memory fits well with the notion of bringing together separate pieces of information. This is a novel feature because searching on current systems is considered one–dimensional. For instance, the *MyLifeBits* [25] system only searches photos based on keywords. This is inefficient, as only one portion of a memory is retrieved; for a real digital representation of a memory to be created "intelligent" searching is required. When past events are remembered, people remember where they were, how they felt, what the environment was like and many other characteristics of that time. Digital memories should do the same. Simply bringing back a photo of an event doesn't provide the contextual information that makes up that memory. The prototype demonstrates how a human digital memory can be created, from various pieces of data. It also illustrates how these memories will look and the level of detail that can be incorporated into them.

5. Evaluation

This section details the results from a number of experiments that have used both the sensor network, for indoor localisation, and DigMem, for outdoor localisation. The purpose of these studies was to create memory boxes of outdoor journeys and to illustrate how "memory black spots" can be overcome. The context of these "black spots" refers to gaps in HDMs. For example; GPS is limited to outdoor environments; therefore, when the user goes inside a building this creates a gap in the HDM, for the duration of time that they are inside. The indoor localisation system can overcome this issue and is capable of locating a user and their behaviours, to room precision. This system can be used with the photo service to not only track users but to illustrate their movements whilst indoors. Results from a developed *QRS Complex* detection algorithm and *RRI* calculation method are also presented. These methods takes obtained ECG results and filter the signal to remove any interference from it. The *QRS Complex* is then detected and heart rate calculated, from the signal. The purpose of this is to demonstrate how ECG data can be processed and how that data can be used to infer feelings and mood from events. When linked with the photo and location data, an image of how the user has changed over time can be inferred.

5.1 Outdoor Localisation

DigMem has been used in three studies to collect lifelogging data, in outdoor environments. During these times only outside journeys were tracked, due to the limitations of GPS. The first study lasted for seven days, whilst the second lasted for five. The third study was a very short demonstration of the system that was undertaken in order to illustrate how physiological data could be incorporated into a memory box.

During the first two studies, the user carried around the *Samsung Galaxy* tablet, whenever they were outside. During these times, the photo and GPS services were deployed to collect data. Location data was recorded whenever a new position was sensed, and photos were collected every 5 minutes. During the first deployment, 171 photos and 14,018 pieces of GPS data were collected. During the second 181 photos and 4,221 pieces of GPS data were collected. The third use of the system involved the tablet again; however, during this time, the ECG *NeXus-10* body sensors were also attached to the user. During this trial, photos were collected every 30 seconds, and GPS coordinates were saved. During the deployment phase of this study, the body sensors collected an extraordinary amount of information. Within 5 minutes, 613,301 pieces of ECG data (approximately 2044 samples per second) were gathered. In order to process the information the ECG data had to be normalised and an average value for each second calculated. These values were then transformed into RDF and used to plot the users ECG information, within the memory box.

In order to demonstrate the system a memory box has been created to illustrate the first study. The query, "Where was I and what was I doing between 07th and 14th March 2012?" has been successfully executed. The location data from that time is displayed in Figure 6a), whilst Figure 6b) displays all of the photos that were collected. The query searches the RDF documents to establish that, on the day in question, the user was travelling around Liverpool and travelled along the motorway, towards Manchester. As it can be seen, the photo and GPS data supports this conclusion.

