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Assistive technology design and development for acceptable robotics companions for ageing years

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Abstract

A new stream of research and development responds to changes in life expectancy across the world. It includes technologies which enhance well-being of individuals, specifically for older people. The ACCOMPANY project focuses on home companion technologies and issues surrounding technology development for assistive purposes. The project responds to some overlooked aspects of technology design, divided into multiple areas such as empathic and social human-robot interaction, robot learning and memory visualisation, and monitoring persons' activities at home. To bring these aspects together, a dedicated task is identified to ensure technological integration of these multiple approaches on an existing robotic platform, Care-O-Bot® 3 in the context of a smart-home environment utilising a multitude of sensor arrays. Formative and summative evaluation cycles are then used to assess the emerging prototype towards identifying acceptable behaviours and roles for the robot, for example role as a butler or a trainer, while also comparing user requirements to achieved progress. In a novel approach, the project considers ethical concerns and by highlighting principles such as autonomy, independence, enablement, safety and privacy, it embarks on providing a discussion medium where user views on these principles and the existing tension between some of these principles, for example tension between privacy and autonomy over safety, can be captured and considered in design cycles and throughout project developments.

Keywords

companion technologies · assistive robots for home · ethics and technology · empathy and social interaction · learning and memory · proxemics · technology acceptability · activity monitoring

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1. Introduction

With the increasing life expectancy in the world, the proportion of people aged 60 years and above will have reached a ratio of around 1

person in 3 by 2060. This is reflected by the statistics showing World-wide trends [4] and from the 27 European Member States showing an almost doubling in number of people aged 65 and above (from 17.57% to 29.54%), while the number of people aged between 15-64 will see a decrease from 67.01% to 57.42% [20]. At the same time, the industrialised countries are facing an explosion of costs in the health-care sector for the elderly. Current nursing home costs range between \$30,000 and \$60,000 per person annually [4]. This changing demographics as well as increasing cost predictions provide a driver for a new stream of research in the domain of care and prevention.

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The ACCOMPANY (Acceptable robotics COMPanions for Ageing Years) project funded by the European Framework 7 programme focuses on a multidisciplinary approach for developing different aspects of state of the art in relation to companion technologies. There have been many national, European and International projects concerning the issue of care and assistance for older age. Different European projects such as those listed in Table 1 have approached this problem from varying different perspectives. Noting that projects listed here are not the only projects targeting this area, and highlighting their increasing number points to the importance and complexity of the topic of care and assistance. Differentiating between these ongoing or finished projects is out of the scope of this paper, thus we aim to focus on the ACCOMPANY project objectives and approaches chosen to achieve those objectives.

Table 1. Some of the existing and previously funded projects in this area

Acronym: Title	Website
SRS: Multi-role shadow robotic system for independent living	srs-project.eu
Cogniron: Cognitive Robot Companion	www.cogniron.org
LIREC: Living with robots and interactive companions	www.lirec.org
CompanionAble	www.companionable.net
IROMECC: Interactive Robotic Social Mediators and Companions	www.iromec.org
Hermes: Cognitive Care and Guidance for Active Ageing	www.fp7-hermes.eu
Florence: Multi Purpose Mobile Robot for Ambient Assisted Living	www.florence-project.eu
KSERA: Knowledgable SService Robots for Aging	ksera.ieis.tue.nl
GiraffPlus	www.giraffplus.eu
ROBOT-ERA: Implementation and integration of advanced Robotic systems and intelligent Environments in real scenarios for the ageing population	www.robot-era.eu
Ambience	www.hittech-projects.com/euprojects/ambience

The ACCOMPANY platform consists of a mobile manipulator robot and a smart home with an array of sensors. The robotic platform, Care-O-bot®3 (COB3), is a state of the art service robot designed for home environments, towards functioning in capacity of an acceptable companion. The choice of robotic platform was due to its availability as a mobile robot in soft-casing with a manipulating arm, researcher's prior familiarity with the control and programming of the platform gained during LIREC project, and its demonstrated potentials for integration with a smart home environment. Issues such as safety and robustness were also considered. Based on these, the COB3 was chosen as the main robotic platform for the project and was complemented with an array of sensors available in a smart house environment.

Project developments focus on social and empathic interaction, as well as robot's ability to learn from interactions. Furthermore, it incorporates the state of the art in environment and activity monitoring towards pro-

viding a home solution for cases where robot presence can complement environmental sensors. These all aim to assist in the context of care for the elderly people. Project developments are guided by incorporating user-centred design through formative evaluation to formulate requirements and summative evaluation to assess requirements' achievements during the life cycle of the project. Furthermore, ethical aspects of utilising artificial care companions at home are considered during the project.

The development of service robotics has so far been mainly driven by technological developments. It has remained close to the mainstream market offering services within the reach of technological developments and within the constraints of safety and affordability. This is understandable from a commercial point of view but it has not been sufficient to generate service robots that can be effective in the domain of elderly care. In order to be effective in this domain, systems need to be tailored to the needs and expectations of its users, elderly and their carers. Moreover tailored functionality needs to become available within these systems to allow customising and personalising them to their intended users. In the ACCOMPANY project the concept of service robotics will be brought into the elderly care domain through:

1. Specification of functionality which answers needs within elderly care and its development and
2. Development of robot behaviour to enhance acceptance and efficiency.

Iterative development: generally research efforts aimed at the development of health robotics start with the technical development based on an assessment of needs from the intended users. After completion of the prototype the outcomes of the evaluation of the system can only seldom be used to improve the system and as a result many only partly developed systems are the result of publicly funded R&D effort [13]. The following sections provide an introduction into different development areas of the project and their progress to-date.

2. Development dimensions

2.1. Identification of users needs based on their experiences

The first area of work focuses on the user requirement analysis & scenario definition. Within this, firstly, needs of independent living elderly people were assessed. Publicly funded care provision to solve these needs was described for four countries, the Netherlands, Italy, UK, and France. Secondly, user panels were formulated in the Netherlands, UK, and France. The user panels included three different types of users: elderly people, informal caregivers and healthcare professionals. Elderly people were selected based on four criteria: 1) aged 60+, 2) living at home (alone or with a partner), 3) no cognitive decline, and 4) receiving some form of care assistance. Informal caregivers (e.g. families, neighbours, volunteers, friends) were at the time of the study taking care of an elderly person or had done so recently. The healthcare professionals were selected based on their activities, with a requirement to intervene at least weekly in the home of an elderly person. Elderly persons and the professional caregivers were both contacted through local care organisations. The informal caregivers were contacted through local care organisations and personal network. The study sample size was intended to account for diversity in the target groups.

The first round of focus group meetings with these panels focused on the needs of elderly people in trying to remain in their homes independently. The metaplan-method [66] was used for the data collection.

The metaplan-method aims at defining different problem dimensions in a moderated discussion amongst group members. The idea is to use the creativity and interaction dynamics of the group members to extract ideas from the group, ideas that single members might not have been aware of before the brainstorming. To create this kind of group dynamics the minimal size of the group should be 4 or more. We used a three-step approach. We started by having each group member write down the issues and specific problems they think are important independently on post-it notes. Second, all these notes were put on a white board and then organised in a discussion by the group members into problem clusters, which were then defined as different problem dimensions. The last step was to rate these problem dimensions, and discuss possible connections between them. Therefore the individual viewpoints as well as the group consensus were taken into account. The focus groups were carried out in sessions with groups of 4-10 participants. Each session was moderated by a researcher, sometimes with the presence of a local partner (coordinator of the healthcare service, geriatrician, psychologist, etc.). After the introduction and signing of the informed consent, participants were given the following questions: "Which problematic activities in the daily life of elderly persons are threatening their independent living?" The duration of the focus groups varied between 1.5 and 2 hours.

A total of 41 elderly persons, 32 informal caregivers, and 40 professional caregivers participated in the Netherlands, UK, and France during this first round. During the recruitment phase, the aims of the project with respect to the use of a robot were explained, however, at the start of the meeting and during the group discussions, it was clearly stated that the subject of this focus group would not be on the use of robots or technology. This first round of focus group meetings made clear that there is no single activity that can be selected as "the activity" causing elderly people to lose their independence. Overall, activities concerning three activity domains (i.e. mobility, self-care, and social activities) were found to be the most problematic. These results are in line with the literature reviewed in [6]. The perspective of the three countries was introduced as there are differences in the way care is provided and the range of activities supported by public care provision. The assumption was that this would significantly differ between countries and was expected to influence the problems experienced and/or reported by the participants. There were some small differences between the three countries: in France the problem concerning the coordination of care was quite prominent, while this was not mentioned in the Netherlands or the United Kingdom. This is the result of the differences between the organisation of care in the three countries. This will mainly influence the business case implementation in a later stage of the project, but not the robot on a functional level as elderly age in much the same way everywhere as they face similar problems resulting from physical and mental decline. A more detailed discussion of the results achieved in the UK focus groups can be found in Lehmann et al. [44]. It is notable that not all the difficulties expressed are inevitably collected as needs, insofar as relevant answers or strategies of adaptation are set up. For example for dressing: the elderly use devices to allow them to slip on stockings or socks more easily. Furthermore, the expression of the same difficulty can have different meanings within the three groups of users. For example, the definition of isolation is diverse: for the elderly it may be a feeling, for the professionals, it may be a lack of coordination and support, and for the informal caregivers, a shortcoming of social policies.

It is important to underline that the lack of prioritisation made in each of the groups, even when it is required and promoted in this type of research, gave rise to certain criticisms from the participants: they first underline the instability and the possibility of evolution of needs. The elderly and the informal caregivers point out in particular that needs are particularly prone to evolve, and thus that the order of the priorities may

change quickly. Some participants therefore refuse to express priorities, because they consider that such a judgment is too unpredictable. Then they point out the variability of care work. The professional caregivers explain that the same tasks can be performed differently with the same person, because they have to adapt to the person's condition, humour or capacities which may vary from day to day. For example, a person can one day be capable of washing his/her face, but not the following day. For the professionals caregivers, the priority is thus less situated at the level of the tasks to be realised than in the necessity to adapt and adjust care from day to day.

