SmartPowerchair: Characterisation and Usability of a Pervasive System of Systems

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***Abstract*—A characterisation of a pervasive System of Systems called the SmartPowerchair is presented, integrating pervasive technologies into a standard powered wheelchair (powerchair). The SmartPowerchair can be characterised as a System of Systems (SoS) due to focusing on selection of the correct combination of independent and interoperable systems that are networked for a period of time to achieve the specific overall goal of enhancing the quality of life for people with disability. A high-level two-dimensional SoS model for the SmartPowerchair is developed to illustrate the different SoS lifecycle stages and levels. The results from a requirements elicitation study consisting of a survey targeting powerchair users was the input to a Hierarchical Task Analysis defining the supported tasks of the SmartPowerchair. The system architecture of one constituent system (SmartATRS) is described as well as the results of a usability evaluation containing workload measurements. The establishment of the SmartAbility Framework was the outcome of the evaluation results that concluded Range of Movement (ROM) was the determinant of suitable technologies for people with disability. The framework illustrates how a SoS approach can be applied to disability to recommend interaction mediums, technologies and tasks depending on the disability, impairments and ROM of the user. The approach therefore, creates a 'recommender system' by viewing Disability Type, Impairments, ROM, Interaction Medium, Technologies and Tasks as constituent systems that interact together in a SoS.**

***Index Terms*—Assistive technologies, Pervasive computing, Recommender system, System of Systems, Ubiquitous computing, User interaction.**

I. Introduction

The importance of improving quality of life of people with disabilities is the result of 500 million people worldwide having some form of disability that affects their interaction with the environment and society [1]. People with disabilities can encounter many difficulties when performing daily tasks and may require the assistance of a support worker [2]. This is the driving factor for an ever-increasing market for assistive technologies [3]. By integrating off-the-shelf pervasive technologies into a System of Systems (SoS), known as the SmartPowerchair (a novel concept), independent living and improvement of lifestyle of people with disabilities has been addressed. Pervasive technology is a concept first introduced by Weiser [4] to embed microprocessors into everyday objects to communicate information [5]. Evans et al. [6] demonstrated the effects that pervasive technology can have on quality of life, where automatic lighting, data-logging and messaging services were integrated into the home of a person with dementia. The results of this case study highlighted that independent living could be achieved whilst maintaining the privacy of the individual. When designing the SmartPowerchair, the best possible usability needed to be achieved as usability has greater importance when the users have disabilities [7]. It was also imperative that the SmartPowerchair requirements were elicited from the intended user community (i.e. people with disabilities) to ensure that it was designed appropriately to consider the interactions with the environment, which have not been previously supported by a SmartPowerchair.

The successful integration of pervasive technology into an existing assistive technology is demonstrated by the system architecture and usability evaluation of one constituent system (SmartATRS). Based on the evaluation results and the rationale of [1][2][3], the SmartAbility Framework has been established to address an issue highlighted in a user survey conducted by Ari and Inan [8], where it was noted that people with disability often do not have knowledge of the extent to which, technology can assist them in their lives. The SmartAbility Framework is an addition to the previous publication of the research [9], which described the SmartPowerchair from a SoS perspective and the results of the SmartATRS usability evaluation. Therefore, this paper firstly summarises the design of SmartPowerchair from the concept view of a pervasive SoS. Secondly, the SmartAbility elements and the rationale behind their creation based on the results from state of the art review, requirements elicitation and usability evaluation are illustrated. The SmartAbility Framework is perceived to be relevant to the Human Machine System area, as the aim of the framework is to utilise human characteristics (i.e. impairments and Range of Movements) to recommend interaction mediums and technologies (i.e. the 'machine' aspect).The research is significant as this type of recommendation system does not currently exist.

II. State of the Art

A. System of Systems

Since the late 1990s, developments in areas such as Systems

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Engineering and Complex Systems have resulted in an emerging interdisciplinary area called System of Systems Engineering (SoSE) [9][11], where a SoS is defined as "an integration of a finite number of constituent systems which are independent and operable, and which are networked together for a period of time to achieve a certain higher goal" [11][12][13]. Traditional Systems Engineering focuses on building the right system, whereas System of Systems Engineering focuses on selecting the right combination of systems and their interactions to satisfy a set of frequently changing requirements [13]. They are characterised by Maier [14] as being composed of many heterogeneous systems that are geographically distributed; independently managed and/or operated; evolve over time; and exhibit emergent behaviour. The capability of the entire SoS should not be possessed by any constituent system, with each having the ability to function independently [12]. There is a need to better understand the enterprise nature of the domains (e.g. health, defence, utilities, and transport) to enable human participants in such systems to cope more effectively with the increase in socio-technical issues that SoS imply [13]. The techniques of Characterisation of SoS [15] and the Two-dimensional SoS Model [16] can be used to analyse a SoS.

Examples of SoS exist in a variety of domains, with one of the earliest instances being the Deepwater Coastguard Program in the United States [17]. The SoS consisted of the necessary constituent systems to ensure security of coastal borders in unforeseen circumstances and included satellites, helicopters and aircraft. The Boeing Commercial Aircraft Division developed the 'e-enabling' SoS to facilitate aircraft design [18] by incorporating architectural components in the factory and at locations such as airports. Airports themselves can be classified as a SoS by the decomposition into smaller systems such as baggage handling, air traffic control and customs [19]. In transportation, Keating [20] described the slowdown of traffic in a motorway tunnel as a SoS with the tunnel, vehicles and the motorway being constituent systems resulting in the emergent behaviour of reduced traffic speed. Korba and Hiskens [19] characterised electrical power systems as a geographical-extensive SoS, comprised of diverse components that are fundamental to the generation of electricity.