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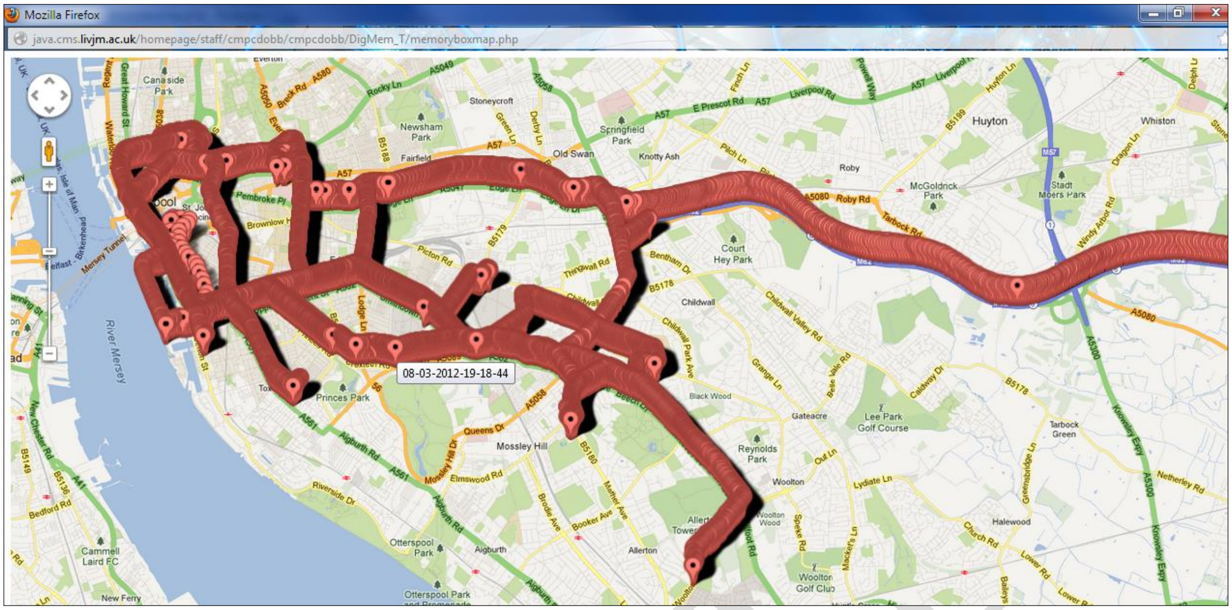
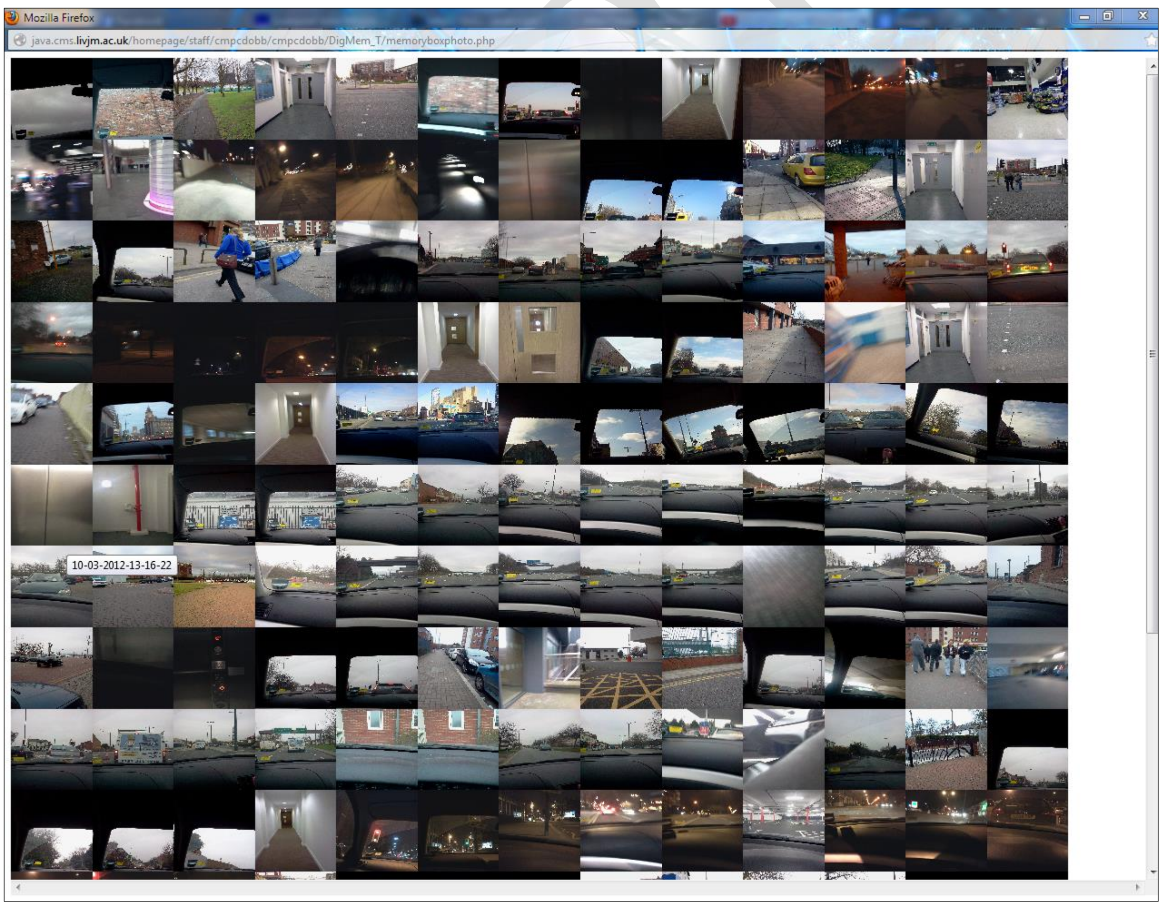


(a)



(b)

Fig. 6 DigMem Memory Box Data from 07th – 14th March 2012 – GPS (a) and Photos (b)

The photos give a visual illustration of the surroundings. At the same time, the GPS data adds more detail to the memory, about the specific locations. Data from distributed devices has been semantically searched and brought together to form a memory box of that week.

DigMem has been used to extensively track the user's outdoor movements and to photographically document those times. However, the limitation of the system is the identification of memory "black spots". As stated above, memory black spots occur when the user goes indoors and the GPS service is unavailable. To overcome this, an indoor localisation system has been developed that can locate the user, to room precision. It is also able to detect behaviours, such as sitting, standing or lying down, as we shall see in the next section.

5.2 Indoor Localisation

During the indoor localisation study, the user was monitored for four days, between 10:00 am and 5:00 pm, each day. Using the following configuration, in Figure 7, static sensors were fitted, within their home, to track their location and behaviours.