Within the ACCOMPANY project a basic fetch-and-carry task was selected (related to the activity domains mobility and self-care within the International Classification of Function) and a preliminary scenario was created. More detailed user feedback concerning this preliminary scenario was required for the formulation of basic system requirements. Therefore a second round of focus groups were conducted in the Netherlands, UK, and France, in which this first preliminary scenario was discussed. The group consisted of elderly persons ($n = 39$), formal caregivers ($n = 44$) and informal caregivers ($n = 24$). In these focus groups meetings the scenario was presented as a series of pictures to the participants (the robot fetching and carrying a bottle of water for the user). Afterwards every picture was discussed in the group. The participants were asked what should be kept in mind when designing a robot for this scenario concerning the topics interaction, sensory/memory, recognition, the environment and daily activities. Questions such as "Where should the robot be?", "What should the robot need to know about the user?", "Do you foresee problems concerning the robot and the interior of your living room?", "What could be problematic?", "What do you like/dislike?", and "How should the robot act in [a given] situation?" were example questions asked. All these resulted in comments that were gathered and translated into user requirements. This led to a total of 68 user requirements concerning, amongst others, the execution of the task, visitors, robot behaviour, and additional robot functionalities. There were some conflicting requirements: e.g. care professionals in France and informal carers in the UK preferred not to have a camera in the house, while elderly in the UK liked the idea of a camera for monitoring and for cases when images could be save once something out of ordinary happened. These conflicts were resolved by considering functionality so for example we made sure that cameras are used as sensors and images will not be made available to other parties so that concerns on privacy could be addressed. It is also important to note that tension between ethical values such as safety versus privacy could be considered by considering cameras in the project scenarios (see section 2.6.3). From here a more elaborated scenario (see section 2.5.3) was developed in which various roles of the robot were outlined for evaluation in smart homes in Netherlands, UK and France. In the first sub-scenario of this more elaborated scenario, 17 of the 68 requirements are implemented, and in the second and third sub-scenarios 20 requirements are implemented.

2.1.1. Exploring roles and expectations for robots in elderly assistance

To supplement the requirements analysis as described in 2.1 and to understand people's expectations of and attitudes toward robots in care-taking or re-enablement roles, an interview study was carried out [39]. The goal of the present study was to describe and understand the daily life of independent living elderly people, as well as their interests, hopes and dreams. We aimed to identify their needs for support and roles people and technology currently play in their lives to eventually help them maintain their independence. Contextual analysis is a qualitative approach to collect rich context data that is relevant to a small set of representative participants in order to gain a deep understanding into the relationships between important factors

in people's daily lives [39]. Seven elderly persons from a city near Madrid, Spain, participated in in-depth interviews carried out in-situ, in their homes. The results from the qualitative data analysis indicated a great variability in the coping capacity of the participants. Feelings of loneliness and lack of motivation appeared as common burdens in their lives. Robot roles were proposed that could help fulfil the needs of independent elderly people. Self-efficacy and other related constructs were identified to have an influence on older people's motivations and their predisposition to disability. Finally, a "motivational" robot role was proposed that could enhance the self-efficacy of independent elderly in physical therapy contexts, hence decreasing their risk of losing independence.

Appropriate behaviours for robots in context

Elderly people in the ACCOMPANY project are envisioned to receive assistance and support from robots in a limited set of roles. We want to understand what happens when robots take on different roles in the homes of elderly people. We base this question on the premise that robots in different roles will be expected to display different behaviours. For instance a coach is expected to behave differently compared with a cleaner. In order to successfully design robot behaviours in order to optimise acceptance of ACCOMPANY robots, we investigate people's responses to robots in specific tasks and roles. We expect that people have an expectation of the robot and that they perceive robots to have certain personalities, based on their behaviours. Previous research has found support for two contradicting theories: similarity attraction and complementary attraction. The similarity attraction theory [38] implies that people prefer a robot with a similar personality to their own (e.g., an extroverted person prefers an extroverted robot). According to the complementary attraction theory [38], people prefer a robot's personality opposite to their own (e.g., extroverted people prefer an introverted robot). In contrast to both theories, we argue that what is considered an appropriate personality for a robot depends on the task context. We investigated this assumption in a controlled laboratory study [72]. In a 2x2 between-groups experiment ($N = 45$), we found trends that indicated similarity attraction for extrovert participants when the robot was a tour guide and complementary attraction for introverted participants when the robot was a cleaner. These trends show that preferences for robot personalities may indeed depend on the context of the robot's role and the stereotype perceptions people hold for certain jobs. Robot behaviours likely need to be adapted not in complimentary or similarity to the users' personality but to the users' expectations about what kind of personality and behaviours are consistent with such a task or role. In the ACCOMPANY project the roles of co-learner or butler are considered. Because our findings indicate that people may hold stereotypical expectations of behaviours for particular task-contexts, we will carry out further studies to understand which behaviours are deemed most appropriate and acceptable for ACCOMPANY robot roles.

2.2. Social & empathic interaction design

An aspect of our developments pivots around social and empathic behaviour in interaction between people and their technologies, here more specifically about elderly people and the Care-O-Bot in the smart home. We address empathy as it is considered to be a "key component of social interaction" [36] in which it functions as a primal level of interpersonal interaction whereby signals from one person are picked up by one another [46]. This interpersonal sharing of context is constructed of cognitive as well as affective aspects. The aim of our work is to explore several modi operandi in which empathic relationships between elderly people and the robot can be constituted and developed targeting primarily the emotional capabilities of the elderly people.

Our work is highly informed by philosophical perspectives derived from Gibsonian Ecological Psychology [26] and Merleau-Pontian Phenomenology of Perception [48] as well as a designy stance in which the human experience and the bodily capabilities are to be addressed as a whole in respectful manner [55]. Therefore, empathy is not considered as result of internal judgment or merely cognitive activity. We consider empathy to be a social product emerging dynamically as an outcome of the interaction whereby actions and perception of people synergise with one another. The reciprocal meaning emerges in interaction, by direct experience in the world.

In our approach, we take the human capabilities as central to achieving an empathic relationship. We aim at mapping the continuities of our being to the discreteness of machine. With this we mean that the way people are in the world is of continuous nature contrary to the discrete way machines are engineered. In order to reach people's emotional skills, the skills that concern how we feel and develop empathic relationships, interaction should be of continuous and of expressive quality matching these skills. As the meaning emerges in direct interaction with the surrounding, in a Gibsonian and Merleau-Pontian way, the design should further be context-dependent and pay attention to the elderly persons unique experience more than predefining and generalising in accordance with the phenomenological stance. [73].

In the design process we take a Research-through-Design approach which is grounded in Donald Schön's Reflective Practitioner [67]. Through confronting elderly people with low and high fidelity prototypes that embody our vision we further develop the concepts throughout several iterations towards the intended goal of achieving an empathic relationship between elderly and robot. Empathy is explored and applied in several elements of the Care-O-Bot. The intuitive mappings are further extended with a moody interaction: in case the elderly person makes the robot run around like a mad assistant, the Care-O-Bot will start to behave in ignoring manner to send across the message that this attitude of the elderly person is not appreciated. The objective is not to create anthropomorphic characters per se, but this moody interaction does evoke behaviour that does not get boring in the first place and secondly becomes a subjective part of the context; ready to grow an empathic behaviour with. The moody interaction aims to build an understanding of 'feelings' and invites the person to change his/her behaviour towards the robot in order to live in harmony together.

The first element is the graphical user interface (on a remote tablet) that is intended to mediate the capabilities of the robot in the given context. With our graphical user interface the elderly person gets access to high-level functions of the robot such as 'cleaning the table', 'making coffee', 'turning off the light' and so forth. These functions are presented in order of contextual relevance. This means that the smart environment of the Care-O-Bot assesses a likelihood of whether it is possible (in the physical world) and desired (by the elderly person). Concretely, this means that the graphical user interface will not present the function of 'cleaning the table' while the table is clean and will not present the function to 'make a coffee with sugar' while the system assesses the elderly person likes his coffee black. The size of the functions, shown and clickable on the tablet, is mapped to the likelihood; if 'turning on the light' is more relevant than 'closing the curtain' the function will be shown bigger and thereby made more accessible for the elderly person. This likelihood is further used make the Care-O-Bot take initiative. In case the likelihood of thirst (and the availability of clean glasses and water) exceeds an urgent threshold, the Care-O-Bot will propose or even perform to supplying the elderly person of a much-needed drink. Our design for interaction provides ground for empathic relations to emerge. The Care-O-Bot and elderly person immerse in a common understanding of their specific context because of the interaction being shared. The higher-level assisting and collaborative functions of the Care-O-Bot are empowered in the graphical user interface through

contextual-personalisation. The elderly person is enabled to see what the Care-O-Bot can do in the given context. The "Squeeze Me" and "Call Me" are prototyped interaction devices that enable the elderly person to get attention from the robot, simply to make the robot come closer in order to start a more elaborate interaction towards higher-level assisting or collaborative functions desired. The way of asking for attention results in a coherent approach in terms of movement qualities of the robot towards the user to assist [70]. In case of the Squeeze Me, the tablet can be squeezed. If it is squeezed roughly; the Care-O-Bot will approach in a hurry while a small pinch will make the robot come in calm though attentive manner. Similar mappings directed by the Interaction Frogger Framework [69] to create intuitive interactions are applied in the Call Me which controls the movement by expressions in the sound. The intuitive mappings are further extended with a moody interaction: in case the elderly person makes the robot run around like a mad assistant, the Care-O-Bot will start to behave in ignoring manner to send across the message that this attitude of the elderly person is not appreciated. This aims to build an understanding of feelings and invites the person to change its behaviour towards the robot in order to live in harmony together.

The graphical user interface can also function as a 'window to the soul of the robot'. The elderly person can look through the eyes of the robot as a different mode next to the normal context depending appearance of functions or action possibilities. While the seeing through the eyes view is taken, the person can see what the robot is seeing and further see on top of the objects in the environment see the related action possibilities. This view-through-the-eyes interface further explores expressive 'feelings' that the robot can have [71]. 'Feelings' constituted by the internal properties of the Care-O-Bot such as battery level and external properties such as environment temperature or lighting that disturbs vision or the way the user addresses the robot (in rude or polite manner as explored in the moody interaction). The feelings of the Care-O-Bot are expressed via a shape-changing mask and graphical filters such as blur, saturation and opacity that will address the emotional skills of the elderly person. A first evaluation was conducted comparing four scenarios of interaction between a robot and a person at home [56]. The scenarios depicted scenes where the robot was asked to execute tasks. Each scenario was showed in two versions: with a static robot-view and with a dynamic, expressive/empathic robot-view. The results of a questionnaire administered to 60 persons showed a preference of people to interact with the empathic mask. Expressivity was a means to stimulate empathic concern and to facilitate perspective taking during the execution of the scenarios.