Maier [14] and Dahmann and Baldwin [21] suggest four types of SoS: Directed, Acknowledged, Collaborative and Virtual. The SmartPowerchair SoS has been defined as Directed, combining multiple constituent systems (i.e. the integrated pervasive technologies and the standard powerchair) to fulfil specific purposes [22]. The interoperability between all constituent systems and the interaction with the user will determine the success of the SmartPowerchair. The technologies will operate independently and be subordinate to the user performing the tasks.

The System of Interest (SoI) Framework developed by Kinder et al. [16] will be the third approach applied to the SmartPowerchair SoS. One of the multiple definitions of a SoI for a system is "the system whose life cycle is under consideration" [24] however, there is no consideration for the resultant behaviour of the SoI. The behaviour is established by the interactions between constituent systems, without which the SoS would be a set of independent systems. The SoI framework is a top-down approach defining the interaction both at generic and specific levels to identify the mediums and types. The evolution of the SoS and the constituent systems is described by the framework, thereby defining the dynamic attributes. The research into SoI has been combined with Characterisation of SoS to provide a greater understanding of the capabilities and functions of the SmartPowerchair. The resultant behaviour of the SoS was achieved by the interaction between components.

B. Assistive Technologies

The success of any system is dependent upon the usability from the 'user-perspective', which can only be achieved by adopting a user-centred design approach [25] early in the design process. Valtolina et al. [26] highlighted the importance of such an approach for assistive technologies where the design process of a collaborative multimedia e-learning system is described that caters for both able-bodied and students with disability. Teachers and students were jointly involved in the design process, thereby developing a system that could be customised to suit an individual's needs.

Ari and Inan [8] conducted a user survey targeting people with disabilities to assess the assistive technology needs of students in higher education. The aim of their research was to determine the extent that technology enabled equal opportunities, as only a minority of students were aware of the assistive technologies available. It was found that quality of life was increased where students had access to a computer and the use of the internet for communication, indicating the relevance of integrating pervasive technologies with powerchairs. An example of an assistive technology requirements elicitation process was conducted by Robinson et al. [27] as part of the Keeping In Touch Everyday (KITE) project, where views were obtained from people with dementia about a proposed armband and electronic notepad. This led to the scoping stage that consisted of performing a 'needs analysis' to accurately assess how the technologies would facilitate independence from the perspective of the user group. A similar 'needs analysis' was provided by the results of the SmartPowerchair requirements elicitation and identified the tasks to be supported to improve quality of life.

Cowan et al. [28] stated that not all persons who would benefit from a powerchair have the required cognitive and neuromuscular capabilities to navigate using a standard joystick, but may benefit from an alternative user-technology physical interface. To assist these types of users, SmartPowerchairs have previously been developed [29][30][31] to respectively navigate by either an obtrusive electroencephalogram, artificial intelligence or tongue movements (monitored by an invasive ferromagnetic tongue piercing). A SmartPowerchair has also become a form of telemedicine to monitor the physiological parameters of the user [32]. However, there has been a lack of research into

SmartPowerchairs that integrate pervasive technologies to assist users to interact between the home or vehicle environments.

The research case study focuses on a pervasive SoS called the SmartPowerchair, comprising different systems, components, interactions and functions. SmartATRS is an example of one constituent system within the SoS that supports the interaction between a powerchair and vehicle. SmartATRS operates the Automated Transport and Retrieval System (ATRS) and replaced the keyfobs (electronic devices used to operate the ATRS components) that were very small and could be easily dropped (highlighted by visitor demonstrations at the 2011 Mobility Roadshow). The objective of ATRS was to create a reliable, robust means for a wheelchair user to autonomously dock a powerchair onto a platform lift without the need of an assistant [33]. ATRS requires the vehicle to be installed with the three components shown in Fig. 1.

Fig. 1. ATRS components

The system uses robotics and Light Detection and Ranging (LiDAR) technology to autonomously dock a powerchair onto a platform lift fitted in the rear of a standard Multi-Purpose Vehicle while a disabled driver is seated in the driver's seat. Using a joystick attached to the driver's seat, the user manoeuvres the powerchair to the rear of the vehicle until the LiDAR unit is able to see two highly reflective fiducials fitted to the lift. From then on, the docking of the powerchair is completely autonomous, as the powerchair drives and locks onto the platform lift independently without intervention from the user.

C. *Disability Classification*

Numerous disabilities exist as humans are susceptible to diminishing health and therefore have the potential to develop a disability. Various disability classification systems have been established worldwide including the International Classification of Functioning, Disability and Health (ICF) Framework [34] developed by the World Health Organisation. Andrews [35] conducted research into the relationship between ICF, the Downton Scale and impairment types to map disabilities into three categories; 'Motor Control', 'Senses' and 'Cognitive Ability' each with resulting impairments, e.g. acquired brain injury and cerebral palsy. The ICF and Andrews' classification system provided the impairment and disability types for the SmartAbility Framework.