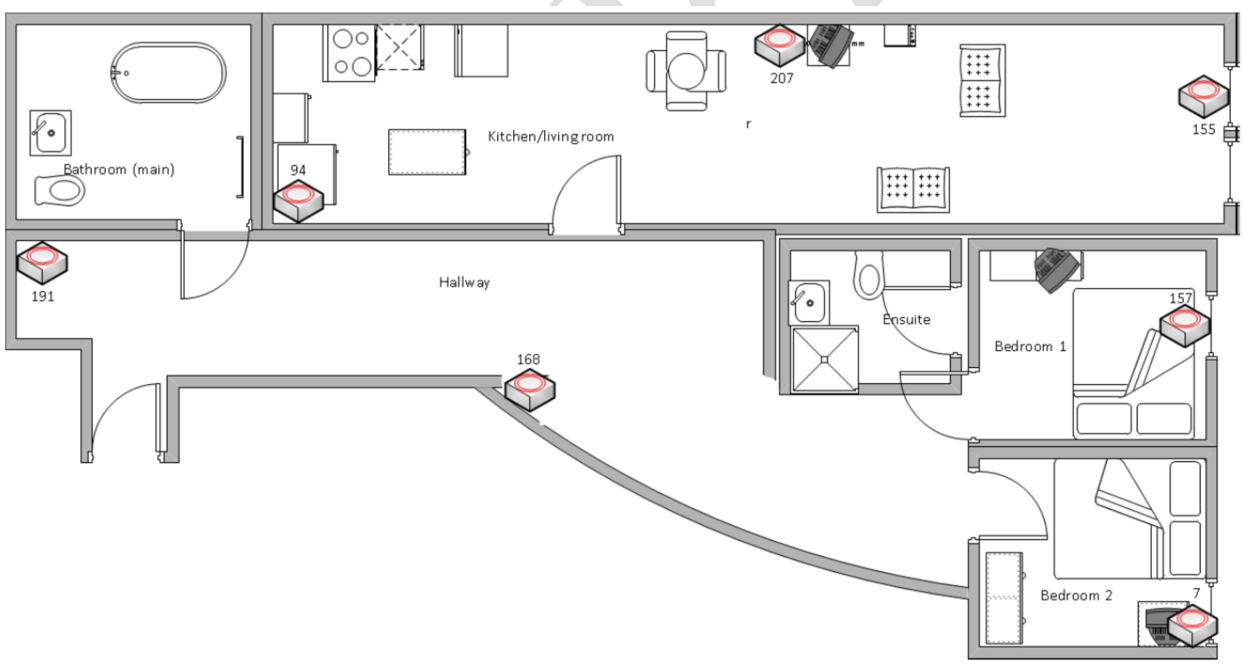


Fig. 7 Apartment Layout with TelosB Sensors Fitted

A mobile *TelosB* sensor was attached to the user, and has two tilt switch sensors that are used to determine specific body positions. The tilt switches were attached to the user's chest, to detect upper-body inclinations, and to the right thigh, to detect lower body inclinations. During one day of observation, 41,421 samples were recorded. In total 216,654 samples of data were produced.

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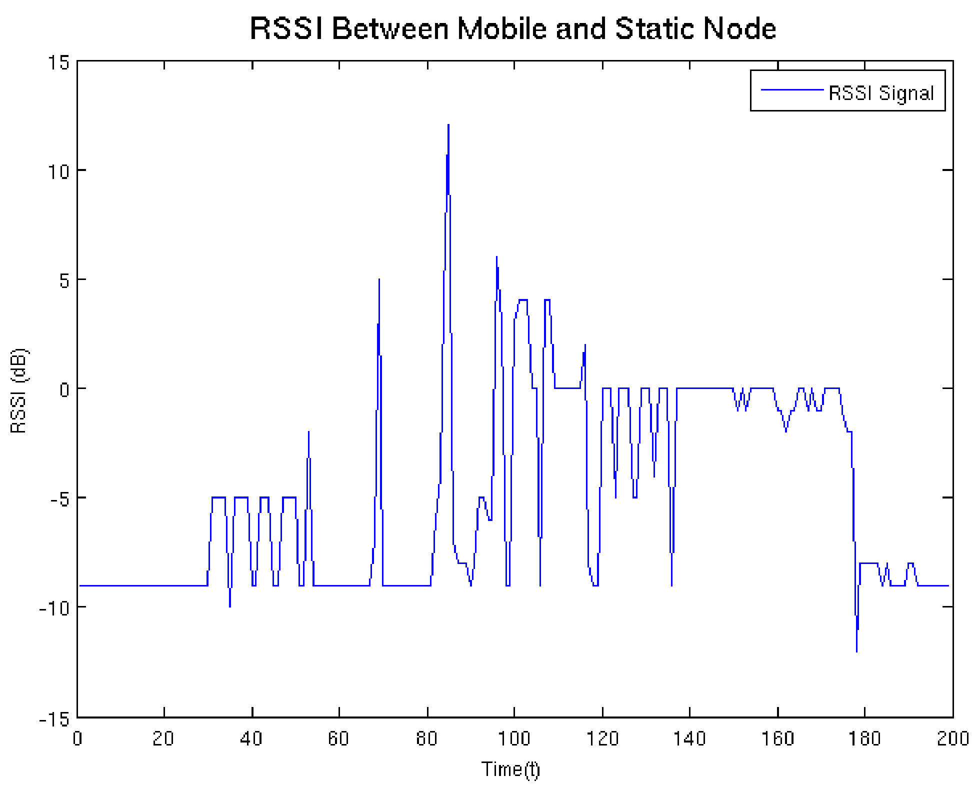
Using the complete data set, the information has been filtered based on the results from the dominant sensors only, i.e. the sensors with the highest Received Signal Strength Indicator (*RSSI*) values. Figure 8 illustrates the analysis of this data. Samples were chosen based on those whose *RSSI* values were between -15 dB and +15. Figure 8 a) shows the filtered normalised *RSSI* values, over Time (t). Figure 8 b) is used, in conjunction with the plot in Figure 8 a), to determine which sensor generated the *RSSI* values (Sensor ID) at Time (t). The *x*-axis represents the time (the duration of the data collected, over the entire study, as described above), and the *y*-axis represents the Sensor ID. Interestingly, the data shows the sensor transitions, between the dominant sensors, over the four-day study. It illustrates the key locations; within the apartment, the resident visited and more importantly the duration that they spent at each location. From this data, it is possible to determine the resident's behavioural patterns and can be used to determine how their environment is used. While, this data is only from fixed times, within a particular day, it demonstrates how indoor environments can also be monitored to detect habitual behaviours.



