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A Review and Classification of Assisted Living Systems

Caroline A. Byrne [1,*,†], Rem Collier [2,†] and Gregory M. P. O'Hare [2]

1. Department of Computing and Networking, Institute of Technology Carlow, Kilkenny Rd, R93 V960 Carlow, Ireland
2. School of Computer Science, University College Dublin, Belfield, D04 V1W8 Dublin 4, Ireland; rem.collier@ucd.ie (R.C.); gregory.ohare@ucd.ie (G.M.P.O.)

* Correspondence: caroline.byrne@itcarlow.ie; Tel.: +353-(0)59-917-5534

† These authors contributed equally to this work.

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Abstract: Europe's social agenda for the "active elderly" is based upon a series of programs that provide a flexible infrastructure for their lives so that they are motivated, engaged in lifelong learning, and contributing to society. Economically speaking, Europe must engage in active aging research in order to avoid unsustainable health costs, and ambient assisted living (AAL) systems provide a platform for the elderly to remain living independently. This paper reviews research conducted within the area of AAL, and offers a taxonomy within which such systems may be classified. This classification distinguishes itself from others in that it categorises AAL systems in a top-down fashion, with the most important categories placed immediately to the left. In this paper, each section is explored further, and AAL systems are the focus. Entire AAL systems still cannot be fully evaluated, but their constituent technical parts can be assessed. The activities of daily living (ADLs) component was given further priority due to its potential for system evaluation, based on its ability to recognise ADLs with reasonable accuracy.

Keywords: assisted living; review; classification

1. Introduction

Ambient assisted living (AAL) systems enable older individuals to continue living independent lives whilst facilitating their health management as it becomes increasingly complicated. Research suggests that at least 35 percent of those living in care homes could live independent lives with technological assistance, and that 89 percent [1] of older individuals prefer to live in their own homes. Projected population trends [2] predict increased numbers of older individuals living at home, and that by 2050 22 percent [3] of the world's population will be aged 60 years or older. AAL systems empower older individuals to live independent lives, and will reduce escalating state elder care costs [4] through multi-faceted technological support, such as activities of daily living (ADLs) systems, healthcare, and interactive social media systems. Evaluating the efficacy of AAL systems is necessary, and this paper offers for consideration a taxonomy within which current and future AAL systems could be compared and classified according to their primary function.

AAL Evaluation Reviews

Independent living involves older people managing their ADLs in conjunction with increasingly complicated health issues. AAL systems offer the elderly sophisticated support lifelines, but in the absence of an agreed evaluation framework, research is unlikely to advance in a structured fashion. A framework which offers a set of criteria against which AAL systems could be classified would ensure that future system features include the minimum requirements necessary for AAL research and commercial usage, thus ensuring that the elderly and their families have systems capable of meeting their current and future ADL needs. Previous reviews have taken different approaches, yet all failed to provide a framework within which all AAL systems could be classified according to their primary function [5,6]. Some applied specific guidelines to predominantly single-use systems, compared platform performance, or personalised healthcare systems. The evolution of AAL technology [7] has taken us through three generations, from wearable devices that respond to an emergency, to automatic response home sensors, to a third generation combining less-intrusive monitoring with preventive functionalities. Another review approach of surveying ambient environment services [8] under event-, context-, or device-aware services was categorised in terms of a service-oriented, user-centered, and event-aware monitoring service. This review technique compared various ambient services of response time, success rate, low/high-level failures, power consumption, and service reliability/adaption, yet offered no classification. A comprehensive literature review [9] on platforms and systems [10] provided no taxonomy for researchers, and excluded ambient intelligence (AmI) research that is pivotal within robotics and wearable computing. A recent review paper [11] described AAL as the culmination of the following five technologies: sensors, context awareness, machine learning, and artificial intelligence, announcing the importance of device interoperability, yet offering no template for achieving this goal. AALIANCE [12] proffered a roadmap for AAL system standardisation and a possible future evolutionary structure for systems, yet this aspirational template lacks the necessary structure to accommodate current and future systems. This paper reviews AAL systems, classifies each according to their primary function, and formulates a taxonomy within which all systems may be accommodated. The need for an agreed-upon framework for effective categorisation of the disparate nature of AAL systems is acknowledged within this paper. A standardised taxonomy would facilitate the future creation of a de facto summary of system requirements deemed necessary for system inclusion within each classification category.