Through user experimentations, it was established that Range of Movement (ROM) was the determinant indicating whether users could operate technologies. ROM is defined as "a measure of movement about the axis of a joint that a person can produce using his/her own strength" [36] and can be measured accurately using a goniometer. However, for the SmartAbility Framework, ROM was considered as a Boolean parameter, i.e. whether the user could or could not perform the movement. The conducted state of the art review and previous research influenced the resulting framework, where the relationships between disability type, ROM, interaction mediums, technology and tasks were considered as constituent systems. The SmartAbility Framework is viewed as a 'recommender system' that proposes assistive technologies based on the physical impairments and ROM characteristics of the user. This enables people with disability to become aware of life enhancing technologies.

III. Methodology

The research methodology consisted of a requirements elicitation phase comprised of surveys, interviews and Hierarchical Task Analysis (HTA). This characterised the SmartPowerchair as a SoS by adopting SoI and conducting a Controlled Usability Evaluation to identify whether integrating pervasive technology into ATRS improved usability. These techniques have been utilised to produce a full understanding of the problem domain. The SoS analysis methods were deemed to be suitable as the SmartPowerchair consisted of a number of independent constituent systems. Use cases could have been an alternative form of analysis, but have the disadvantage that the associations between actors and use cases do not fully describe the functional aspects of the system [36]. There is also a tendency for the use case approach to have a large number of actor-use case relationships, excessive use case specifications, or more use cases than necessary [38], all resulting in an overly-complex analysis, thus deeming it unsuitable.

A. *Requirements Elicitation*

For the SmartPowerchair requirements elicitation survey, it was necessary to collaborate with the intended user community by approaching UK disability organisations to establish a niche user group of participants. A representative sample of 17 selected participants who had varying disabilities from a variety of working backgrounds (from students to retired adults) was formed. The survey consisted of questions concerning the difficulty of home tasks and possible integrations of pervasive technologies. The functionality of the SmartPowerchair was determined from the most difficult tasks identified by the user group. To maximise the number of responses, the organisations were either approached with an online survey and/or offered semi-structured interviews using the same questions as the online survey. The semi-structured interviews had the advantage of a captive audience compared to the relatively low response rate of the online survey.

B. *Hierarchical Task Analysis (HTA)*

HTA [40] was conducted to define the SmartPowerchair functionality from the survey/interview results by a arranging the most difficult tasks (identified by the participants) hierarchically, thereby determining the task to be supported by the SmartPowerchair. HTA was also applied in designing the Controlled Usability Evaluation of ATRS and SmartATRS to determine the tasks to be performed by the evaluation participants. Applying HTA ensured that all functionality would be assessed during the evaluation.

C. *System of Interest Characterisation*

The Two-dimensional SoS Model based on the Capability Cube Model [15] (initially developed by the defence industry) was adapted to suit the SmartPowerchair. The lifecycle stages of this model cover the timeline from concept to retirement and are described as Concept and Technology Development, Component, Systems, System of Systems Engineering and Capability.

D. *Controlled Usability Evaluation*

Two techniques were used to evaluate the user interface design of SmartATRS, System Usability Scale (SUS) [41] and NASA Task Load Index (TLX) [42]. The combined results provided an accurate usability assessment.

System Usability Scale (SUS): Ten statements were adapted from SUS to assess the usability of the keyfobs, SmartATRS by touch and joystick. Participants rated each statement on a 5-point scale of strength of agreement from 'Strongly Disagree' to 'Strongly Agree'. Typical statements included "I thought using the keyfobs was easy"; "I thought that the Emergency Stop feature of SmartATRS by touch was safe" and "I would imagine that most people would learn to use SmartATRS by joystick very quickly". SUS was selected as a usability measurement, as each participant was able to provide a single score in relation to each question [43], enabling a detailed statistical analysis to be performed and conclusions drawn. An alternative to SUS that could have been applied is the Questionnaire for User Interaction Satisfaction (QUIS) [44], where participants rated 27 questions on a 10-point scale based on their satisfaction with specific sections of the user interface. QUIS was deemed relatively complex for the usability evaluation of SmartATRS and had the risk of being more tedious for the participants to complete than SUS.

NASA Task Load Index (NASA TLX): The workload demands experienced for each interaction method were measured using NASA TLX and consisted of Physical, Performance, Mental, Effort, Temporal and Frustration. NASA TLX was applied as it is a well-established method of analysing a user's workload [42]. The advantage of NASA TLX is that it is a quick and easy method of estimating workload that can implemented with a minimal amount of training [45]. The Subjective Workload Dominance Technique (SWORD) could have been an alternative to measure the workload experienced. However, SWORD is not as widely used as NASA TLX [46], the main difference being that SWORD rates the workload dominance of one task against another. Therefore, SWORD only provides a rating for the tasks that create greater workload than others and is not a rating of the participant's workload. This would not have been suitable for SmartATRS, as the differences between the interaction methods needed to be measured rather than the differences in domination between the tasks [47].

IV. Systems Architecture

Fig. 2 shows the System Architecture diagram describing the technology architecture and the interoperability between the existing ATRS components and the additional hardware for SmartATRS (black and brown lines), as well as the user interactions (red lines) relating to touch or joystick. Junction boxes were manufactured so that the existing handheld pendants remained operational.