(a) RSSI Between Mobile and Static Nodes

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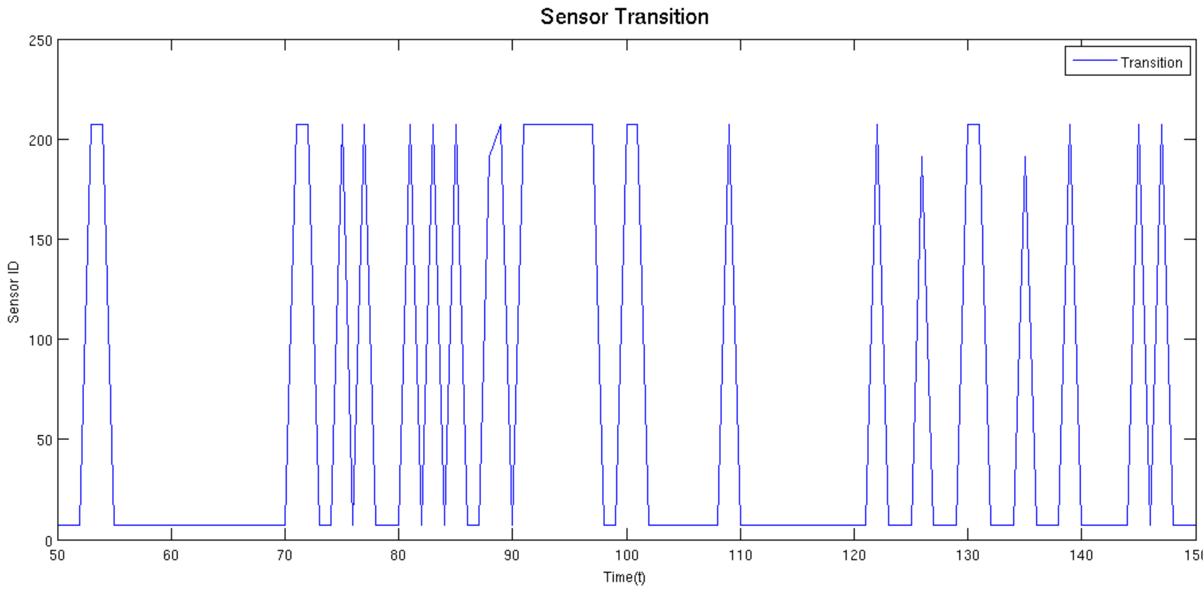

b) Sensor Transitions

Fig. 8 Combined Signal Strength and Transitions for Study

So far, it can be determined how the user's environment is used, i.e. what rooms were occupied the longest. However, it is also important to understand how each particular space is used. This can be achieved with the use of the tilt switches, which have been fitted to the resident's right leg and chest. Using this configuration, they are then linked to the mobile *TelosB* sensor, are used to measure three distinct body positions; standing, sitting, and lying down.

Using the complete data set, Fig. 9 illustrates the frequency of the position transitions of the combined values, for both tilt switches. By combining both values this allows us to determine the different positions achieved. In the sensing system, the values produced by both tilt switches when the resident is standing, is 0,0. When they are sitting the values are 0,1 and when they are lying down the values are 1,1. For all non-identifiable positions, the values are 1,0. Fig. 10 illustrates the position that the resident is in at Time (t). Most notably, the data illustrates the transitions between distinctive positions, over the entire study. It illustrates the key behaviours associated with the resident being monitored, and this allows us to quantify different kinds of behaviour.

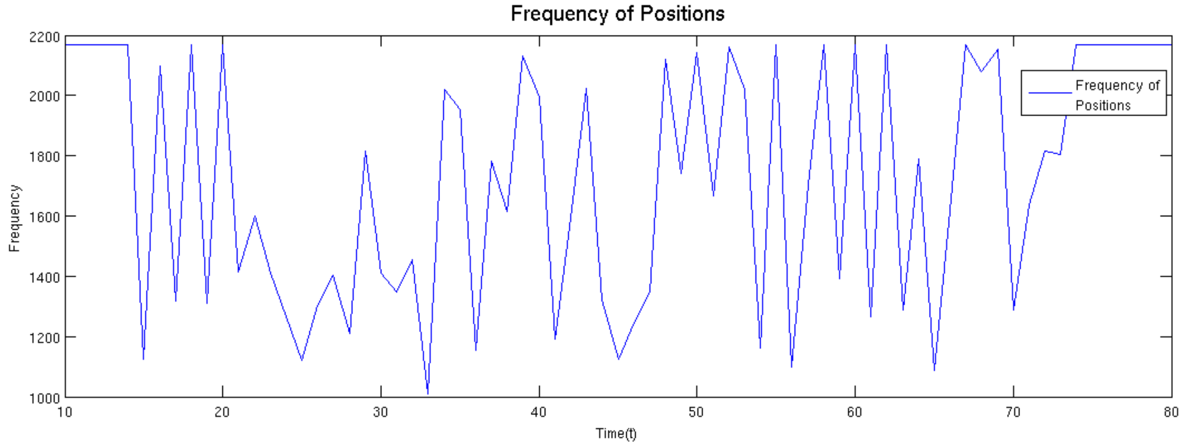

Fig. 9 Combined Frequency Positions

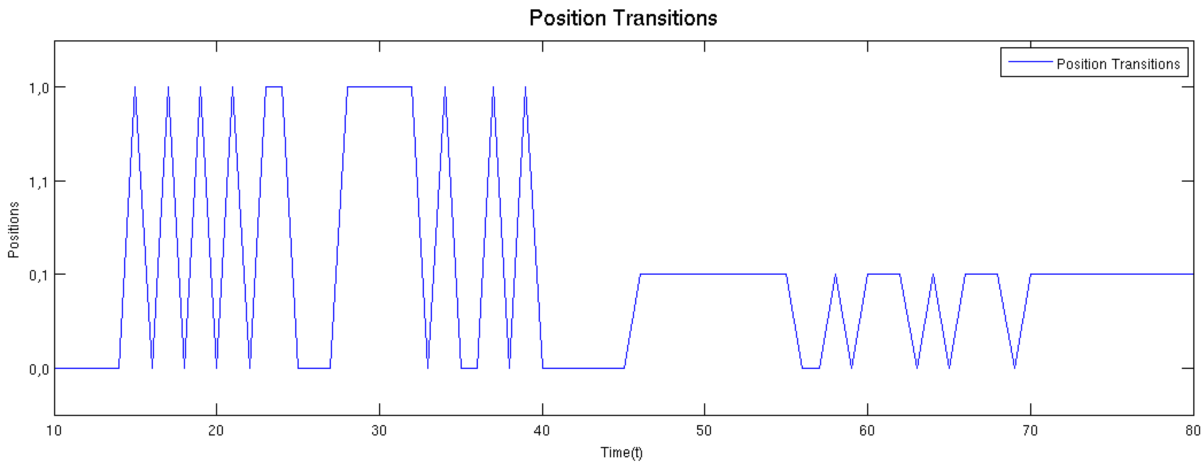

Fig. 10 Combined Transition of Positions

Together with DigMem, the user can collect lifelogging information, in both indoor and outdoor environments. Both platforms enable the user to be continuously tracked. The photo service also enables the user to visually establish what they were doing, whilst the sensing platform enables their behaviours to be monitored. However, in order to build up a complete picture of a user's day, and life, combing these two systems is essential. It is through these promising results that the research is progressing into the amalgamation of both systems. Being able to collect lifelogging data, in any environment, is vital in building towards a continuous lifelogging system.