2. Classification Framework Overview

A comprehensive review of AAL systems research [13], including the AAL Joint Programme ICT for aging well, identified four top-level categories under which all systems could be accommodated: smart homes, intelligent life assistants, wearables, and robotics. Taking these four pillars as the core categories of our framework, this paper systematically places each system within a sub-category, where the primary function of each is comparative. Current AAL system research is diverse. It addresses the specific aspects of assistive living technologies, health monitoring needs, or offers robotic assistance, in the absence of a clear taxonomy within which each system could be adequately compared. The creation of this framework offers a template for system categorisation, thereby providing a referral point for researchers and possibly a structure around which a set of metrics could be formulated, against which each system could be compared for category inclusion. The primary focus of this review is the classification framework and not an AAL systems inventory, but a significant number of AAL systems have been categorised in order to illustrate the framework's versatility. This review concentrates on classifying entire systems which provide a combination of services including medical and social for users with a specific single medical ailment addressed by a single sensor to those with complex health needs requiring the assistance of several combined sensor systems.

2.1. Taxonomy

This AAL classification framework comprises four core categories: smart homes, intelligent life assistants, wearables, and robotics, with distinctive sub-sections containing systems categorised in accordance with their primary function (see Figure 1). Smart homes and intelligent life assistants present a greater diversity of systems and are often the most common initial technology adopted by the elderly or their families. Hence, they are placed first within the framework. Wearables is a stand-alone category due to its primary function being on-the-body sensors. Due to the fiscal outlay associated with Robotics, its prevalence within the general population is minimal and is still predominantly located within the AAL research space. This paper reviews AAL systems [10–12] and categorises them according to their primary function within a taxonomy where future systems could be accurately placed, thus providing researchers with a sub-category of systems to compare their work against.

2.1.1. Smart Homes

A smart home or eHome [14] commonly has sophisticated electronic systems that automatically control particular everyday tasks. These smart homes help older people to maintain an independent life within their own homes, as they provide platforms upon which systems function and provide general health monitoring opportunities [15].

Platforms

Previous AAL reviews [16,17] have concentrated on the issue of platform interoperability in order to provide an open, scalable version for researchers. However, this paper does not distinguish between the functional aspects of each platform, but groups them according to their primary function. Europe's largest AAL project UniversAAL [18,19] inherits features from similar research projects, facilitating the development of an open source platform retaining interoperability as its overall goal. Open architectures have been proposed [20,21], some experimental [22,23], some evaluating remote care, and a modular platform [24] for event recognition. The reuse of components within projects is difficult, as many platforms are too complex for recycling [25]. However, TinySEP offers the advantages of a modularised monolithic platform. Location awareness for mobile platforms [26] was addressed by wrist-worn wireless sensors notifying carers/family of an older person's current location via a network placed on the body. The SOPRANO [27] platform provides an extensible open AAL approach, and has been described as a combination of ontology-based techniques with a service-oriented device architecture grouped under three categories:

- Home Automation
  - INHOME [28], EASY-LINE+ [29,30] projects.
- Agent-Based AAL Systems
  - DynAMITE [31], PERSONA [32], AMIGO [33], MONAMI [34], SENSACTION-AAL [35], I-Living project [36].
- Monolithic Intelligent Systems
  - EMBASSI [37], MAP [38], SmartKom [39], EMERGE [40].

Unlike SOPRANO, few AAL systems are commercially viable due to their inadequate underlying architecture, and consequently the projects ALADIN [41], OLDES [42], ENABLE [43], and SHARE-IT[44] were developed to comply with commercial criteria. Platforms frequently utilised with AAL systems include PERSONA [23], and OpenAAL [12] (an open source initiative producing an agile middleware). HEREiAM [45] and GeTVivid [46] operate via a TV set, whereas PeerAssist [47] concentrates on providing an agile peer-to-peer (P2P) platform. AAL system objectives encourage remote long-term care within the home, with benefits for both older people and their carers. The OpenCare/Sekoia and ZAINGUNE [10] platform supports individual health monitoring via healthcare software and telehealth provisions, whereas Hydra [48] can link user identities over several social media platforms, providing developers with pertinent profiling information.