2.2.1. Improvements to social acceptance using context awareness

To improve users' social acceptance of the Care-O-bot, a context-aware planner for the generation of robot's social behaviours [42] is currently under development.

The initial stage of the technical work involves development of a knowledge-driven rule-based user activity recognition system [18] that can derive a user's activity of daily living based on data from the sensor networks embedded in the environment (i.e. geo System [54] - real-time energy consumption monitoring system for electrical devices, and Zigbee Sensor Network [52] - for detecting non-electrical devices such as opening and closing of drawers and door, occupation of chairs, opening of cold and hot water taps etc.) Our approach is different from object-use based activity recognition systems [50, 57, 82] that used RFID-based sensor modalities, which require the user to wear RFID bracelets on their hands. The knowledge-driven rule-based activity recognition system used [18] has three main advantages over learning based methods [17, 68] that 1) it does not require large variety of datasets (which are difficult to obtain from our target group of elderly

people), 2) rules defining each activity can easily be adapted to similar environments (i.e. through sensor remapping), and 3) rule definitions for new user activities can be easily created. This system is very similar to other knowledge-based methods [3, 34, 59].

Current work focuses on improving the Care-O-bot's proxemic behaviour when approaching the user for interaction. Literature has indicated the importance of proxemics in human-human interactions [1, 32, 58] as well as in human-robot interactions [41, 74, 78–80]. Findings from the human-robot interactions literature has also indicated that users' proxemic preferences vary depending on the robot's appearance, context of interaction as well as their robot experience and familiarity with the specific robot they are interacting with. Therefore we believe by using contextual information retrieved from the sensory information embedded in the environment [18], the Care-O-bot can improve and adapt its proxemic behaviours (adapt its approach distances and orientation) over time, taking account of the interaction task (e.g. activity, location, role), the user's context (e.g. activity, location, preference, social situation) and context history, hence improving its social acceptance. Development of the Care-O-bot's proxemic behaviours involved developing proxemic algorithms based on the literature and then further fine tuning of the algorithms for the Care-O-bot. User studies will be conducted to understand and verify participants' responses and preferences to the Care-O-bot proxemic behaviours.

2.3. Robot learning and adaptive Interaction

Eldercare presents many challenges, both technical and social, which a care robot will have to address. The concepts of co-learning and re-ablement are two such challenges which encompass both the technical and the social. The first concept, that of co-learning extends the ideas of learning, and is outlined by the UK Department of Health as follows: *"Services for people with poor physical or mental health to help them accommodate their illness by learning or re-learning the skills necessary for daily living"*, UK Department of Health's Care Services Efficiency Delivery [15]

Within the ACCOMPANY project we interpret this ideas as being that the person and the robot work together to achieve a particular goal. Often the robot will provide help and assistance, however, we envisage that the robot will never be fully pre-programmed with the ever changing requirements of the user, and therefore in return the robot also requires help and assistance. This implies that the end user must provide, via the robot, directions which would support their own changing needs. Co-learning would operate with the robot assisting the user by informing the person that it has particular capabilities which may prove fruitful (or indeed that it already knows how to address this particular problem) but the user may provide the necessary cognitive scaffolding to ensure these capabilities are used effectively. A first instantiation of these ideas exist in the 'sequencer' and 'teach me, show me' user interfaces described below. The second concept, re-ablement, is defined as follows:

"Support people 'to do' rather than 'doing to / for people' ", Welsh Social Services Improvement Agency [60]

Rather than a robot always providing direct solutions and support, the idea of re-ablement suggests that the robot should actually promote 'activity' in the person via interaction, and this interaction should be empathic and socially acceptable to the user. E.g. the robot, rather than always offering service solutions, which may inadvertently encourage immobility or passivity in the user, should instead re-able the user by making motivating suggestions or giving alternative strategies which encourage the user to be more active. This should provoke the user to find a solution by themselves or alternatively to find a solution cooperatively with the robot (for a complimentary approach using decision theoretic approaches see [9]). Thus the robot could prompt the user to

carry out tasks, for example: taking a walk in the garden if the weather is warm, writing a greeting card after reminding the user of a relative's birthday, or bring relevant events to the user's attention and suggest to the user an activity in order to avoid social isolation.

Realistic goals of this research include the integration of the sensorised house and the behaviour generation capabilities for the robot, both of which present many challenges. To date both of these goals have been achieved, with the latter proceeding in three stages. Firstly a semi-technical facility of teaching the robot new behaviours based on sensory and abstract events occurring in the house. This facility we envisage being used by semi-technical personnel when setting up the initial environment (this is the 'sequencer' shown in Figure 1). Secondly, a teaching facility for the elderly, carers and relatives which hides much of the technical complexity and displays an easy to use interface for creating behaviours. This is the 'teach me' part of the 'Teach me - Show me' interface shown in Figure 3). Both of these interfaces have been completed and used in our evaluation scenarios. The final part, the 'Show Me' part of the interface is currently under development. The aim here is to allow the user to demonstrate to the robot what needs to be achieved. This will typically be carried via teleoperation of the robot itself in conjunction with sensory feedback from the house. Our approach is based on our preceding research using information theoretic techniques to combine robot actions and ongoing sensory inputs (see [65] [49]).

Our research assumes the robot forms part of an integrated home environment. This means that the users living accommodation is 'fully sensorised' i.e. a 'smart home' environment containing real-time sensory information from many sources, such as electrical appliances, occupancy of beds, sofas, chairs, user location tracking, water flow sensing for bathrooms and kitchens etc. Our first challenge to support the ideas outlined above was the disciplined integration of the smart home sensors, the sensory capabilities of the robot itself, and the social memory aspects from the user, into a common framework. Procedural mechanisms were implemented which allowed activities within the house at both a sensory level and a more abstract contextual level to be amalgamated as rules or preconditions to create robot behaviours and to apply temporal constraints where necessary to such rules. We also required facilities to invoke actions on the robot, at both a primitive/actuator level or a more distant abstract level. And, in order to support co-learning, flexibility in behaviour creation and scheduling. Given that our robot may be asked to carry out a large number of tasks, which may not be originally envisaged by the system designer, a flexible and 'easy to use' way of creating robot behaviours together with a mechanism for effectively scheduling such behaviours was required. Our goal was to make such facilities available to non-technical personnel such as the elderly persons themselves, carers or relatives. The underlying ideas for the approach are based both on 'behaviour based' approaches and 'deliberative' architectures [2, 21, 53, 81]. The learning approach is based on previous work described here [65].

The learning architecture was implemented following an analysis of the various robot components, user needs via scenario conceptualisation [44] and an analysis of the robot house ontology. This analysis led to a design for a centralised relational database which formed the central memory hub and overall ontology for both the robot, the house sensory network and the users. Additionally the database has been designed to support the procedural and behavioural components for the robot including behavioural rules, actions, goals and pre- and post- conditions. These behavioural components encompass both physical and social behaviours on the robot. For example, a behaviour might be to wake the user up if they sleep too long, alert them if there are problems in the house (e.g. fridge door left open), remind the user to take their medicine, suggest they watch TV, remind the user of upcoming birthdays, suggest they both play a game of chess or suggest they

chat to their friends or relatives etc. To achieve the twin goals of co-learning and re-ablement, facilities with ever increasing behavioural abstraction were designed to allow non-technical persons to implement robot behaviours and form the first stage in generating autonomous behaviour in the robot. These abstractions range from the automatic generation of python programs, to detailed scripting without programming (via a GUI), to a higher level rule generation processes exploiting existing robot behaviours. Three main components deal with robot behaviours, firstly, the *sequencer* (Fig. 1), which allows rules based on the robot, house sensors, users and goals to be connected to robot actions to create behavioural units. Secondly, these behavioural units can then be scheduled to run using a priority based arbitration mechanism called the *scheduler* (Fig. 2). Thirdly, a facility to allow end users to create behaviours directly, hiding away many of the underlying logical conditions, called the *teach me, show me* (Fig. 3) interface.

The robot memory, as described above, can contain not only items related both to real-world items and events but also hold ideas related to social relationships and activities such as friend lists, images, cultural interests (e.g. chess, opera, bingo). Polling of such semantic memory can yield behaviours for execution. For example, polling an activities list and finding 'gardening' as an activity would create a behaviour with the appropriate sensory conditions for its subsequent execution e.g. if the 'weather is warm' and it is 'during the day'. When these conditions are met the robot might suggest that the user does some gardening. This is the strategy by which re-ablement is crystallised.

An implementation of memory visualisation and narrative has also been implemented into the overall memory architecture of the robot. The facility allows users and others (carers, relatives) to review the behaviours of the robot both visually and through a temporal narrative of behaviour execution. We believe that such a facility will benefit users by allowing review of past events, allow exploitation of the robot by learning from previous experiences, aiding socialisation between users and carers, and serving as a memory prosthetic.

2.4. Environment and activity monitoring

Environment and activity monitoring is a very important aspect in robot assisted-living scenarios. A good modeling of the environment and human activities is a prerequisite for object manipulation, robot navigation and human-robot interaction.

Our monitoring system embraces three tasks: a) data fusion for object detection and identification, b) data fusion for human detection, tracking and identification, c) human posture recognition. The system incorporates multiple types of sensors, including robot on-board sensors (i.e. cameras and laser range finder on the robot) as well as the ambient sensors (i.e. cameras on the ceiling and other simple sensors such as switches on the kitchen cabinets, pressure mats on the seats). Data from different types of sensors are fused to ensure the state of both the objects and people are estimated accurately. Next we introduce our data fusion approaches applied in the three tasks.