As previously demonstrated, the incorporation of physiological information enables another dimension to be incorporated into the HDM. This data enables memory boxes to become richer and allows behaviour and moods to be quantified, over a lifetime. The collected ECG data provides vital information about how the user felt during captured situations. However, in order to infer the feelings and moods of the user more complex processing of the physiological

Dobbins, C., Merabti, M., Fergus, P., Llewellyn-Jones, D., & Bouhafs, F. (2013). Exploiting linked data to create rich human digital memories. Computer Communications, 36(15-16), 1639–1656. doi:10.1016/j.comcom.2013.06.008

data is needed. This is a significant challenge that the two previously discussed systems have not addressed. In order to overcome this problem a *QRS Complex* detection algorithm and heart rate calculation method are used to filter the ECG signal in order to detect the *QRS Complex* and calculate the heart rate, as it shall be seen in the next section.

5.3 QRS Complex and Heart Rate Detection

In order to process the ECG signal, so that the heart rate of the user can be calculated, a *QRS Complex* detection algorithm and *RRI* calculation method have been developed. Firstly, power line interference and baseline wander have to be filtered from the signal. The reasoning for removing power line interference is because this type of interference can make the line, on the ECG reading, look thicker and be distorted. Furthermore, baseline wander causes the ECG signal to change position and makes the default amplitude change. In order to remove these unwanted signals it is important to filter the data before further processing can occur. A notch filter [62], [63] and a high-pass filter [39] have been used to remove the interferences.

In order to detect the *QRS Complex*, the filtered signal is processed in Matlab. *R* waves are used to detect the *QRS Complex*, since they have the largest amplitude in the ECG signal. By using this amplitude, a threshold can be set, which when exceeded, a *QRS Complex* is detected. The equation that is used to detect the *QRS Complex* is as follows:

$$Threshold = \frac{(Sig(max) - Sig(mean))}{2} \quad (1)$$

By subtracting the mean value of the signal from the maximum value, and then dividing by two, gives more of a chance for the *R* wave to be detected, since the *R* waves might not have the same amplitude. A developed *QRS Complex* detection code is then executed, in Matlab, to process the signal. This code uses Eq. (1) to set and store the threshold. When the threshold has been exceeded, the *QRS Complex* is detected (see Fig. 11). In Figure 11, the top graph shows the original signal and the threshold limit (the dotted line). Anything that exceeds that line is *QRS Complex* (red triangles). The second graph in, Figure 11, illustrates when in time the *QRS Complex* was detected.

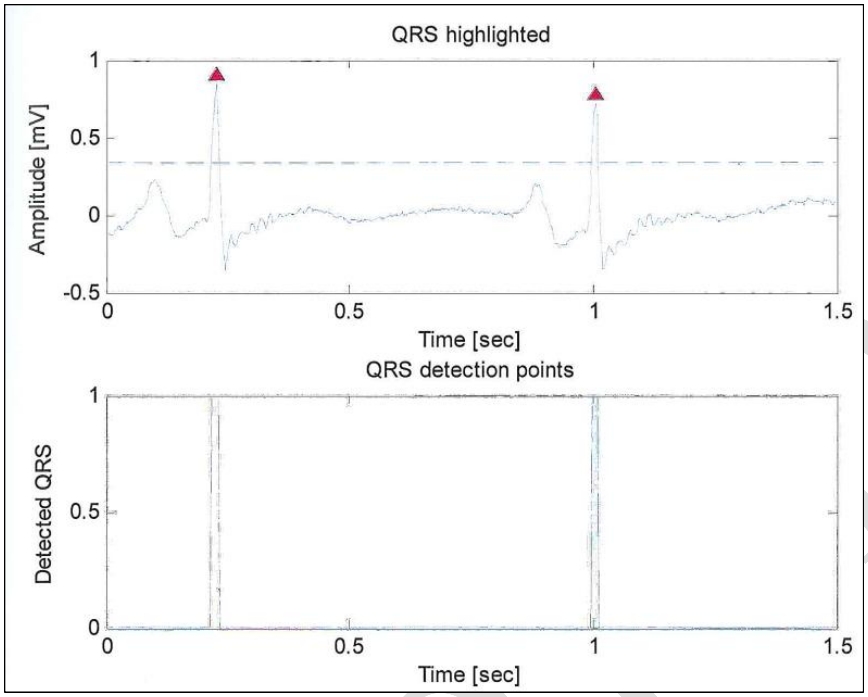

Fig. 11 QRS Detected Points

In order to calculate the heart rate of the user the *RRI* needs to be calculated. In order to achieve this, a developed *RRI* calculation algorithm is executed, in Matlab, to process the ECG signal. Using the *R* waves, found in the previous *QRS Complex*, the *RRI* calculation firstly converts the peaks back into seconds. This is achieved by taking the peak value (*locs*) and dividing it by the sampling frequency (*Fs*). The following equation is used to achieve this:

$$rrpoin = \frac{locs}{Fs}$$

(2)