To integrate the System Architecture into standard ATRS, wiring diagrams were analysed which identified that each component contained a relay. A relay board was therefore required to interface between the ATRS components and the JavaScript. Six relays were utilised for the functions of ATRS; Seat In, Seat Out, Lift In, Lift Out, Tailgate Open and Tailgate Close. The relay board comprised of an embedded web server storing the HyperText Markup Language (HTML) and JavaScript Graphical User Interfaces (GUIs) as webpages. JavaScript eXtensible Markup Language HyperText Transfer Protocol Requests (XMLHTTPRequests) were transmitted to access an eXtensible Markup Language (XML) file located on the web server that contained the timer durations for each ATRS component. These durations were integers that represented the number of milliseconds each function had to be switched on and were dependent upon the vehicle used (e.g. longer Lift Out durations would be required for vehicles that have greater distances to the ground) and the preferences of the user (e.g. a greater Seat Out duration maybe required to ensure safe transfers to the powerchair). An XML editor allowed the durations to be easily viewed and changed by an installer via a matrix. Safety guard timers were incorporated into the GUI so that in the event of a loss of Wi-Fi connection (and hence the access to the XML file), the functions were switched off. These timers were set to the same duration as the XML timers so that there was no adverse effect to the functioning of SmartATRS if the GUI malfunctioned or the Wi-Fi communication was interrupted.

The process of editing the XML file was not visible to the end users, thereby ensuring the safety of ATRS. Ethernet was used to connect the web server to a Wi-Fi router located in the rear of the vehicle. A smartphone communicated with the Wi-Fi router over a secure Wi-Fi Protected Access II (WPA2) network and the GUI was loaded by entering the Uniform Resource Locator (URL) of the webpage but could be accessed via a bookmark created on the smartphone. Joystick control of SmartATRS was achieved using iPortal developed by Dynamic Controls [48] that communicated via Bluetooth to the smartphone. Navigation through the GUI was achieved by moving the powerchair joystick left or right and buttons were selected by moving the joystick forwards.

User feedback and safety features were incorporated into SmartATRS, which were not present in the keyfobs. Seven command buttons on the GUI activated each ATRS function and the smartphone was securely mounted onto the arm of the powerchair, making the system easier to use.

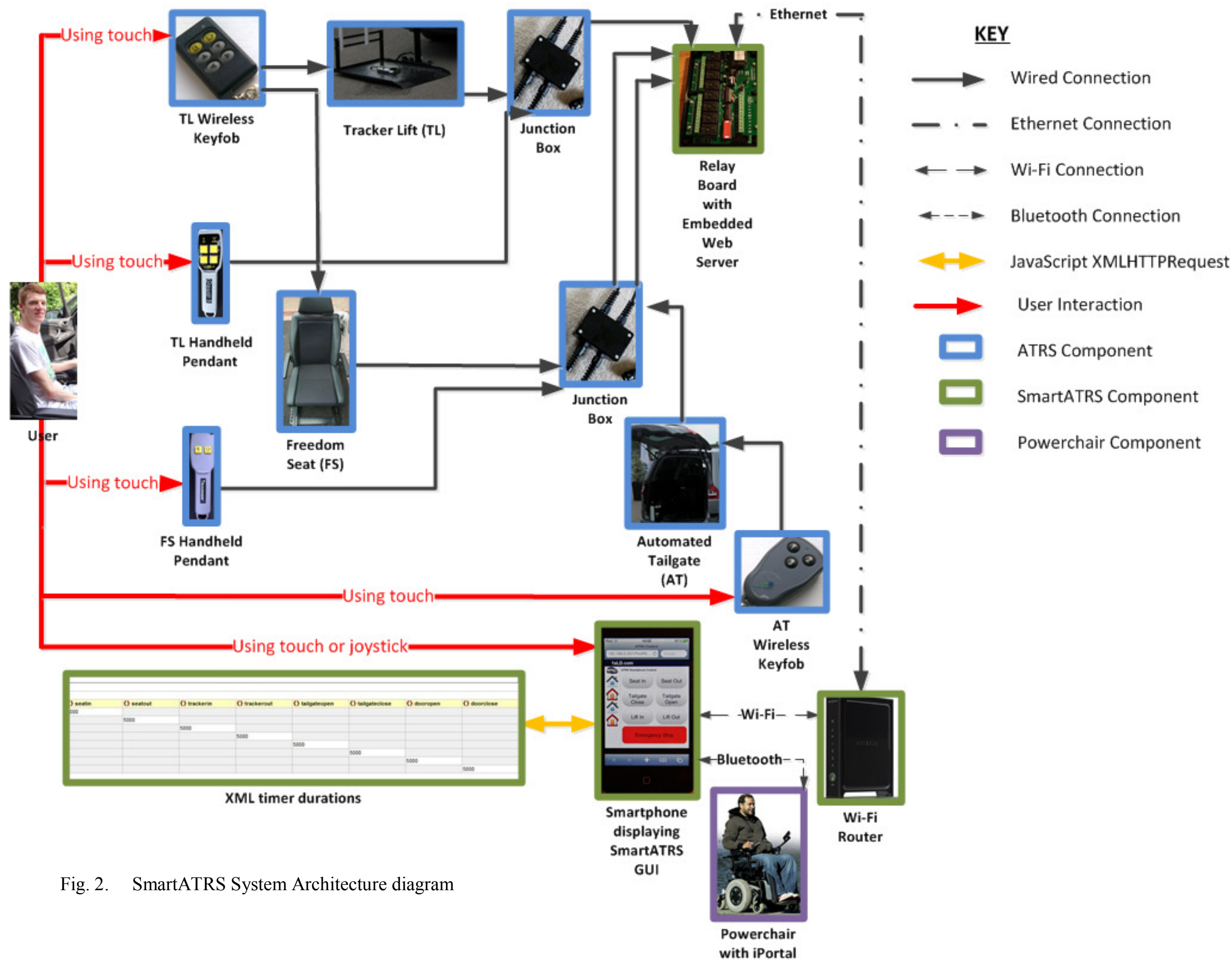


Fig. 2. SmartATRS System Architecture diagram

V. Results

The research results highlight the difficulties currently encountered by the user community, leading to a categorisation using HTA. A comparison of the interaction methods of keyfobs, touch and joystick was shown by a Controlled Usability Evaluation.