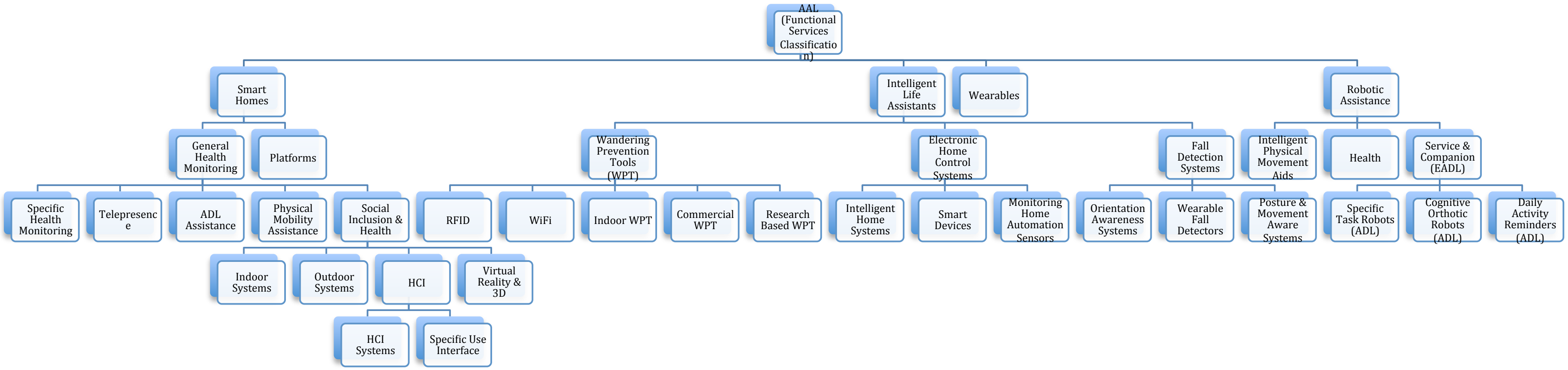

Figure 1. Ambient assisted living (AAL) functional services classification. ADL: activity of daily living.

General Health Monitoring

The second level of this classification contains interlinked platforms and general health monitoring systems. All systems utilise a platform upon which each performs general health monitoring duties and specific health systems, tele-presence, activities of daily living (ADLs), physical mobility assistance, and social inclusion functions. Commercial health monitoring systems for older people living at home include EDLAH [49], which monitors a user's health status, offers advice regarding daily task completion, and provides medication reminders via a tablet. The Inductive Monitoring System (IMS) [50] facilitates health monitoring by generating a knowledge repository for complex systems to recreate with a computer. INHOME [51] is a sensor network and health monitoring platform which interfaces with e-Health software, offering daily monitoring of patients discharged from hospital. The OASIS [52] project's contribution towards evaluating in-home health is valuable. eHealthCOM [53] promotes independent health monitoring whilst providing a health platform tailored to meet localised health service criteria for monitoring an older person's physical and emotional well-being. Care4Balance [54] manages daily communications and activity notifications between elders and carers, MPower [55] is simply a service platform, and U-Health [56] is a mobile health provision system supported by various necessary operational modules. VirtualECare [57] offers off-site health monitoring, with the ability to make decisions based on problem-solving methods, whereas vAssist [58] facilitates in-home health care via a multi-lingual voice-controlled service. The international aspect of this project is important, as it provides another method for communication with older people .

General monitoring within hospitals and research facilities includes the Keep-In-Touch (KIT) project [59–61], which collates health monitoring data. The Center for Future Health (CFH) [62] at the University of Rochester operates a smart home where daily tasks are monitored, communications occur via infrared, bio-sensors, and liberally placed cameras. The user interacts with an HCI capable of conversing whilst establishing ADL adherence and deviations from normal routines. Another example is the I-Living Project [63], in which the home has integral sensors and bluetooth-enabled medical devices acting independently of others or cooperating within an Assisted Living Hub (ALH). The Secure Active Aging Participation and Health for the Old (SAAPHO) Project [64,65] involves health monitoring, ADLs, and independent living through intelligent HCIs on various devices. Project HOME SWEET HOME [66] evaluates the impact of tele-monitoring on an older person's physical/mental health, and whether ADL reminders had an impact upon their lives. A simple user-friendly interface monitors each individual's health and well-being via data collected from environment sensors, video conferencing, and other support services.

Elder health invariably becomes complicated over time, and the specific management of conditions may become necessary. For example, cardiac monitoring is provided by WeCare [67] (a smart telecardiology system), Health@Home [68] provides home health communication management, and DIA [69] assists diabetics with an insulin dependency. Elder mobility and exercise is assisted by CAMMInA [70], and amiCA [71] evaluates daily fluid and solid food intake as well as location/fall awareness. Those with chronic obstructive pulmonary disease (COPD) are given the opportunity for self-management provided by BEDMOND [72,73].

Tele-presence in the home for e-health notifications is provided by COPLINTHO [74], and ExCITE [75] encourages elders to interact socially with an HCI [61] on a daily basis.