2.4.1. Fusion of camera data on the robot

The first task concerns the fusion of data from the robot itself for object detection and identification. The Care-O-Bot has a powerful sensing head with two colour cameras used for stereoscopic vision and one time-of-flight sensor that directly delivers 2.5D range data. A challenge is to combine both modalities to create accurate 3D point clouds with associated colour information even in unstructured image areas. In general, there are two kinds of approaches towards this goal: global methods [31, 83], which state smoothness constraints over all measurements and solve a global optimization problem, and local methods, which select the optimal depth estimate based on the local matching

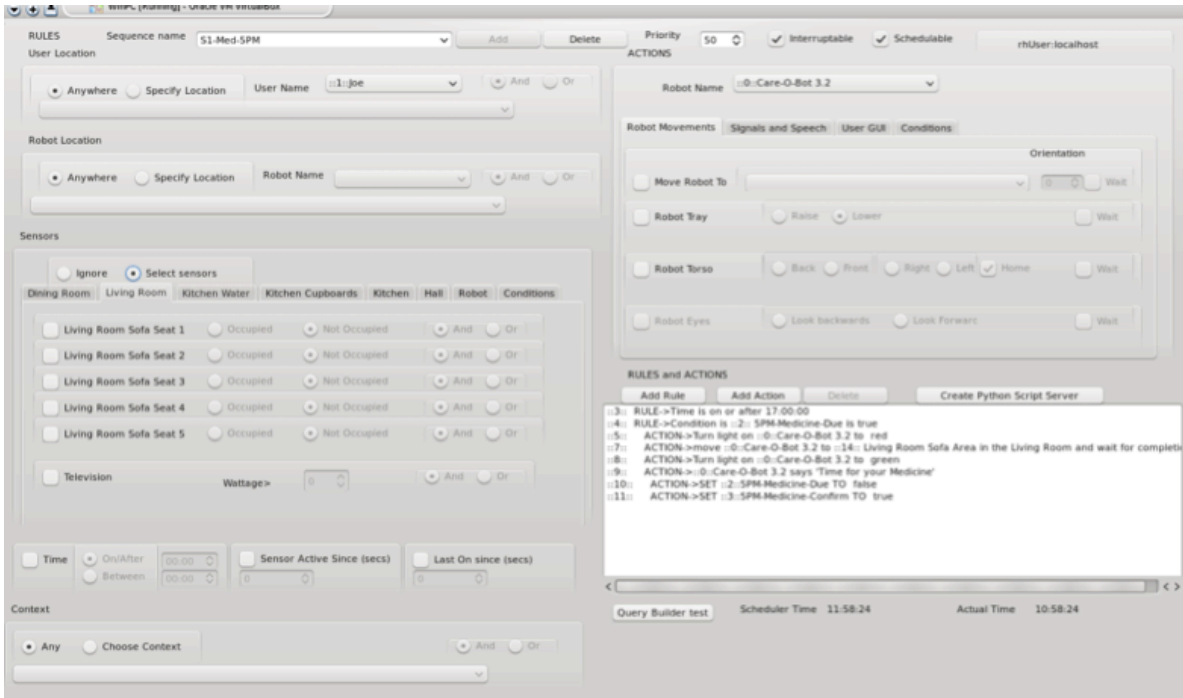


Figure 1. The Sequencer allows behaviour and sequence generation between rule sets based on the robot house ontology and actions to be carried out the robot. Rules can be generated based on user, robot, context, sensors, goals or conditions. Actions on the robot can be physical, sensory (light/speech), virtual (setting new conditions/goals) or user generated via calls to the users tablet computer. The interface also allows direct creation of python programs to control the robot directly.

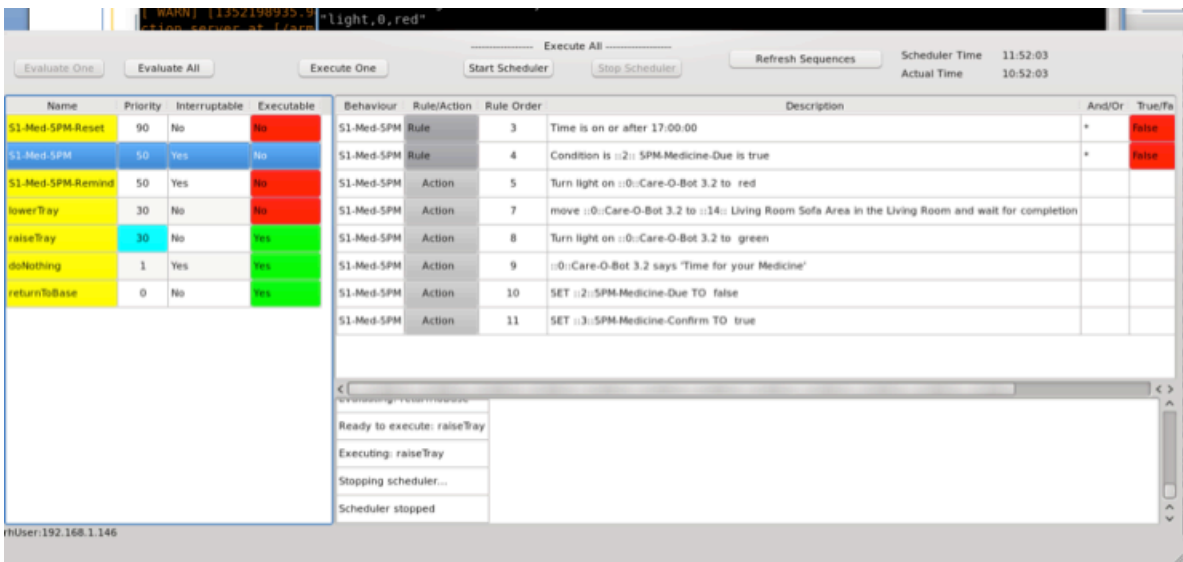


Figure 2. The Scheduler. This is a priority based arbitration scheduler. Each behaviour/sequence is show (in yellow). Currently executing sequence in shown in Blue. Available behaviours are shown in green. The rule/action sets per behaviour are shown on the right.

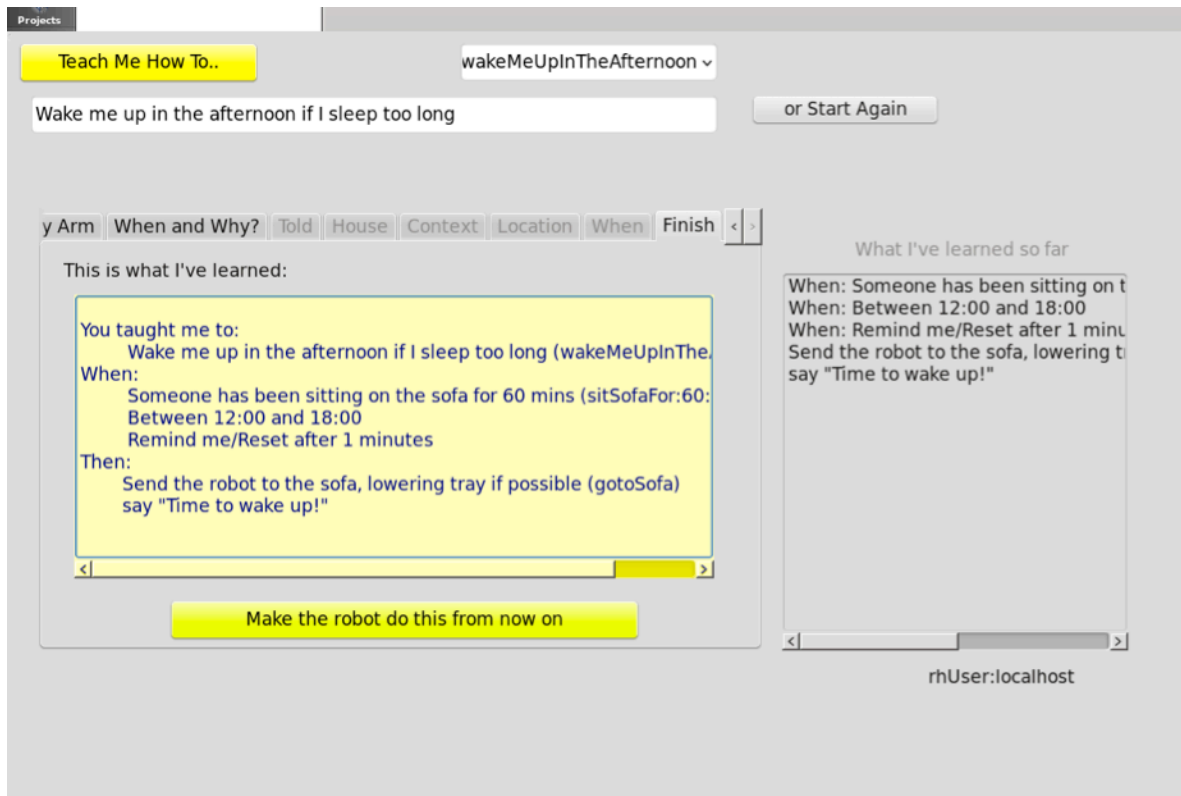


Figure 3. The TeachMe-ShowMe interface (only one screen shown) is a more abstract version of the 'sequencer'. The user exploits existing behaviours to create and scaffold new competencies on the robot. Behind the scenes the necessary supporting software and behavioural/logical pre and post conditions are generated automatically.

costs [30, 51]. Global methods are usually slow in computation (order of seconds and more) but very accurate whereas local methods compute fast while producing inaccurate and blocky depth estimates. The proposed method [23] is novel in the sense that it uses semi-global optimization for fusing the depth estimates from stereo vision and a depth sensor to yield accurate depth maps with a speed of 10 Hz on a Intel i7-2860QM with 2.5 GHz. In particular, it first undistorts and rectifies the colour and range images. The projected time-of-flight measurements serve as a first guess for the disparity computation from the rectified stereo images. A cost function is developed that compares the depth estimates from block matching in stereo and the time-of-flight estimate. The optimization is then solved in a semi-global fashion along 16 1D paths in the neighborhood of each pixel. After thresholding and filtering a final depth image is created that is more dense than the stereo-only estimate yet highly accurate, as is shown in Figure 5. The improved depth measurements are necessary to achieve accurate results with the object recognition system that is described next.