Using the results from Eq. (2), all of the values of when the peaks occurred, except the first one, are stored as variable *secoin*, whilst all of the values, except the last one, are stored as variable *fipoin*. The *RRI* points are then determined, using the following calculation:

$$rrint = secoin - fipoin \quad (3)$$

Using the results from Eq. (3), the total time and the number of *RRI*s are determined. The total time of all the *RRI* points are summed and stored as variable *rrtot*, whilst the number of *RRI*s that are present are counted and stored as variable *rrnum*. Using the following equation, the heart rate is then calculated:

$$exhr = \frac{60}{(\frac{rrtot}{rrnum})}$$

(4)

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At this point, the *exhr* value, calculated using Eq. (4), is rounded and the result, i.e. the heart rate, is displayed (see Fig. 12). Figure 12, below, illustrates the values for the variables *secoin*, *fipoin*, *rrtot* and *rrnum*, as well as the results that have been calculated using Eq. (3) and Eq. (4). The final heart rate value is circled and the graph of the *QRS Complex*, which was used to detect the *R* waves, is also displayed.

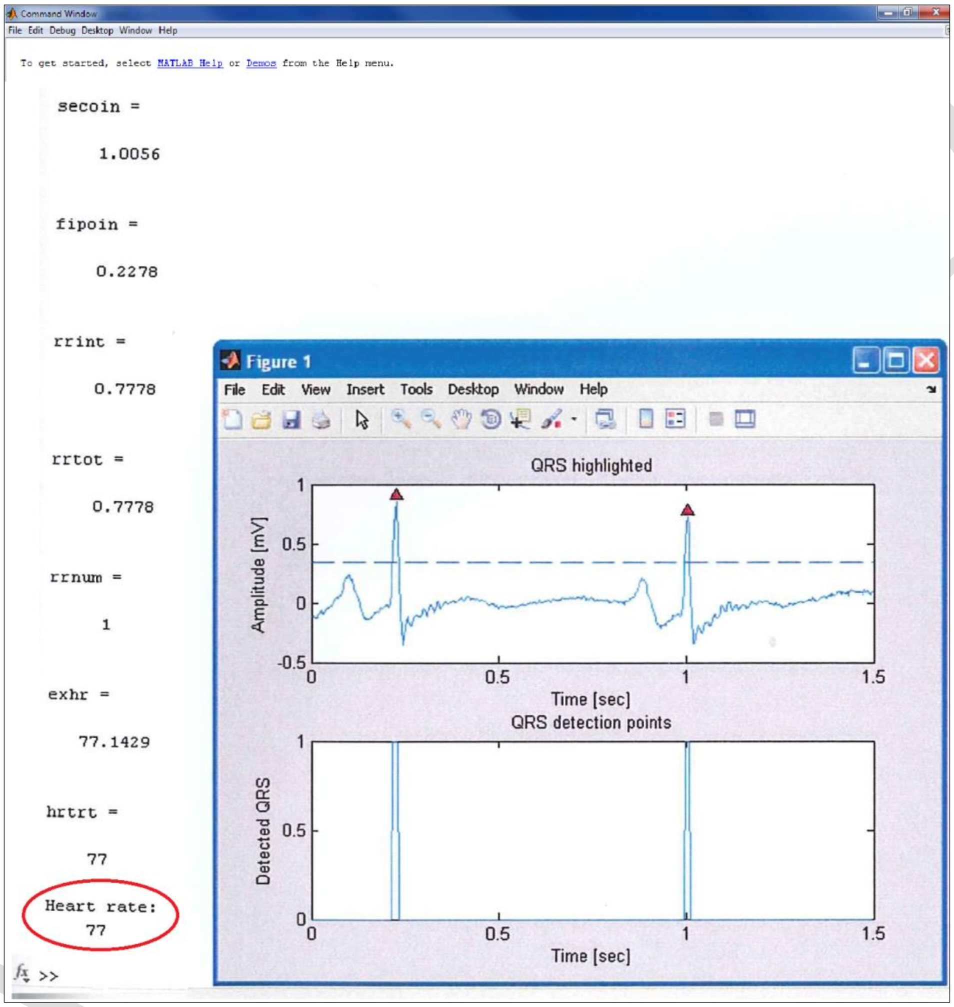

Fig. 12 Heart rate Displayed

Overall, this method establishes how to detect the *QRS Complex* and heart rate, from a filtered ECG signal. As it can be seen, the results from all of the studies are encouraging. Not only are journeys, with added context, able to be documented but tracking and identifying behaviours, indoors, is also possible. Furthermore, complex processing of any collected ECG information has been undertaken. By filtering and processing the ECG data and combining it with the GPS and Photo services enable the user to see how certain situations made them feel. However, in order to build up a better illustration of a user's day, and life, combining these two systems is essential. It is through these promising results that the research is progressing into the amalgamation of both systems. This method has the capacity to search information, from any point during our lives. Any information collected can be brought together and transformed into a memory box. It is through utilizing linked data, and semantic web technologies, that have enabled this novel method of building memories to be the driving force behind current research.

6. Discussion

In this paper, a prototype has been developed and evaluated, which demonstrates how HDMs can be created in both indoor and outdoor environments. Physiological data has also been processed to provide a more accurate illustration of the user's heart rate, in order to discern how certain situations can make the user feel. Memory boxes are created using linked data and based on information obtained from the surrounding environment, thus no two memories are alike. The gathered data is queried, using SPARQL, and a temporal memory box is created. Creating memories, in this way, is a novel solution and a great deal can be learnt from this implementation.

DigMem is mimicking, to a degree, the Serial Parallel Independent (SPI) model of human memory, which postulates process-specific relations among human memory systems [64], [65]. In this model, Tulving [64] states that, "*Information is encoded into systems serially, and encoding in one system is contingent on the successful processing of the information in some other system, that is, the output from one system provides the input into another. Information is stored in different systems in parallel*". DigMem mirrors this concept, to an extent. Creating a memory box relies on data successfully being stored, transferred and transformed from one layer to the next. The system is not intended to precisely re-create how human memory works, but as it can be seen, certain aspects are mirrored.