ADLs as defined by Katz [76] and ADL assistance span two categories: smart homes and robotics. Software applications assist in smart homes providing reminders, whereas robotic assistance involves hardware and software. This section consists of accurate ADL evaluation systems [59], including home care services and tracking systems (active) and social inclusion systems (passive). Active systems are user-instigated in an emergency and react with an alert (e.g., about-the-body alarm systems). In contrast, passive systems are sensor-activated, sending alerts to carers if a situation has deviated from the norm. Systems whose primary function is accurate ADL recognition within a controlled environment include the assistive living laboratory apartments [61], EMERGE [40,77], and BelAmI [78], evaluating recognised hygiene tasks, bathroom activities, and tasks associated with preparing meals. The Aware Home project at Georgia Tech [79] knows its inhabitant's current location and ADLs, as does the Smart in-home sensor monitoring system at Virginia University [80]. Intel's Age-in-Place smart-home system [81] has the largest industry-led Alzheimer's research project integrating technologies such as sensors, home networks, activity tracking, and ambient displays. The I-Living Project opted out of video cameras for privacy reasons, and focused on context-aware computing for home applications, wireless networking, or HCI within a dynamic environment. As a systems category is determined by primary function, the lack of cameras does not preclude it from inclusion.

ADL Assistance within the home for those suffering from a limiting visual condition include HearMeFeelMe [82]. For those requiring retail assistance, ELDERHOP [83] facilitates mobility within venues, thus redefining the task as a pleasurable interaction. For transport issues, MobileSage [84] is a location-aware device offering geographical advice for mobile elders, and WayFiS supports the older person's confidence to research and complete their own transport routes within variant situations. NACODEAL is an AAL communication tool [85], and complicated ADLs such as meal preparation are supported with ChefMyself [49]. DIET4Elders [86] attempts to address the subject of elder malnutrition by encouraging self-management.

Within smart homes, various technologies can be employed to monitor fuels and sensors for automating daily tasks [87] plus safety review policies [88] for systems. The CONFIDENCE system [89,90] uses radio tags for location and speed of travel, eCAALYX [12] creates easily understood TV User Interfaces (UIs) for the elderly, ROSETTA [91] accesses video coverage and accelerometers, and CODAMOTION [12] utilises infra-red. The EMERGE [40] system monitors/detects emergencies and deviations from expected ADLs. However, all of these lack accuracy in real-life situations. The research focus for EMERGE was its ability to autonomously evaluate and detect emergency situations based upon ADL deviations. SAMDY [92] is focused on the laboratory testing of smart meter technology and home automation sensors before deploying them to some 100 homes. A central web platform connects the information being gathered with prior assessment results, offering researchers database access to test future AAL systems.

Physical mobility is a crucial constituent of an older person's daily routine, hence its inclusion within AAL systems. Systems encouraging elder mobility include SENSACTION-AAL [12], in conjunction with posture and movement recognition systems [90]. IMAGO [93] understands the perspectives of people with dementia whose physical mobility often outlasts their cognitive ability to interpret their surroundings in a meaningful and functional manner. Projects that evaluate an older person's physical activities include Trainutri [94] (a smartphone developed to measure movement) and E-MOSION [72], a tool designed to assist with daily activity levels whilst away from home. PAMAP [95] provides an in-house monitoring/fitness teaching facility for older people. Those with depreciating physical and mental agility can access ASSAM [96], which is a mobility location aid for platforms used by walkers, wheelchairs, and tricycles. IWalkActive [97] is a mechanically powered walking aid which assists the user with their mobility. Software assistance for physical and mental tasks includes ASSISTANT [98], offering navigational assistance in densely populated areas. Older people with depreciating physical and mental agility require location assistance tools provided by NavMem [99] or MOBILE.OLD [100], a monitored geofencing service. AHEAD [101] offers individual physical activity assistance, and T/Tnet [102] maintains an individualised navigation tool for organising international real-time travel assistance. Finally, ASK-IT [103,104] provides a question-and-answer mobility service.

Social inclusion and health with indoor systems encourages interactive social relationships. SoMedAll [105], the Social Media for All elders project offered flexible easy-to-use UIs, which developed and maintained shared online information, mindful of the users' limiting physical and cognitive faculties. The emotion-aware system in [106] gives continuous sensor feedback, thus improving motor skills. Glam i-Home Care [107] emulates the user's daily routine and reflects their emotional state in order to produce a sustained continuum of well-being. Keep-in-Touch (KIT) [108] accumulates and distributes important health data within health facilities. FoSIBLE [109] is community software, and relevant devices can interface to test sensors for elder social interaction. Finally, V2me [110] is a socially interactive virtual elder network. Daily levels of physical activity throughout our lifetime are important for long-term health goals, and the MoMo [111] study recognised that this ingredient was critical within the lives of teenagers, highlighting benefits found in bones, body mass index, reduced cardiac incidences, and improvements in well-being. DfA@eInclusion [59,112] encouraged the development of electronic inclusivity within older people, EU4ALL [113,114] provides an agile electronic teaching system, and amICA [68] offers personalised health monitoring.