2.4.2. Object recognition and categorisation

Care-O-bot needs to perceive objects in its environment in order to fulfil useful tasks on them and to display appropriate action possibilities on the user interface device. In ACCOMPANY, we approach the perception task along two avenues, namely the recognition of previously seen

and modeled objects [22] as well as the class recognition of previously unseen objects [10, 11].

The recognition of objects is based on previously learned models that comprise texture information of outstanding feature points with the 3D location of their occurrence on the object. The model learning step requires the object to be placed on a rotary table with attached sensors for model capture or in the gripper of the robot. In both cases, the object is turned so that it can be recorded from different perspectives. From each perspective, a set of distinctive feature points and descriptors is detected and inserted into a consistent 3D model of the object at hand, which is eventually improved in accuracy by bundle adjustment optimisation. The robot stores all known object models in its internal storage. The modelling pipeline is state-of-the-art and only differs from other work in the choice of certain algorithms; e.g. it employs bundle adjustment for model optimisation instead of a Kalman filter in combination with an ICP variant and RanSac [43] and the utilised feature descriptor is a novel, scale-invariant extension sORB [22] of the ORB descriptor [62]. The recognition of learned objects in captured scenes proceeds by the computation of feature points and their descriptors all over the image and by the search for object models that fit clusters of the found feature points in their texture and 3D arrangement. The recognition method operates on data from a single perspective and is suitable for detecting objects with occlusions and multiple occurrences in highly cluttered scenes. An exemplary detection result is

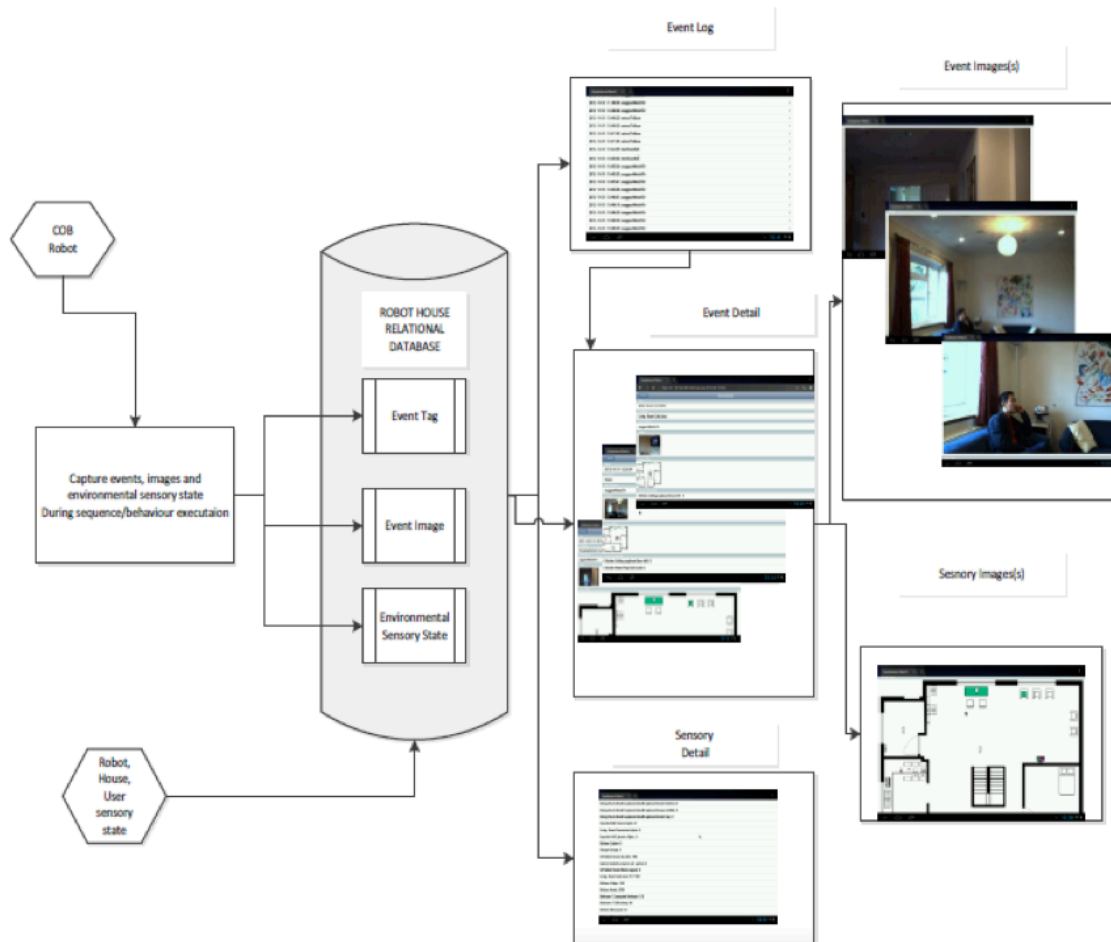


Figure 4. The memory visualisation and narrative system integrated into the overall memory architecture.

displayed in Fig. 6. Similarly to modelling, the recognition pipeline follows the state-of-the-art procedure differing in details like the used feature descriptor or the matching procedure. Whereas other approaches use Bayesian filtering together with 3D SIFT features [29] or Markov Random Fields to hierarchically encode the spatial arrangement of features [16], which have high storage demands and suffer from a time-consuming inference procedure on recognition, the proposed system applies a confidence-guided matching procedure on fast sORB features that considers spatial constraints and which computes very accurate matches at a rate of 1 Hz.

Although there is a set of very important objects of which the robot might obtain appearance models, it remains impossible to model every single object in a household. To enable the robot to interpret unmodelled objects anyways, we employ an algorithm for class recognition of unknown objects. Today's approaches for object categorisation in the robotics domain commonly assume that objects are placed on a planar surface and segment a recorded point cloud of the scene into

several potential objects [8, 47, 64] and so does the present approach that models object classes with the novel SAP descriptor [10, 11] which encodes the shape of their surface. However, the SAP descriptor is different from Global Fast Point Feature Histograms (GFPFH) [64], Global Radius-based Surface Descriptors (GRSD) [47] and Viewpoint Feature Histograms (VFH) [63] insofar as it neither relies on normal computations nor on local feature representations. Instead, the SAP descriptor is constructed directly in a global fashion on the point cloud data and hence the data preparation and normal computation can be avoided resulting in a faster computation time of 72 ms in contrast to 93-957 ms in case of the other methods. Moreover, the SAP descriptor achieves a 11.5%-25.5% better categorisation rate on categorising 151 objects into 14 classes. Specifically, the SAP descriptor orients the surface of the object in a repeatable way, first, and cuts it with several planes perpendicular to the camera plane. The geometry of the surface cuts is then approximated by a polynomial function whose parameters are stored as the descriptor besides general size information on the ob-

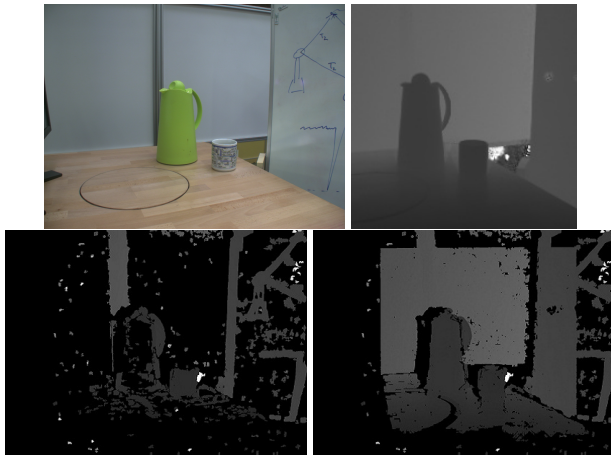


Figure 5. Original recordings of the left color camera (top left) and the time-of-flight sensor (top right) as well as disparity maps obtained from stereo vision (bottom left) and from sensor fusion with time-of-flight data propagation (bottom right).

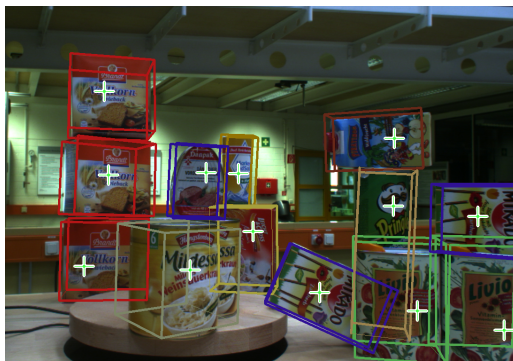


Figure 6. Exemplary result for object recognition (unique colour and bounding box for each object).

ject. It is sufficient to present a couple of training objects of a certain class to the robot to model that class with a statistical machine learning method using this kind of descriptor. Scene analysis for present objects proceeds by segmenting objects from the point cloud with Euclidean clustering and by the computation of a SAP descriptor for each object cluster. The machine learning procedure then determines the respective class for each descriptor. Some examples for object class recognition are provided in Fig. 7.

2.4.3. Human localisation

The second task focuses on robust localisation of humans. We developed a Bayesian framework for fusion of data between a fish-eye camera mounted on the ceiling and the laser range scanner mounted on the robot. The camera system is based on our earlier work for people detection [19], where we match a human template with the foreground blobs, and the persons are found at the local peaks of match-



Figure 7. Exemplary result for object categorisation.

ing scores. For the laser range finder, we also use a template based approach in combination with a probabilistic background model. We learn a probabilistic occupancy grid for the background objects as well as the appearance of human legs in the laser data. For each possible human location in the grid map, we combine the leg model with the background model, and we evaluate the probability of a person at each location based on the observed laser data points (see Figure 8). We apply a particle-based sampling method for fusion of the two types of sensor data. After persons are localised with the single camera, particles are sampled around the location of the persons with a Normal distribution. These particles are then weighted by the likelihood of the laser observations. The final detection is computed by the weighted sum of the particles that are sampled from the same person [37]. The next paragraph explains how we enable the robot for person-specific behaviours by attaching names to the localised people.