A. Requirements Elicitation

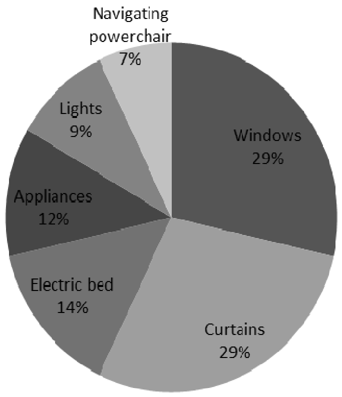
A spreadsheet combining the responses to the user surveys and interviews was used to create graphical representations, shown in Fig. 3 (a) and (b), as well as becoming an input to the SmartPowerchair HTA. The key findings from the full analysis of the results by Whittington et al. [1] were:

Tasks: 58% of participants found the most difficult household tasks were opening/closing curtains and windows. The feedback suggested that causes of this difficulty were due to the curtains/windows either being out of reach, inaccessible (due to obstacles such as furniture) or requiring a significant level of physical activity to be exerted. Navigating the powerchair around the home was the next most difficult task (due to narrow internal doors).

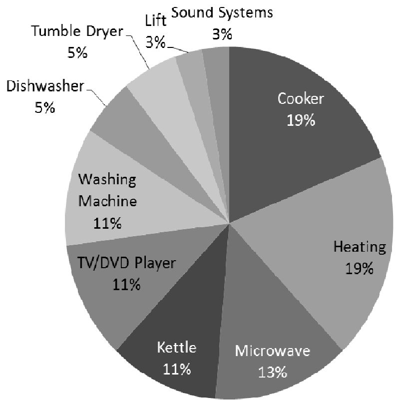
Doors: 27% of participants identified front, back and patio doors to be the most difficult doors in the home to open and close. Garage doors were the second most difficult for 20% of participants. A comment was that opening/closing doors required concentration to simultaneously drive the powerchair and open/close the door. Participants with dexterity impairments found the door handle positions, the weight of the doors and locks to be issues. Some participants commented that they could only manage doors if they were left unlocked (obviously presenting a security risk).

Appliances: Cookers and heating controls were identified as the most difficult household appliances to operate by 38% of participants due to the heat produced by cookers and small heating control dials. Microwaves and kettles were the next most difficult for 25% of participants.

Technologies: An important finding was that 48% of participants stated a smartphone operated by either touch or head tracking had the greatest potential. A smartphone controlled by voice was only popular with individuals who did not have speech impairment. Head mounted displays were the



Household Tasks



Appliances

Fig. 3. (a) and (b) Difficult household tasks and appliances

least popular technology at 10% due to being obtrusive and difficult to wear for people with disabilities.

B. Hierarchical Task Analysis (HTA)

By performing a HTA on the survey results, it was identified that the SmartPowerchair would have two categories of functionality; 'Tasks in the Home' and 'Household Appliances'. Through analysis of the survey results, the tasks that created the greatest difficulties for the powerchair users were included in the HTA and therefore would be supported by the SmartPowerchair. Example tasks included operating doors and windows.

The application of HTA to SmartATRS illustrated which ATRS tasks were supported by SmartATRS, thereby deriving the tasks to be performed by the participants during the Controlled Usability Evaluation. Tasks consisted of driving the seat out of the vehicle, opening the tailgate, driving the lift out of the vehicle, performing an emergency stop (whilst simultaneously driving the seat and lift into the vehicle) and closing the tailgate.

C. System of Interest (SoI)

A Two-dimensional model was created for SoS to illustrate the mapping of requirements to the SoS lifecycle, incorporating the capabilities, systems, components and future integrations. The model determined the aspects that were needed to address each stage, such as ensuring successful integration with the technologies and compatibility with the existing powerchair. An important aspect of the development of the SmartPowerchair was the Capability Phase involving collaboration with an industrial partner (Dynamic Controls [22]), which determined the capabilities and functionality. To identify the components of the SoS, a System Architecture diagram (Fig. 2) was developed to describe the interoperation between the components and the user interactions. On-going concept and technology development can be implemented on the SmartPowerchair, where pervasive technologies could be integrated into the existing system architecture and be evaluated by the user community.

D. Characterisation of SoS

The SmartPowerchair system components when integrated with SmartATRS and their interactions are illustrated by the Characterisation of SoS (Table 1). The table was based on research conducted by Loughborough University [16] focusing on SoI and described the relationships between the components and their individual capabilities. The key components of the SoS were a smartphone, ATRS, relay board and vehicle components. The interface between ATRS and SmartATRS was created by a relay board, where each relay was connected to an ATRS component (the seat, lift or tailgate). Commands were received wirelessly by the relay board from the JavaScript being executed on the smartphone. The command type sent determined whether the relays were switched on or off. As an alternative interaction method to 'touch', joystick control was developed by using iPortal that communicated with a smartphone via Bluetooth.