Current lifelogging systems only collect a limited amount of information and searching is often one-dimensional, based solely on keywords, and typically using one source of information, usually a single data store [24], [25], [66], [67]. However, DigMem uses SPARQL [58], a query language for RDF documents, to search the RDF data and to execute queries. SPARQL enables values to be pulled from both structured and semi-structured data; it can explore data by querying unknown relationships; complex joins, of disparate databases, are able to be performed, in a single and simple query, and RDF data can be transformed from one vocabulary to another [68]. This method also enables queries to be expressed across diverse data sources, whether the data is stored natively as RDF or viewed as RDF via middleware [58]. Therefore, a wider range of information can be included in the memory; the user is not limited to searching one set of information. This method enables much richer and more-detailed memories to be created, than previously seen.

Furthermore, the benefit of transforming the data into RDF, besides its compatibility with SPARQL, is that this approach enables data to be incorporated into a memory, regardless of its format. Saving the information in this way allows links to be set between data items, from different data sources, and also permits the execution of "smart queries" (SPARQL). Memories created, in this way, are a "mash–up" of all the data of a specific time. Linked data is being used as a technique to bring all of this unrelated data together. These methods have primarily been used within military applications or within the semantic web. Utilizing them for creating memories is a novel solution, within this field. Linked data/data fusion offers an ideal platform for bringing together different types of data, so that a more accurate memory can be created. It allows us to obtain inferences of events that are impossible from a single data source, reduces data overload and allows a lot of data to be transformed into a smaller amount of more meaningful information. When humans remember events, a load of different information is processed, subconsciously, and without too much effort. Memories can be imagined as little "boxes" or "episodes" of events, which can be recalled in the mind. For example, in the case of recalling a birthday party that happened last week, recalling attendees, location, feelings, temperature (if it was particularly hot or cold), what was eaten and other pieces of information are quite easily remembered. This type of memory is known as "episodic memory", and relates to the memory of temporal periods of experienced events and episodes [2]. However, trying to remember a birthday party that happened 20 years ago, recalling the same level of detail is a lot harder, as opposed to an event that happened recently. DigMem aims to bridge this gap, so that any time of life can be easily recollected. This feature is especially useful because, as previously stated by Fitzgibbon and Reiter [7], in their report *Memories for Life: managing information over a human lifetime*, "*How can we ensure that data is still accessible in 50 years time, despite inevitable changes in software, hardware and formats?*". As demonstrated in this work, the use of RDF, principles of the semantic web and SPARQL are used as a way to address this question. As time goes on and new devices and formats emerge, they can still be incorporated into the memory box. The DigMem system is flexible to adapt over time and a lifetime of data can be captured and turned into memory boxes. The method of using linked data enables any piece of recorded information to be included in the HDM. This technique enables a richer HDM to be created, as the pool of resources widens, and more data can be included.

As mentioned above, the delivery of the collected data is based on a P2P infrastructure. This choice is beneficial for a variety of reasons. Most notably, this decision has been motivated by the fact that P2P networks scale well against an increase in the number of communicating devices, or amount of transmitted traffic, hence reducing the probability of congestion and bottleneck nodes. As more peers join the network, the network's capability increases and strengthens [69]. These features make P2P a very popular choice, especially for Video Streaming over the Internet [70–72]. A number of studies have shown that packet loss is the main factor that might affect the Quality of Experience (QoE) for these P2P Video Streaming applications [73–75]. The work presented in [73] shows that a packet loss, in excess of 14%, could affect the smoothness of video playback. Nevertheless, these effects could be mitigated by implementing buffering and Forward Error Correction mechanisms. However, in the context of DigMem, collected data includes sensor measurements and photos, all of which do not have specific QoE requirements. Moreover, the size of the data broadcasted by these devices, and the frequency of transmission, is low in comparison to video streaming applications, which makes them suitable for wireless communications. Furthermore, as peers exit the network this also does not affect a peer's ability to exchange information. If one peer is unavailable, then another one, with similar capabilities, can provide information. This fits in well with creating HDMs, as memories created in various environments will require the use of different services. Being 'tied-down' to a set number of services does not fit in with the diverse composition of HDMs. Memories are not composed of a fixed number of items, as we move through different environments; the requirements of a memory will change. This idea does not fit in well with a client-server situation. As Parameswaran *et al.* [76] states, "*A client-server scenario like the Web depends on a single server storing information and distributing it to clients in response to their requests. The information repository remains essentially static, centralized at the server, and subject only to updates by the provider. Users assume a passive role in that they receive, but do not contribute, information. A P2P network, on the other hand, considers all nodes equal in their capacity for sharing information with other network members*". Therefore, by incorporating data from a dynamically changing environment enables a greater level of detail to be integrated into the memory. These devices shape the memories. Devices present in one environment will differ to those of another, thus altering the information that is available. A P2P network can handle this dynamically changing set of peers. This P2P architecture is used purely to gain access to the services that devices have to offer.

This system also addresses "memory black spots" that occur when a device cannot cope with certain situations. For example, in previous work [77], outdoor journeys were only documented, because of the limitations of GPS. When the user was inside the HDM stopped. During those times inside memory black spots, or "gaps" in the HDM occurred. Consequently, whilst tracking users indoors is feasible, using such technologies as Radio-Frequency Identification (RFID) or Near-Field Communication (NFC), there are still limitations. For instance, in the case of RFID technology,

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position accuracy depends on the type of tags used, which are either active or passive [78]. Generally, in order to get good position accuracy, existing solutions use the active RFID tags; however, the cost of such tags are quite high [78]. Additionally, studies in this area also indicate that this solution does not provide an efficient tracking system [78], [79]. Alternatively, NFC is a low-cost solution that enables short-range communication capabilities [80]. However, a drawback is that its typical range is less than 10 cm [80]. If NFC tags are not within range, a signal will not be received. This implementation addresses the limitations of current indoor localisation technologies, by presenting a low-cost sensing platform that is capable of tracking a user indoors, whilst additionally also determining specific body positions [54]. The incorporation of the sensing platform, the ability to extract information, from distributed resources, and the *QRS Complex* detection algorithm and *RRI* calculation method enables a better-rounded representation of our lives to be constructed. The development of this system allows the user to keep track of their entire lives and to reflect on how experiences made them, and others, feel.