2.4.4. Person identification

For identifying the localised persons, the cameras mounted on Care-O-bot's head are used because they have a better perspective on people's faces. The identification module is based on data fusion between the time-of-flight sensor and a colour camera as well. The depth image is exploited to detect heads in the range of sight of the robot and those regions are inspected in the colour image for the appearance of faces [24]. In both cases a Viola-Jones detector [77] is utilized to detect heads in the range image and faces in the colour image. All detected faces are analysed by an identification module based on Fish-

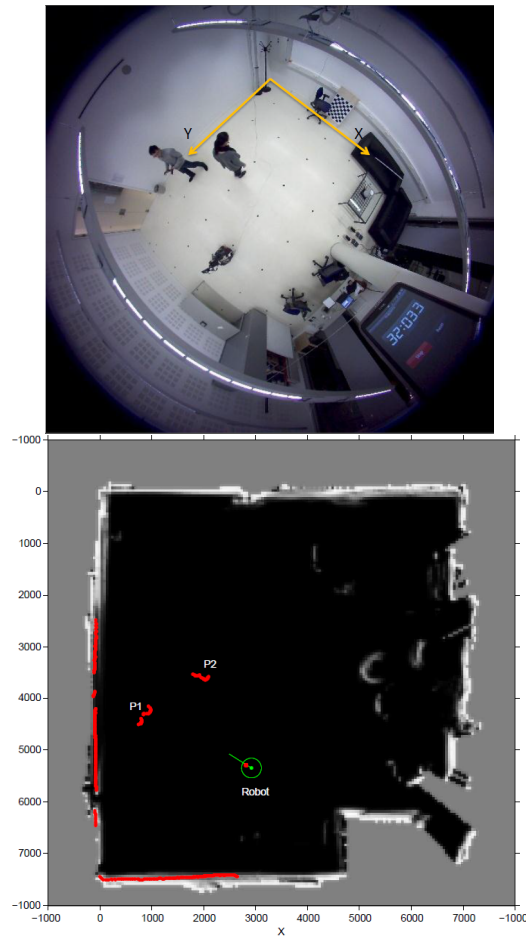


Figure 8. An overview of data that are used in our data fusion system. The top graph shows an image frame captured by the overhead camera, where the yellow arrows indicate the direction of X and Y axis in the world coordinate system. The bottom graph shows a pre-computed probabilistic background map of the same area (in grey scale). The green circular marker indicates the location and the orientation of the robot. The red dots are the laser detection points in world coordinates. We show that the two persons (P1 and P2) in the camera image are also detected by the laser scanner. In our system, the two data source are fused to jointly estimate human locations.

erfaces [7] that asserts the name of the found person if the person is in the database of known people or tells that the person is new to the robot. To increase the robustness of face recognition, each face is pre-processed by gamma correction [27] and discarding the low-frequency Discrete Cosine Transform coefficients [14] to decrease the sensitivity against different lighting and shadows. Furthermore, the head orientation is determined by finding the eyes and the nose, and then a virtual frontal perspective is computed for each face. This measure limits errors originating from faces that are poorly aligned with the camera. Eventually, the recognised faces are accumulated over time using a Hidden Markov Model that filters sporadic misclassifications. The data association between two consecutive frames is driven by spatial proximity and similarity of predicted labels. Figure 9 summarises the three

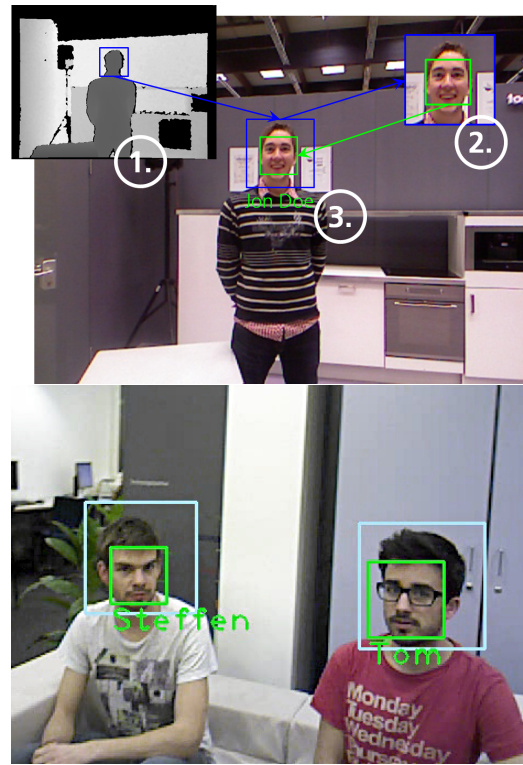


Figure 9. Person identification in three steps: 1. detection of a head in the depth image (blue frame), 2. detection of a face in the color image (green frame), and 3. the identification of the face.

stages for human identification and shows another example of the person identification module in operation. The whole person detection and identification system is a collection of the mentioned state-of-the-art methods selected, put together, and extended with having the special constraints of robotics in mind, such as limited computation time, robustness against pose and illumination variations, or limited control on training data [12]. Other systems for face detection base upon a single modality like colour image data [40, 45] or depth images [35] whereas the present system combines both for an increased robustness against false alarms at a very high detection rate and a fast runtime of 5 Hz. The implemented face recognition method belongs to the class of projection-based methods like the worse performing Eigenfaces [75]. We present extensive experimental proof in [10] that Fish-erfaces achieve a high recognition rate at a low computational load in conjunction with the discussed preprocessing steps regarding illumination and face alignment. Generative approaches that aim to model the illumination cone [5, 25] to reduce the effect of varying illumination instead are not well-suited for robotics as the training data has to be captured under very specific lighting conditions that cannot be arranged in realistic situations.

As the robot is localized in its environment and because the ceiling cameras are calibrated against the same map, it is possible to fuse the information from person tracking and person identification simply via map coordinates yielding trajectories of person movements that are labelled with the person's name. Consequently, persons that have been

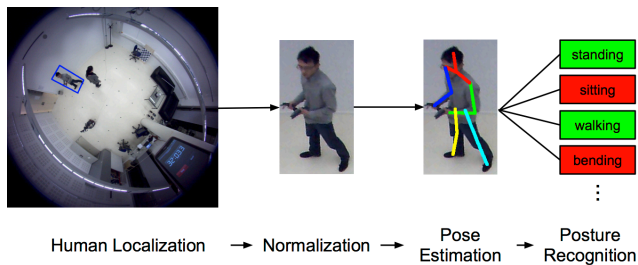


Figure 10. An overview of the posture recognition system. After the humans are detected by the second task, we project the 3D location back to the image space, and we generate the bounding box of the human based on the template. All human images are then rotated to the upright orientation. Pose estimation is applied to generate a set of body part locations in together with a confidence value. Human postures are recognised by classifying on these confidence values instead of body part locations.

identified once with the robot's cameras keep their name tag even when they are not visible to the robot anymore since the human tracking system assigns the name to a unique tracked person. Amongst others, this enables the robot to find a target person in the house quicker than by random search and facilitates activity monitoring for individual users.

2.4.5. Human posture recognition

Our third task is to recognise human postures using the overhead camera. Recognising human postures is important as it provides frame-based evidence for inferring human activities. In our work, we apply a posture recognition approach to assign human posture labels per image frame using the overhead camera. Based on the scenarios, we recognise the postures including people standing, sitting, bending, walking, stretching and pointing. The challenges of the task comes from the the top-view attribute of the camera. The reason for adopting overhead cameras is that in this way a good overview of the overall environment is given, and there are less inter-person occlusions compared with the robot-mounted cameras. However, the overhead camera do suffer from severe self-occlusion. Posture estimation based on body part detection will fail in this case. To deal with that, we trained *pose descriptors* to characterise the human poses. A pose descriptor provides a mapping from image features to the pose categories. For the classification of posture labels we use the confidence values of the descriptors rather than applying on the body part locations directly. (see Figure 10). Our next step is to apply temporal inference for human activities based on the frame-based posture recognition.

2.5. Integration and showcase

Another area of work relates to integrating all components developed so far, to ensure that the robotic platform meets all interface requirements for the developed components and all functionality required in the scenarios. This includes in particular also adaption to the existing software architecture based on the ROS open-source framework as well as software components and to a certain extent also hardware components. Furthermore this activity coordinates the implementation of the scenarios within the different integration phases and the final showcase. In the following, the methodology for swift integration is described, as well as the adaptation of the robot and the smart home environment, and the contents of the first integrated user scenario that was derived from the requirements input of the user panels.

2.5.1. Integration workflow

Thinking early about integration is the key to lead a robotics project with multiple partners to success. A good start in ACCOMPANY was to formulate project goals and present all project partners with the current status of hardware and software right at the beginning. Consequently, necessary hardware modifications could be identified immediately, as detailed in Section 2.5.2. Furthermore, apart from the available software modules a list of required functionalities was established quickly. Dividing functionalities into self-contained software modules allowed to distribute necessary development work suitably among the project partners. To simplify the later integration of software modules developed by numerous people it has proven very valuable to define clear interfaces between modules at an early project stage. Using the robot operating system ROS as common middleware, which offers a couple of standardised ways for communication with a large set of defined message types, supported the early definition of communication channels between software modules further. Consequently, the experiences from integrating the first scenario showed that many components in ACCOMPANY could work together quickly because of the preparation ahead.

As the project proceeds with more sophisticated scenarios for the second and third year many components will have to mature with more elaborate functionalities or algorithms. To implement new functions in an ordered manner without harming the whole system to fail the following integration process, developed from the experiences in a German research project with many partners integrating their components into one common demonstrator [61], has been adopted in ACCOMPANY. It bases upon an iterative development process, but is distinguished by the separation of component development and application development (see Fig. 11). The component development phase starts with the adaptation of the (partially existing) components according to the application requirements. After successful execution of component tests (on partner level in each work package), the component is tested by the system integrator in the whole system context. If the component is approved, a new release is generated that now can be used by the application developers. This procedure prevents a mixture of component and application development, where often application tests fail because of insufficiently tested and erroneous components.

For the implementation of the scenario, a simulation environment of the robot house has been generated (see Fig. 12), such that the distributed partners could individually pursue their component and integration tests even if they did not have access to a real robot.