E. Controlled Usability Evaluation

The Controlled Usability Evaluation validated the SmartATRS requirements, which were defined using a shortened version of the Volére Requirements Shell [49] and included the types: Functional (FR), Safety (SFR) and Reliability (RR). The main requirements were:

- (SFR1) SmartATRS shall not prevent ATRS from being operated by the handheld pendants or keyfobs.
- (FR1) SmartATRS shall be able to control the following functions: the Freedom Seat, Tracker Lift and Automated Tailgate.
- (SFR2) SmartATRS shall ensure safe operation of all ATRS functions.
- (RR1) SmartATRS shall be reliable, as a user would depend on the system for their independence.

The evaluation assessed the usability of the interaction methods of keyfobs, touch and joystick and was simulated by forming a user group of 12 participants in powerchairs who could drive a vehicle. The objective was to verify that the GUI design was 'fit for purpose' for ATRS users. The participants performed six predefined tasks derived through a HTA of SmartATRS. The HTA defined the tasks that could be completed with SmartATRS, with each task decomposed into subtasks. The tasks supported by the smartphone interface were differentiated by using an image of the GUI. The tasks were specifically chosen to provide a full usability assessment of SmartATRS compared to the keyfobs

Fig. 4 shows the SmartATRS GUI, which was designed from the views of visitors at the 2011 Mobility Roadshow regarding the limitations of the keyfobs. User feedback and safety features that did not exist in the keyfobs were incorporated into SmartATRS, to improve usability.

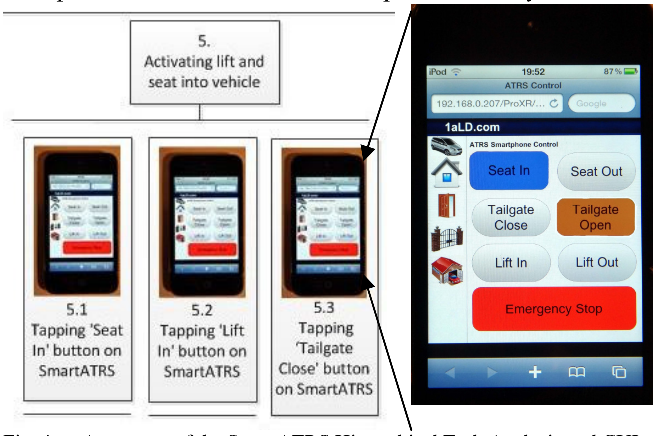


Fig. 4. An extract of the SmartATRS Hierarchical Task Analysis and GUI

Seven command buttons were used to activate each ATRS function, with the red Emergency Stop button being twice the width of the other buttons, so that it could be selected easily in an emergency situation. The use of large command buttons and clearly defined icons reduced the risk of incorrect selection and ensured visibility in adverse weather conditions. The background colour of each command button changed to blue when the function was operating and only reverted back to the original colour on completion. The exceptions to this were the Tailgate Close, Tailgate Open and Lift Out buttons that changed to orange and were disabled when necessary to maintain the safe operation of ATRS. The disabling of the tailgate buttons ensured that the tailgate could not be closed when the lift was outside of the vehicle (which is possible in standard ATRS), causing damage to the tailgate and lift. The Lift Out button disabled when the lift was on the ground to prevent the user from driving the lift into the ground causing strain on the mechanism. The Seat In and Seat Out buttons were not disabled in any situation, as the seat mechanism automatically stopped when fully inside or outside the vehicle.

The Adjective Rating Scale [50] was used to interpret the System Usability Scale (SUS) scores. The keyfobs achieved a rating of 51.7 ('OK Usability'), 'touch' achieved 90.4 ('Excellent Usability' / borderline 'Best Imaginable Usability') and joystick achieved 73.3 ('Good Usability'). The results clearly highlighted that 'touch' was the most usable interaction method; however, a joystick interface was a significant improvement to the keyfobs. A second notable result highlighted the safety of the emergency stop function that revealed a standard deviation of 6.8 seconds for the keyfobs, compared to 1.2 seconds for SmartATRS. The differences in the workload experienced when using each interaction method is illustrated by the box plots of the NASA Task Load Index (TLX) results in Fig. 5.

It is evident that a touch interface exerted lower mental and physical demands on the user, therefore indicating that keyfobs were less efficient to use than 'touch'. All NASA TLX workload types (i.e. Temporal Demand, Performance, Effort and Frustration) were analysed and showed conclusively that a touch interface was the least demanding interaction method.