Another benefit of the system is that it is more cost-effective than buying specialist equipment (e.g. *SenseCam*). For example, as demonstrated in [1], this system "*requires the user to bring the relevant equipment and to have it turned on*". This is a very cumbersome method, especially if the user is older and has trouble remembering all the items that they would need. However, the DigMem system reduces the burden that is placed on the user, by using mobile devices, such as tablets and smartphones, and devices within the environment. These are everyday items that almost everyone carries around with them, daily. There is no need to buy specialist equipment as the data, required for the memories, is gathered remotely, from devices prevalent within the surrounding environment. This method is flexible enough to adapt to any environment, thus allowing memories to be created over a lifetime, and with as little user interaction as possible. The ability to see how we were feeling, at any time of our lives is also another unique feature of the system. Data, collected over a lifetime, is semantically linked and any instance of our lives can be re-constructed. The use of the Dropbox cloud storage service also enables all collected data to be available, from any computer or phone [56]. Transferring the data to the cloud enables it to be distributed across many stores, and accessed from anywhere in the world. The storage capacity of mobile devices is also limited. Therefore, transferring data to the cloud enables more material to be collected, and more complex processing can occur, at a later time. This is a very simple and effective way of using Cloud Computing technology to send data, via the Internet, to different locations [81].

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The paper provides a successfully developed implementation. The experiments that have been undertaken demonstrate the core idea of creating a memory in any environment, using linked data. As it can be seen, the system has been implemented to gather memory data in a variety of situations. This data can then be used to create a memory of any specific time of our lives. This method offers the user the flexibility to define exactly what information they want to retrieve. The *QRS Complex* algorithm, and *RRI* calculation method, enables complex ECG data to be processed so that specific times of elevated heart rate can be established. When linked with the photographs and GPS data, we can visually see how situations made us feel. The use of SPARQL allows the user to execute "smart" queries, such as "What was I doing and how did I feel on *x day and time*?" The data can then be organised in a visually pleasing manner. Although the system is only collecting a limited amount of data, for a limited period of time, it is believed that the applicability of the design has still been fully demonstrated.

Many systems exist that capture human digital memories, however these are very device specific and collect only a limited amount of information. For a more well-defined representation of our lives to be digitally encapsulated, enabling data to be collected, regardless of environment or device constraints, is fundamental. The approach presented aims to address the limitation of searching and creating more detailed memories. Creating memories, based on the services of the current environment, and linking various data sources together, enables more information to be included in the memory. The system also has the ability to adapt to new technologies and is a viable, long-term, solution to creating memories for life.

7. Summary and Future Work

Memories are a powerful tool that influences every aspect of human life. As technology advances, the landscape of our world is rapidly changing. Devices, prevalent within the environment, are now able to capture a multitude of data, both physiological and ecological. Harnessing and creating HDMs, composed of this information, is not only useful for reminiscing but has the potential to influence almost every aspect of people's lives. RDF and SPARQL provide an ideal solution for linking distributed data together, as any type of data can be used and different sources of information can be queried, whilst the P2P aspect of the system widens the range of devices that are accessible. This feature can handle our dynamically changing environments, as devices enter and leave the network.

In this paper, the DigMem system has been presented. Through the utilization of linked data and pervasive devices, the system creates dynamic HDMs, in a variety of environments. This method enables a more detailed memory to be created. This has been achieved through accessing the data from a number of services, thus resulting in

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a vast amount of diverse information that has been generated. This approach offers a novel solution into building memories that are composed of a variety of information. A prototype has been developed, which demonstrates the design and illustrates how this data can be used in real-world scenarios. The experiments, which have been undertaken, demonstrate the idea and the results indicate how a memory can be retrieved from any point in our lives, how lifelogging data can be collected, whilst indoors, and how complex ECG data can be processed. The use of everyday items, as data sources, also limits the need to buy specialist equipment (e.g. like a *SenseCam*). This approach is flexible enough to withstand new technologies and file formats, due to the use of linked data and RDF. As we evolve, and experience events, our digital counterparts can record these moments and a lifetime of data can be searched, with any moment in our lives being reconstructed in a memory box.

While, initial results are promising, several challenges still remain. Future work aims to build upon the ideas presented within this paper. Clustering techniques will be explored so that information is retrieved based on the closeness of the data to each other. In other words, instead of explicitly defining a specific query, which requires extensive knowledge of the data, the user is able to retrieve data based on its similarity, e.g. data retrieved around a particular time would have similar timestamps. In this way, behavioural models can be established. This has the potential to reveal interesting insights about our behaviours and ourselves. Markers relating to health and wellbeing can also begin to be identified, such as what factors contribute towards an increase/decrease in activity? Alternatively, how do national events, such as the Olympics, affect us? Are we more active during the summer? Through this type of continuous monitoring, of a subject's HDMs, these questions can soon begin to be answered. Furthermore, additional work is required to develop the DigMem application to provide added services, such as clustering algorithms for bringing together related memory boxes and creating group profiles, based on user's HDM profiles. This has the potential to strengthen social interactions. Highlighting and automatically tagging these important events also poses quite a problem. Additionally, although the system has been tested, in various experiments, long-term monitoring, of multiple participants, is an area that also needs further investigation. These are significant challenges to consider, and ones that will be propelling this research forward.

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