Systems encouraging the social involvement of older people highlight that emotional needs are critical to sustained well-being [115]. I2Home [116] is an example of such systems or those with physical disabilities tailored to provide maximum levels of technological and physical assistance aids. An HCI pivots on the premise of its usability [117], and constant developments within these areas, sensor networks [118], and assistance offered by the HOMER online repository [119] propels such research.

Mobile health maintenance is provided by systems such as CAALYX [120] and eCAALYX [121] because location awareness is necessary for the mobile elderly, and these platforms offer a base for software development. Older people need easy-to-use UIs to assist them with their daily lives, as their desire to participate is fundamental to system success and uptake. The EasyLine+ and SHARE-it projects focused on UIs activating electronic kitchen appliances from a distance, and are commercially available.

ADL monitoring and subsequent sensor data interrogation in order to establish patterns and deviations is fraught with difficulties. The EMERGE system's approach to solving myriad possible sensor data complications is to employ a multi-agent-based approach in the form of their Event-driven Activity Recognition System (EARS). This solution is a compilation of various algorithms [122] used in artificial intelligence and complex event processing (CEP). Another considered solution was a time map approach [123] for analysing a typical temporal network of sensor events involved in an ADL. The complex event recognition architecture (CERA) includes the non-fuzzy recognition [124] of particular events as they occur, with rules externally imposed in syntax similar to Lisp. The event pattern programming language RAPIDE [125] is commonly used with CEP projects, but naïve Bayesian classifiers [126] were used for instant ADL detection in homes.

Humans are social animals, and our social network diminishes as we age. The opportunities for extending these networks are supported by systems such as the 3rD-LIFE [127], a 3D virtual environment for online interactivity. The Rehabilitation Gaming System (RGS) [128] provides those with neurological deficiencies the opportunity to regain limb movement via HCI interaction with various technologies.

As we age, our physical mobility decreases and unique task interfaces such as a Ubiquitous Fitness Influencing Technology (UbiFit) [129] can encourage specific areas of fitness, general or targeted on a daily, hourly, or weekly basis. The sensors are on the person, calibrating motion as it occurs. Banking is another area where the elderly can benefit from a targeted interface, such as the one offered by Bank4Elder [130].

Intuitive elderly interface design is crucial for compliance and uptake, and with this in mind the I2HOME [131] system provides an intelligent interface. AALuis [83] pride themselves on the flexibility of their middleware platform connectivity. GoldUI [49] provides interfaces for various technological end-users, and DACAR's [132] primary objective is encouraging social inclusion. Consequently, these tools are disseminated into society, becoming part of the fabric of social norms.

2.1.2. Intelligent Life Assistants

Intelligent life assistants combine the areas of commercial outdoor wandering prevention tools (WPT) and research-based WPT. Commercial WPT are robust aids for those with dementia or Alzheimer's, and are restricted to performing their primary function with little tolerance for failure.

Research-based WPT have greater failure tolerances and scope for combining system functions for experimental purposes.

Wandering Prevention Tools

This section describes wandering prevention tools (WPT) [133], electronic home control [134–136], and fall detection systems [137], with discussion of their sub-categories. Each review paper in this section discusses wandering prevention but does not provide a framework within which all could be evaluated. Instead, they evaluate systems against each other competitively. Systems utilising RFID [138] include SpotOn [139], which incorporates GPS technologies for locating items or persons, and LANDMARC [140], which adopts a closest neighbour algorithm for RFID location with less flexiblity. WiFi [141] networks assist with locating users in care-home wheelchairs fitted with devices, and provide alerts to carers when appropriate if users breach a designated GPS geo-fenced zone. Systems providing a base within the user's home include MOBECS [142], thereby providing an indoor and outdoor security system encouraging physical activity. Indoor WPT [143] background wandering behaviour is frequently seen in older people with cognitive impairment. The prevalence of patients exhibiting wandering behaviour has been estimated to be 11.6 percent in traditional units, and 52.7 percent in Alzheimer's units. NOCTURNAL [144] offers users the option of extending their independent lives by collecting data on their night-time wandering routines and alerting carers when such habits are not adhered to.

These outdoor wandering systems help those with declining mental agility to live independent lives with technological assistance. Systems offering the ability to track persons with the propensity to wander or get lost include QuestGuard [145], those utilizing GPS include EmFinder and Comfort Zone [146], recommended by the American Alzheimer's Association. The user's location is constantly monitored via a geo-fenced map, and breached zones trigger system alerts. GPSshoes [147,148] is also a GPS fenced tool and tracks the user, sending coordinates to a central monitoring base in the user's shoes. Deviations from pre-designated geo-fenced zones will alert carers to the user's current unauthorised map location.