2.5.2. Hardware modifications

In the beginning of the reporting period, the project demonstrator, Care-O-bot 3 was introduced to all project partners to collect the requirements for hardware adaptations of the current demonstrator. One major result from the requirement analyses was that the fixed height of the tray would pose problems to sitting persons and persons in a wheelchair. In particular, the integrated touchscreen was not found intuitive as human-robot interface, as the touchscreen served at the same time as tray to place objects on. As a result from this a new kinematics for the tray manipulator was developed that allows for a higher flexibility of tray positioning and separates the user input from object placement through the usage of both sides of the tray: One side contains the user interface in form of a tablet pc that can be removed, and the other side provides space for object placement along with sensors to detect if the space is empty or occupied (see Fig. 13). The new kinematics of the tray manipulator has now 3 degrees of freedom compared to only one in the original solution. This kinematics allows e.g. for adjusting the height of the tray for object handover, or to tilt the tray in order to re-

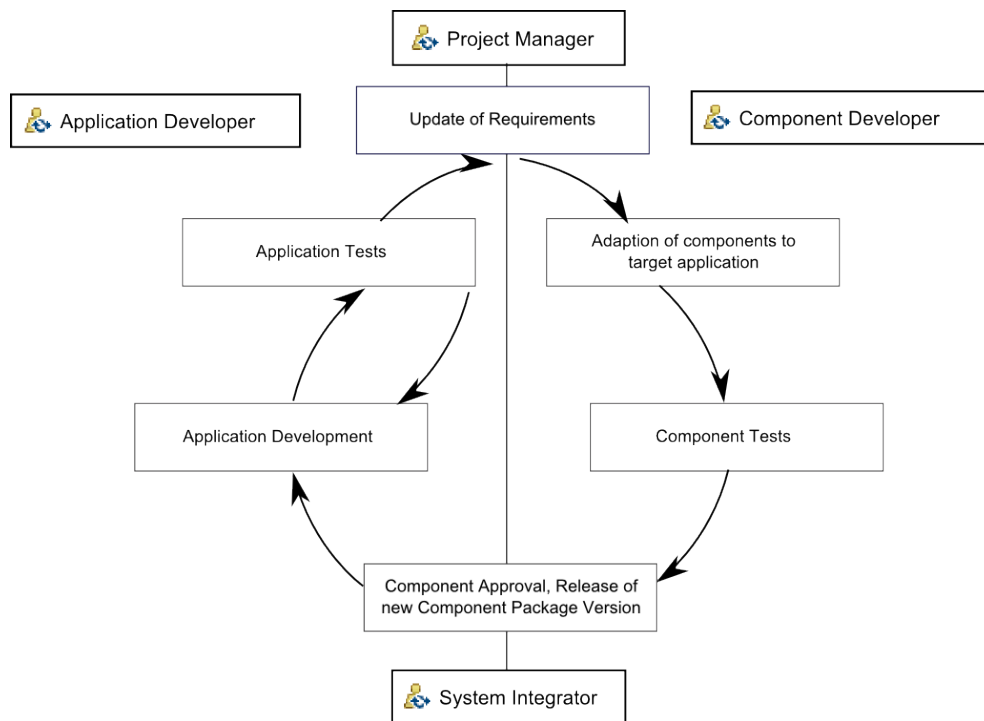


Figure 11. Schematic view of the distributed integration process. Component Development is separated from application development. Component packages are released on a regular basis.

quest user input via the touchscreen. The tray could be even placed vertically, e.g. for the transmission of a skype call.

2.5.3. Scenarios

Within project runtime, three different scenarios will be implemented that showcase the newly developed components and features to assist elderly people in their homes (in particular the social-empathical behaviours of the robot and the re-enablement concept). The scenario that has been implemented in the first year provides the foundation for the remainder of the project: all new components are integrated and available in a first functional prototype. In the following passage the background story of the first year's scenario is given: "The user sits on the sofa in the living room and watches TV or reads. The robot has noticed that she has been sitting there for 2 hours and has not had anything to drink for a while (in fact for 5 hours). It approaches her in a friendly/un-intrusive manner with slow/gentle movements/trajectories, adopting an appropriate social interaction distance, produces appropriate attention seeking behaviour - according to previously learnt user-preferences. The robot waits for the user to turn towards the robot. The robot then reminds the user of having something to drink by showing on the interface the action possibility 'drink'. This action possibility is displayed with a big label to highlight its relevance. The user selects 'drink' via the interface. The robot then uses learnt information on the user's drink preferences, goes into the kitchen, picks up a small bottle of water, brings it to the user, offering the bottle with an inclination of the torso. The robot notices when the user has taken the bottle from its tablet. The robot observes if the user drinks and otherwise, would remind the user to drink some water. After completing the tasks the

robot adopts an empathic position (next the user, pretending to watch TV), shifting position in synchronisation with the user."

2.6. Evaluation and ethical issues

2.6.1. Acceptability

Current acceptance models and studies (e.g. the Almere model [33]) are too general and based on "data" collected in various kinds of lab settings (mock-ups, lab installations and videos). Instead, acceptance should be studied over longer periods and in real-life settings. No research model exists across varying technological and organisational settings. The Unified Theory of Acceptance and Use of Technology (UTAUT) [76] challenges to further explore the specific influences of factors that may alter the behavioural intention to use an information system in alternative settings. Experience, gender, age, and voluntariness of research participants are also considered for inclusion in a future model (See also the discussion section in Heerink et al. [33]).

We aim to research acceptance of specific functions, roles and behaviours in specific practical situations faced by the elderly, with specific personal, mental, and physical properties and (dis)abilities. To do this, longitudinal field studies are required.

2.6.2. Evaluation activities:

The aim of the evaluation carried out in ACCOMPANY is twofold. Firstly, the potential usage of the robot will be evaluated as part of the needs assessment mentioned earlier. Secondly, a summative evaluation of usage will be carried out with the stake holders as described here. The

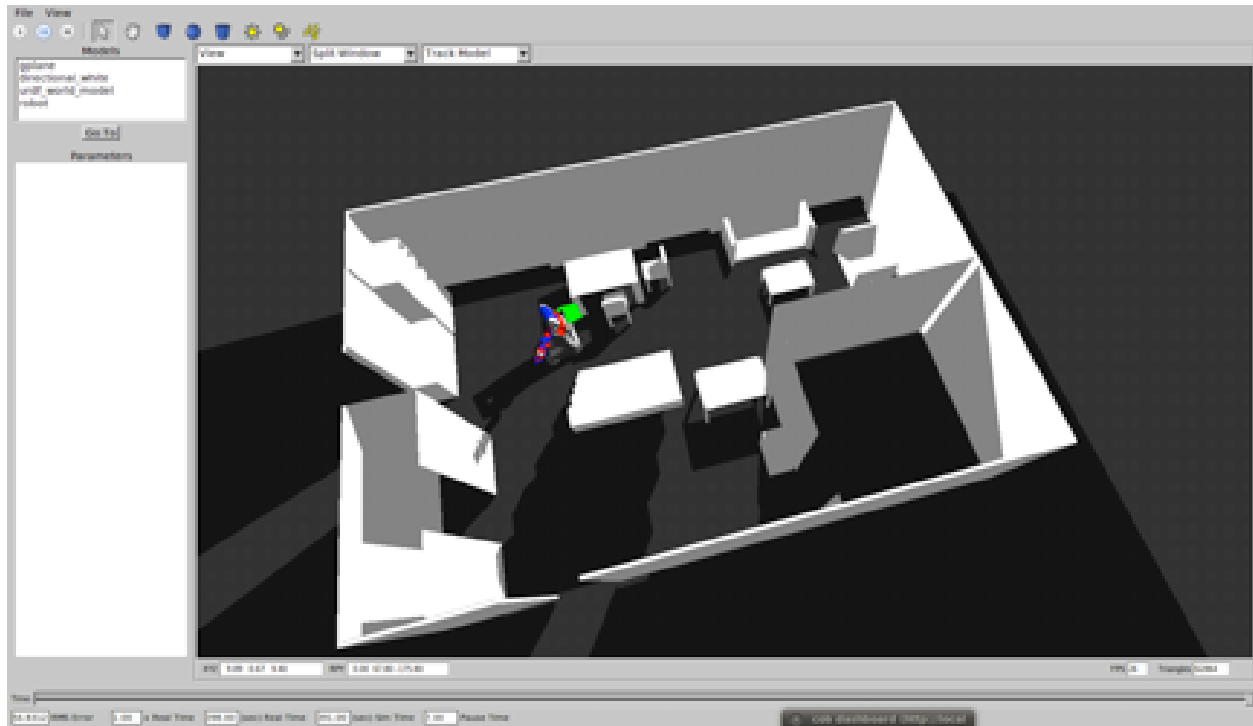


Figure 12. Simulation environment of the robot house allowing developments in absence of robot and robot house.

needs of the users arising from the first evaluation will be used define a scenario that will then be tested with the stake holders.

The methodology developed is based on a multi-criteria grid that will take into account issues related to all the evaluation domains: acceptability, ethics, usages, effectiveness compared to the functionalities defined as well as the economic model. This evaluation grid will take into account the state of the art from both a European (HTA) and French (GEMSA) perspective in respect to evaluation[28], in order to evaluate the usage performance of the ACCOMPANY robot.

The evaluation protocol considered here will reproduce as closely as possible a real-life situation. In order to make the artificial testing environment as close as possible to the real life and to make the users feel more at home, the evaluation protocol will simulate the relational conditions with the robot that would be encountered in their homes. In real terms this means that the usage evaluated will take place in a relational network, a triad that could facilitate but also potentially hinder the acceptance of the robot:

This exploratory technique should enable factors that influence the acceptance of the usage of the robot, as well as manner in which the robot could be used to be better identified. The work currently underway is focused on the development of the protocol in a smart-house in which relational triads (an elderly person with their own informal carer and healthcare professional) and an observation system (video camera, two researchers present) will be used, coupled with a face to face debriefing that will be both individual and collective (by triad).