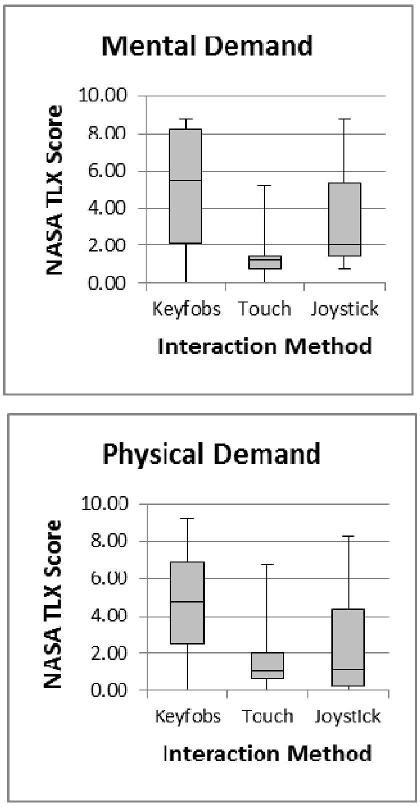


Fig. 5. Comparing the Mental and Physical Demands of ATRS interaction methods

VI. Discussion

A. Characterisation of SoS

The SmartPowerchair pervasive SoS has been described, where off-the-shelf pervasive technologies can be integrated into a standard powerchair to improve the quality of life for people with disability. To elicit the SmartPowerchair requirements, the current difficulties experienced by the user group were efficiently obtained through online surveys and semi-structured interviews conducted with students at a special educational needs school. The results provided an efficient 'needs analysis', with the motivation being to ascertain the tasks to be supported by the SmartPowerchair. The combined results identified that the difficult household tasks for a powerchair user to perform were opening and closing doors, windows and curtains, and operating cookers, microwaves, kettles and heating controls. Based on the results from the 'potentially useful' pervasive technologies, it was concluded that the most suitable technology to integrate into a powerchair was a smartphone either operated through a touch interface or by head tracking. Voice control and eye tracking were less popular, as only a minority of users possessed the required clarity of speech or eye control to interact with the

Table 1. Characterisation of SoS for a SmartPowerchair

SoS Components	Capabilities		Functions Services
	Purpose	***Examples of use***	
Smartphone	- To interact with pervasive technologies. - To communicate with users.	- Enables integration of a powerchair with home and outdoor environments.	- Display graphical user interface. - Execute JavaScript. - Communicate with wireless router.
Powerchair	- To transport users.	- Accesses home and outdoor environments.	- Connect with joystick controller. - Receive commands from joystick controller.
Joystick controller	- To control powerchair navigation and secondary functions.	- Allows the powerchair to be driven. - Allows communication with iPortal.	- Drive powerchair. - Operate lights and horn. - Display malfunctions and battery charge status.
iPortal	- To communicate with smartphone via Bluetooth.	- Triggers functions on smartphone.	- Control smartphone operating system. - Navigate web pages.
Automated Transport and Retrieval System	- To aid transition between the vehicle and powerchair.	- Remotely navigates powerchair to rear of vehicle. - Autonomously docks powerchair on to lift in rear of vehicle.	- Connect to LIDAR unit. - Control powerchair using LIDAR and sensor data.
SmartATRS	- To interface with relay board via JavaScript.	- Used to operate seat, lift and tailgate. - Used to perform ATRS emergency stops.	- Control timeouts and interlocks. - Provide status feedback to users.
Relay board	- To receive commands from JavaScript.	- Used to control SmartATRS.	- Switch seat, lift and tailgate relays on/off as appropriate. - Communicate with wireless router.
Seat	- To follow a predefined path to exit /enter the vehicle.	- Used to transport users into/out of the vehicle.	- Enable a safe transfer to powerchair - Stop at a predefined distance from ground.
Lift	- To drive into/out of the vehicle.	- Used to transport powerchair into/out of the vehicle.	- Enable the powerchair to be lifted into/out of the vehicle. - Stop when ground sensor is activated.
Tailgate	- To open/close.	- Used to enable lift to exit and enter the vehicle.	- Driven by a pneumatic ram. - Stop when fully opened/closed.

mediums. The findings from the requirements elicitation phase formed the basis of developing a Characterisation of SoS to identify the capabilities, purposes and functions of the individual system components of the SmartPowerchair SoS, as well as to understand the overall SoS objectives.

The Two-dimensional SoS Model founded from the Capability Cube Model was created for the SoS to illustrate the mapping of requirements to the SoS lifecycle, incorporating the capabilities, systems, components and future integrations. The model described the aspects to be addressed during each stage of the lifecycle, such as ensuring successful integration of the technologies and compatibility with the standard powerchair. The findings from the two SoS analysis techniques complemented each other by producing a thorough definition of the SmartPowerchair. This was vital to ensure that the SoS was suitable to the problem domain and accepted by users. Due to the requirements analysis techniques performed at the initial stage of the lifecycle, it is expected that the SmartPowerchair will provide similar workload reductions as SmartATRS. Management of legacy systems is a major challenge in today's environment due to degradation of unreliable, obsolete systems resulting in potential financial and safety risks [21]. Through the adoption of a SoS perspective, an understanding was obtained of a legacy system (ATRS) that was replaced by a smartphone system to improve safety and usability. A further contribution to knowledge is the SmartPowerchair requirements elicitation that demonstrates how the integration of pervasive technologies has the potential to improve quality of life for people with disability.

B. *Usability Evaluation*

The SoS components of SmartATRS have demonstrated a successful example of the integration of pervasive technology into an existing assistive technology to replace the difficult to use keyfobs, with a smartphone. Developing the SmartATRS HTA was instrumental in identifying the tasks to be performed in the Controlled Usability Evaluation. By deconstructing the overall goal of SmartATRS into individual subtasks and levels, a greater understanding of the processes within SmartATRS was obtained. The tasks currently supported by a smartphone interface were highlighted by the addition of screenshots to the HTA. It is anticipated that the SmartPowerchair will provide a similar reduction in workload when the user performs tasks in the home.