Research-based WPT RFID tags are a common constituent of wandering prevention systems such as COGKNOW [149,150]. Other systems utilise GPS as a method of tracking users, OutCare and WanderHelp [151–153] support normal daily routines and deviations from individual daily signatures invoke an alert. KopAL [154] offer the same service but via a mobile network, others within the same genre include Opportunity Knocks [155], CONFIDENCE and InMyOneWay [20].

Electronic Home Control Systems

Decision-making frameworks [156] respond to wandering patients, predicting their possible next episode, but these systems have not been classified. A classification framework would benefit assessment and detection research into the wandering habits of persons with dementia (PwD) [157]. Continuous offline data from indoor sensors assists in pattern recognition and developing individual wandering signatures. Wandering detection systems can offer PwD and their carers reassurance, gained from online indoor or outdoor sensor data. The EMERGE system has been classified in the smart homes category. Notwithstanding this, it is proactive in fall detection and emergency response alerts, as daily/long-term pattern deviations are monitored and appropriate responses implemented. User situations are monitored with several types of sensors, and the Sensor Abstraction Layer (SAL) [158] offers a simple interface for accessing and maintaining sensor data. Proactive alerts to detect emergency situations are pre-programmed and instantiated in the *Assistance* subsystem, where the Human Capability Model (HCM) [159] assesses an older person's long-term behavior pattern. Electronic home control systems [134–136] such as EMBASSI [160] offer assistance in fulfilling daily activities via dedicated interfaces. OLDES [161], Older People's e-services at home, has created a platform for use by older people within the areas of tele-company, tele-assistance, and tele-medicine. Independent living is supported through ENABLE [43], an about-the-body system, and the University of Essex has developed a smart dormitory called iDORM, offering an intelligent living situation to students [162]. Grenoble Health Smart Home [163] and Gloucester Smart [164] are intelligent environments which unobtrusively monitor those with dementia. RelaxedCare [165] uses pattern recognition to transmit patient status notifications via various technological aids (e.g., a picture frame). Collecting peoples' data unobtrusively as they conduct their daily lives is paramount to the success of smart homes and their devices, such as smart pillows [166], dressing tables, mats, pens, and smart sofas [167]. Monitoring systems like SAMDY [168] and eHOME [169] support independent living, yet assistance is available via alerts if deviations from routines occur.

Fall Detection Systems

Fall Detection Systems are categorised according to their ability to detect if a fall has occurred. SPEEDY [170] is a wrist aid using orientation in space to detect falls, and sends alerts following the algorithm being invoked. SOFTCARE [171] endorses the premise that smart living situations should be entirely facilitative in all areas of living one's daily life. Many fall detection systems require user interactivity and are rendered void if the wearer is physically incapable. Systems offering a solution to this problem include FEARLESS [172], which facilitates depth awareness using sensors, and SIMBAD [173], which utilises array-based infrared detectors to monitor levels of physical movement. RITA [174] supports fall awareness with alerts, and monitors users via a constant video channel. This option may not suit everyone, but offers reassurance to those with a life-limiting physical disability. Accelerometers in CODAMOTION [175] and posture and movement aware systems [176] unobtrusively detect location, movement, and position within the environment, only intervening when a reading invokes an alert.

2.1.3. Wearables

This section concentrates on sensorising the person rather than the environment, and is consequently a stand-alone core with no sub-categories. This core's primary function is that of being worn on the body for long periods of time, and has evolved significantly in the past decade [177–179].

Wearables feature in several core categories, such as health-monitoring, fall detection, and ADLs unobtrusive daily monitoring. On-the-body biometric monitoring [180] via minute sensors woven into fabrics collecting vital signs and chemical data provide not only unobtrusive ehealth monitoring, but also offer reassurance that assistance is available via alerts. Wearable comfort has improved [181] in tandem with their agility in robotics [182] and fabrics [183], both facets contributing to significant improvements within this area of research. Product evolvement in this area has witnessed the command-input watch Gesturewrist [184] being superseded by Nenya [185], where the sensor input is via a magnetic ring. Health-monitoring systems within clothing are popular. Vivago [186] monitors normal physical movements, and Lifeshirt [187] monitors patient biomedical readings in an operating theatre, sending alerts if deviations from normal parameters occur. Tailored wearable health clothing monitors certain health aspects. Healthvest [188] is specifically aware of heart and lung functionality as well as current user temperature. Sensor-laden wearable clothing feeding biomedical readings to users on their fitness regimes has seen the emergence of the BioHarness chest strap [189]. Serious heart or lung disease sufferers utilise AMON [190], which offers sophisticated biomedical observation with alerts if observed data is deemed unsatisfactory. BIOTEX [191] evaluates bio-markers through the unobtrusive chemical assessment of human body fluids, and can react to deviations from specific personal parameters. This smart sensor-based clothing project is EU-funded to encourage research within biomedical reading, thus facilitating patient discharge from intensive care situations to independent living at home. Wearable biometric systems are touted as being economically competitive, easy-to-use, and ubiquitous, and Healthy Aims [192] boasts financial viability, Code Blue [193] claims economics, usability, and empowers users to self-manage their health. The biomedical sensors in VitalJacket [194] merge fabric with electronic technologies, providing constant biometric readings. In combination, ELF@Home [195] also monitors physical exertion levels. Unobtrusive physical activity monitoring assists with particular cardiac and lung-related diseases, along with illnesses affecting balance resulting in falls. In association with myriad smart home sensors, these sensors offer older people an independent life for as long as possible.

2.1.4. Robotic Assistance

The assistance of robots with daily tasks is described as Electronic Aids to Daily Living (EADLs). This section has several categories of robotic assistance, that of, intelligent physical movement aids, service and companion (EADLs), including the sub-categories of specific task robots, cognitive orthotic robots, and daily activity reminders. In conjunction with biometric monitoring and smart home sensing, these assistants offer another avenue for independent living.

Intelligent Physical Movement Aids

This sub-category of intelligent physical movement aids [196] contains systems such as SHARE-IT [197], an agent driven system with decision capabilities; the i-Walker [198], which is an intelligent physical support for those experiencing physical or intellectual disabilities; and EXO-LEGS [199], supporting movement with external robotic limbs returning ambulation to normal levels.

Health

Health maintenance is a constant feature within several categories. Substantial and constant physiological assistance is provided by NurseBot [200] and IWARD [201]. The latter system utilises collected data to intelligently recognise daily user needs, providing assistance with ADLs and health observation tasks.

Service and Companion (EADL)

This area of robotics offers physical and social assistance to users. Paro [202,203] is a robotic baby seal developed to encourage social interactions between elderly users. Varying pressure, camera, sound, and orientation sensors are contained within its white artificial fur and airbag interior. Remarkably, this social robot enhanced the lives of the older people participating in this study. Within social robotics, Pearl [204] is constantly cited for its methods of physically assisting the user with their daily ambulation needs as it moves with the user, giving location awareness assistance. Sub-categories include specific task robots [205], and Wabot House [206] specifically supervises and facilitates human–robotic interaction, thereby improving interactive social sophistication. ROBOCARE [207] is an in-home proactive robotic platform merging hardware and software supporting elders with their daily task.

A cognitive orthotic system [208] is designed to assist elders with declining neuro-abilities live independent lives by giving daily routine task reminders. Autominder assists through individually programmed daily task reminders. Many of these systems include alerts for daily routine tasks which are decided prior to installation. DOMEO [209] offers various UIs for robotics specialising in social interactions.

Several systems provide daily activity reminders [210], such as HealthVault [211], Google Health [212], or MemoJog [213], which remind users of daily health issues, exercises, or medications. AAL robotic assistants are gaining dominance in support roles, and augmented features individually assist the user [204] or provide a range of ADL assistance [214,215]. Total immersion within an AmI platform is provided via a services wall [216] which supports verbal commands and UIs for communicating with elders affected by declining cognitive abilities. Dusty Robot [207] offers household assistance by physically assisting the elder with daily motor tasks.

This paper offers a classification within which AAL systems may be categorised. The framework's top level contains the four core pillars of smart homes, intelligent life assistants, wearables, and robotics. Each core contains sub-classifications, within which systems are categorised according to their primary function. Some topics (e.g., platforms, health, and wearables) feature within several sub-classifications, yet every system within each topic area was classified according to primary function and not the research aspects each system encompassed. This taxonomy provides a structure for researchers to place their system within it based on primary function and assess if a review of system requirements is warranted. A point of reference framework would in the future provide an initial blue-print for the creation of a set of metrics against which systems could be compared. Ultimately, a comprehensive criteria list for system inclusion within each category might encourage research convergence, and would facilitate the end-users' navigation through the myriad AAL assistive technologies.

3. AAL System Evaluation Criteria

The creation of a set of AAL evaluation criteria would provide future end-users or their loved-ones with the ability to assess which system best suits their individual needs. It would facilitate the users' initial adoption of technologies tailored to their requirements based on that sub-category's metrics. The purpose of AAL research is to provide assistive solutions for the families of loved-ones with often complex medical, physical, or social dependencies. A set of criteria pertaining to each category would enhance the navigation experience for the end-user's family and would allow them to assess which technological aid best suits their particular needs. Currently there is no methodology available for assessing all the constituent parts of an AAL system, but there are competitions where the technical aspects of a system have been assessed. The ability to compare systems under certain constituent parts could provide a road-map for a comprehensive set of evaluation criteria in the future.