C. *Proposed SmartAbility Framework as a SoS*

The results of the usability evaluation led to the realisation that disability type was not the sole determinant as to whether a user can operate an interaction method. This was due to some users not being able to use touch-based interaction because of dexterity impairment. It was therefore, considered how the SoS approach could be applied to disability through the establishment of a SmartAbility Framework by recommending interaction mediums, technologies and tasks depending on the disability, impairments and ROM of the user. Adopting a SoS approach enabled the elements of Disabilities, Impairments, ROM, Interaction Mediums, Technologies and Tasks to be seen as constituent systems that interact together to create a 'recommender system'. The development process involved analysing physical disabilities to identify common impairments that characterised the types of ROM that affected disability and formed the basis of the ROM element of the framework. The ROM of the user determined the suitable interaction mediums, as each medium related to ROM. Currently available technologies were contained within the Technologies element (Fig. 6) with each having defined supported interaction mediums.

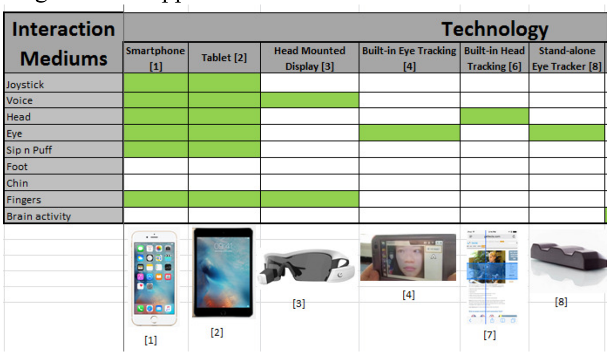


Fig. 6. An extract of the Technology element

Before new technologies or interaction mediums can be introduced, consideration of the interoperability between the other constituent systems [22] (i.e. Impairments and ROM) is essential. This would include the connectivity features of technologies and the extent to which the technologies would communicate with existing systems without causing disruption or interference. It will also be necessary to consider the evolutionary development of the framework, as the SoS will not be created 'once and for all', but will evolve over time as new constituent systems (e.g. Technologies, Interaction Mediums or Tasks) are added, removed or modified [22].

The Task element (Fig. 7) describes daily tasks that users perform with the assistance of technology. The relationships between technologies and tasks were established by considering tasks that are currently difficult for people with disabilities to perform and investigating whether new technologies could provide an alternative method of performing a task. This element could be expanded by the addition of other environments where technologies could offer assistance for people with disability via the recommender system. Any new environment would need to be associated with at least one form of technology or interaction medium.

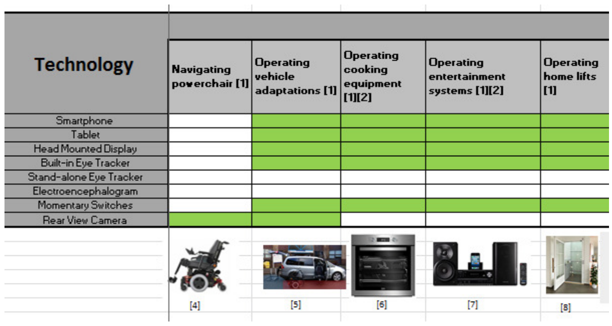


Fig. 7. An extract of the Task element

VII. Future Work and Conclusions

The SmartPowerchair requirements elicitation phase was conducted using surveys and semi-structured interviews specifically targeting people with disability, as this was the intended user group. The SmartPowerchair SoS was perceived as a Directed SoS, where each of the integrated technologies (i.e. the constituent systems) can function independently, but can only provide the functionality of the SoS when combined. One constituent system (SmartATRS) has been the subject of a Controlled Usability Evaluation which illustrated that the system met a functionality metric defined by Metis et al. [54], stating that "an assistive technology must perform correctly in order to serve its purpose".

The interest by the user community in head tracking technology was highlighted from the requirements elicitation phase. Motivated by the improvement that a smartphone made to the usability of the ATRS, user interactions by both touch and head tracking will therefore be integrated into the SmartPowerchair. Firstly, head tracking will be implemented using Tracking Learning Detection (TLD) [51], secondly with an electroencephalograph (EEG) [52] and thirdly by iOS Switch Control [53]. TLD is a real-time object tracking algorithm that tracks the face and learns the appearance from different angles so that it is robust and does not confuse different faces. EEG measures and records fluctuations in electrical brain activity and iOS Switch Control is an accessibility feature that was first introduced in iOS 7. The feature uses the forward-facing camera in a smartphone to track the users head with left or right head movements being configured as triggers for specific iOS functions, e.g. 'move to next item' and 'select item'.

Further experimentations centred on multimodal interactions are planned to enhance the proposed SmartPowerchair and the resulting SmartAbility Framework. The framework will be validated in a focus group involving users with disability and domain experts from healthcare, computing and occupational therapy, with each validating the appropriate framework element(s). The purpose of the validation will be to discover whether the framework is useful for people with disability and to utilise specialist domain knowledge to ensure all of the elements are suitably robust for exploitation to the assistive technology domain.

The SmartAbility Framework will be populated with technology solutions aligned to the abilities of the individual though involving the user community. Therefore, technology recommendations can be made, that will vary depending on specific disabilities of the users, with the aim of assisting with daily tasks and improving quality of life, rather than having a 'single solution to suit all'. It is anticipated that developing a SmartAbility Framework from a SoS perspective will allow disability to become 'Smart' and potentially improve quality of life by providing independence.

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