In 2011, the first EvAAL (Evaluating Ambient Assisted Living) international competition aimed at addressing the complexity involved in evaluating AAL systems was held with the theme of indoor localisation and tracking for AAL. In Barsocchi et al., "Comparing AAL Indoor Localization Systems." [217], a roadmap and framework for this competition and subsequent ones was developed within which AAL systems could be compared. The first EvAAL International competition addressed the complexity involved in system evaluation, and in the absence of an agreed-upon comparison framework acknowledged its need and offered a possible solution. It had the special theme of Indoor Localisation and Tracking for AAL. While it was widely accepted that an appropriate comparison framework for an entire AAL system had not been established, the competition proposed that the technical parts of a system could be evaluated and compared. Supported by the AAL Open Association AALOA association and organised by the UniversAAL project, its primary objective is to improve the current evaluation and comparison methods for AAL systems whilst importantly assessing the inherent impact of an AAL system on its users.

EvAAL: AAL Competitive Benchmarking

EvAAL is a live competition with adjudication based on task accomplishment and competing systems being assessed in a living lab that is representative of a real home, with trained users consistently adhering to the technical requests of the EC (Evaluation Committee). Realising that the comparison of entire AAL systems was not feasible, the inaugural competition opted to evaluate just the systems' technical parts whilst refining its methods of evaluation. This restricted the 2011 competition [217] to evaluating the basic constituents and services of a system (e.g., indoor localisation). A track on activity recognition was included in 2012, as the evaluation methods had been developed to assess more complicated system components and their facilities. In 2013, a demo was added on companion robots for AAL systems, and each subsequent year consolidated previous competition tracks whilst incorporating a different constituent part, furthering the refinement of a set of evaluation criteria for an entire AAL system. Three different tracks evaluated system parts in 2015: smartphone-based, foot-mounted pedestrian dead-reckoning (PDR), and Wi-Fi fingerprinting with the addition of track 4—indoor mobile robot positioning—in 2016. Track 4 changed in 2017 to PDR for warehouse picking. Each successive competition has grown in strength and popularity since its inception in 2011, yet the attempts to further the evaluation of AAL systems fails to deliver a comprehensive set of evaluation criteria.

4. The Evolution of AAL Evaluation Criteria

As demonstrated by the EvAAL competition, curating a set of criteria capable of evaluating an entire AAL system is very difficult due to their complex constituent parts. However, it is possible to compare various system tracks and assess them competently. The EvAAL methodology has been comparing AAL constituent parts since 2011, and has not yet formulated a set of criteria capable of evaluating an entire system. This paper proposes that an alternate approach should be examined to further AAL system evaluation criteria research, and that a sub-section of the outlined classification framework be considered. We propose that ADL assistance be considered as a candidate classification sub-section for an entire AAL system evaluation. It is widely accepted that comparing different systems accurately is complicated, but if evaluation research focused on a classification sub-section (i.e., ADL assistance), then a more accurate comparison for one group of systems might be more achievable.

5. Future Work

As a society, we are living longer, and providing an avenue for independent living through technological means is a social and fiscal priority. Previously proposed AAL classifications have been incomplete, outdated, or not fit for purpose. This research also acknowledges that a possible fifth core pillar (i.e., implantable sensors) was not included within this review, as they were not featured in the AAL Joint Programme original core pillars for aging well. This paper offers a necessary framework within which systems are categorised according to primary function, and proposes that the creation of a set of AAL system evaluation criteria on a sub-category may further research within this refined area. The ADL assistance sub-category is suitable for further investigation as it provides older individuals with the option of remaining at home whilst their daily living routines are unobtrusively monitored through sensor activations. The lack of a universally agreed-upon set of metrics continues to impact ADL assistance research, as it is difficult to quantify how many or even the types of sensors necessary to accurately monitor a persons ADLs within a real-world home. Many factors influence the accurate monitoring of ADLs within the home: whether it is a single or multiple occupancy home, whether the system is sensor-laden or has a minimal level of sensors, whether the system encompasses a fall detection element with alert notifications, and the system's robustness in a daily living situation. This paper proposes an approach to the issue of metric identification within the refined framework sub-category of ADL assistance, where a quotient is devised and applied to systems. The quotient value will be representative of adherence to the minimum requirements deemed necessary for each system to reasonably accurately monitor ADLs. This proposed set of evaluation criteria and the resultant quotients will provide researchers with a template for creating systems which are functionally specific to the needs of the people living with them, and are capable of accurately monitoring daily and longitudinal ADL signatures.

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