2.6.3. Ethics and ethical framework

ACCOMPANY proceeds on the basis that the ethical issues raised by the use of robots as a form of care technology in elders' homes should be addressed as far as possible at the design stage, whilst taking into account the views of potential users. Accordingly, ethics is an important aspect of the project, and fully integrated into work with user groups. ACCOMPANY also recognises that the choices that individuals are able to exercise in relation to their care needs will be constrained by financial considerations as well as by the choices made available to them. The initial research on ethics in relation to the ACCOMPANY robot was concerned with the extent to which a multi-functioning robot could offer more to users than lower cost, lower tech alternatives - such as those already used in telecare. One advantage of multi-functioning robots is that they can unify telecare functions. This has the potential to create more of a presence in the users' home and, in doing so, may be something of an antidote to loneliness. This sense may be enhanced if the robot is itself a platform for alternative forms of human-to-human interaction, for instance virtual interactions using the internet or tele-visual communications in real time. At the same time, however, the potential for the robot to link with the world outside the home also raises concerns about privacy. Accordingly, care needs to be taken to ensure that the correct balance is struck between ensuring that the robot is realistically useful and economically viable care option, and that the user retains control over his or her private information.

The ethics component of ACCOMPANY is organised into three phases that run consecutively throughout the project. The first phase identified potential ethical concerns and suggested several principles that should govern the design of the robot. This research was theoretical



Figure 13. Design Drawings of the new tray kinematics with 3 degrees of freedom that allows height adjustment of the tray and switching between tablet pc and object placement

The robot takes its place in a relational network of care:

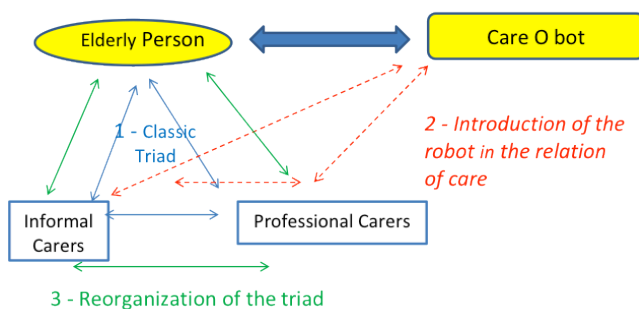


Figure 14. Role of robot in a traditional triad of care

in the sense that it drew on existing literature and established general moral theories and principles, but the researchers were careful to base their thoughts on the capabilities of the emerging ACCOMPANY robot design. The principles suggested by this theoretical analysis were:

- autonomy - being able to set goals in life and choose means;
- independence - being able to implement one's goals without the permission, assistance or material resources of others;
- enablement - having or having access to means of realising goals and choices;
- safety - being able readily to avoid pain or harm;
- privacy - being able to pursue and realise one's goals and implement one's choices unobserved;
- social connectedness - having regular contact with friends and loved ones and safe access to strangers one can choose to meet.

It is obvious, however, that there will be occasions when these ethical principles will be in tension with one another. The tension between privacy and safety has already been alluded to. A robot may well have the capability to detect abnormal, or absence of, movement indicating that the user has fallen. It may be beneficial from the point of view of the users' safety and well being for others to be alerted to the fact that the user may be in difficulties. On the other hand, the user may fear that others associate falling with the need for institutionalised care or with increasing vulnerability. For this reason, the user may prefer to attempt to get up without assistance, and be willing to trade some discomfort and even the risk of longer term damage for the opportunity to exercise this form of independence.

It is not obvious that there is one right answer to the question of how to prioritize these principles when they are in tension. Answers may depend on circumstances and users' preferences and personal values. They may also depend on how the robot is generally regarded. So, for example, a user may expect not to have some forms of privacy - privacy in matters related to his or her health, for example - if the robot is perceived to be a medical device or substitute medical carer.

Accordingly, in the second phase of ACCOMPANY, focus groups of potential users and professional and informal carers will be asked to discuss scenarios designed to highlight potential tensions between the proposed principles. These will include people already exposed to the robot as well as those without prior exposure in two distinct phases of study. This will also enable us to determine whether any significant principles need to be added. This phase of the project is currently on-going. The data collected will be interesting in its own right as an indication of users' concerns, values and preferences concerning robotic care. The results will also be used, however, in the final phase to re-evaluate and, if necessary, modify the proposed principles. The result will be an ethical framework that will be more generally applicable to other similar projects.

3. Conclusions and future work

3.1. Conclusions

As presented in this paper, the design and development of assistive technologies, in this case companion technologies for home care and companionship. This is a moderately new area of development, owing

its progress to recent trends in demographic changes to our populations and increase in number of ageing adults. This article presented a multitude of development areas, from user needs elicitation to development of technologies in multiple fronts such as empathic behaviour, learning and memory and person/activity recognition.

The identified elements in the development of assistive technology presents an effort to respond to slow uptake of care technologies, offered by robotic companions as well as advanced ICT technologies. By highlighting elements such as empathy and social interaction that have a deep root in human-robot interaction and human-human interaction, this article presents an often ignored element of robot behaviour which can enrich and influence robot's acceptance in communities. Elements such as memory and its architecture in support of robot's behaviour towards enabling individuals to stay longer at home highlights pieces of a larger puzzle, for a robot to be more accepted in a social context, its ability to learn and recall is an important feature. We highlighted the complexity of this element in our project while the notion of re-ablement and co-learning and how a memory architecture is required to allow the robot and its environment to recognise the users and to provide interpersonal interaction at an 'easy to use' level was presented. Furthermore, highlighting sensor fusion in context of human detection, object detection and object manipulation was shown as a separate area of development with the ultimate goal to detect person's status at home. Connecting these three strands of development was only possible by incorporating a scenario that supports a fully integrated, in this case diverse set of features, which in turn now await summative evaluation.

Additionally, and perhaps more importantly, aspects of acceptability and ethics form a large part of our project. In the context of acceptability, we have shown that robot's acceptance can be based on proxemics as well as roles and expectations while further experiments in this area will result in adapting robot's behaviour according to expectations arising from assumed roles of a co-learner or a re-ablement coach.

In the context of ethics, using theoretical analysis, a series of ethical principles such as autonomy, independence, enablement, safety, privacy and social connectedness were identified. Designing technologies, throughout the life of the project from start to end, based on these principles allows for have a more human-aware and ethically placed development. To do so, the project has developed a framework that allows us to identify the tension between some of these principles and to highlight these tensions in knowledge transfer activities, while user studies planned allow for prioritising these principles.

Finally, a major challenge is summative assessment of a varying range of developments. An evaluation grid that allows for comparing initial requirements to achieved results is considered while responding to evaluation requirements for acceptability, ethics, use and effectiveness and so on.

3.2. Future work

The project has passed its 18th months of development and in coming months, will start a summative evaluation of its development using three evaluation centres, in the United Kingdom, France and the Netherlands. The results of this evaluation will highlight areas still neglected while identifying the impact of chosen approaches using an economic model to estimate improvements in quality of health of the elderly user, improvements to the quality of user-care relationship, potential improvements to the professional practice and optimisations in a collective of organisational systems. These will be based on a value-chain analysis in the three evaluation countries fore-mentioned.

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References

- [1] J. R. Aiello. Human spatial behavior. *Handbook of environmental psychology*, 1:389–504, 1987.
- [2] R. C. Arkin. *Behavior-based robotics*. MIT press, 1998.
- [3] J. C. Augusto and C. D. Nugent. The use of temporal reasoning and management of complex events in smart homes. In *ECAI*, volume 16, page 778. Citeseer, 2004.
- [4] R. Barea, L. Bergasa, E. López, M. Escudero, J. Hernández, and Y. Willemaers. Tele-medicine system based on a personal robotic assistant. In *10th IEEE International Conference on Methods and Models in Automation and Robotics MMAR*, volume 4, pages 909–915, 2004.
- [5] R. Basri and D. W. Jacobs. Lambertian Reflectance and Linear Subspaces. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 25:218 – 233, 2003.
- [6] S. Bedaf, G. J. Gelderblom, D. S. Syrdal, H. Lehmann, H. Michel, D. Hewson, F. Amirabdollahian, K. Dautenhahn, and L. de Witte. Which activities are threaten independent living of elderly when becoming problematic; inspiration of meaningful service robot functionality. *Disability and Rehabilitation: Assistive Technology*, 2013, Accepted.
- [7] P. N. Belhumeur, J. P. Hespanha, and D. J. Kriegman. Eigenfaces vs. fisherfaces: Recognition using class specific linear projection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 19(7):711–720, 1997.
- [8] L. Bo, X. Ren, and D. Fox. Depth Kernel Descriptors for Object Recognition. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, September 2011.
- [9] J. Boger, P. Poupart, J. Hoey, C. Boutilier, G. Fernie, and A. Mihailidis. A decision-theoretic approach to task assistance for persons with dementia. In *Proc. of the 19th International Joint Conference on Artificial Intelligence (IJCAI)*, pages 1293–1299, 2005.
- [10] R. Bormann, J. Fischer, G. Arbeiter, and A. Verl. Adding rotational robustness to the surface-approximation polynomials descriptor. In *Proceedings of the International Conference on Humanoid Robots*, pages 409–416, 2012.
- [11] R. Bormann, J. Fischer, G. Arbeiter, and A. Verl. Efficient object categorization with the surface-approximation polynomials descriptor. In C. Stachniss, K. Schill, and D. Uttal, editors, *Spatial Cognition VIII*, volume 7463 of *Lecture Notes in Computer Science*, pages 34–53. Springer, 2012.
- [12] R. Bormann, T. Zwölfer, J. Hampf, and J. Fischer. Person recognition for service robotics applications. In *Proceedings of the International Conference on Humanoid Robots*, 2013.

- [13] M. Butter, A. Rensma, J. v. Boxsel, S. Kalisingh, M. Schoone, M. Leis, G. Gelderblom, G. Cremers, M. de Wilt, W. Kortekaas, A. Thielmann, K. Cuhls, A. Sachinopoulou, and I. Korhonen. Robotic for healthcare - final report. http://www.tno.nl/downloads/TNOKvL_report_Robotics_forHealthcare.pdf, 2008.
- [14] W. L. Chen, M. J. Er, and S. Q. Wu. Illumination Compensation and Normalization for Robust Face Recognition Using Discrete Cosine Transform in Logarithm Domain. *IEEE Transactions on Systems, Man and Cybernetics*, 36(2):458–466, 2006.
- [15] CSED. Homecare re-ablement. UK Department of Health Care Services Efficiency Delivery (CSED), Dec 2012. <http://www.csed.dh.gov.uk/homeCareReablement/>.
- [16] R. Detry, N. Pugeault, and J. Piater. A probabilistic framework for 3D visual object representation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 31(10):1790–1803, Oct. 2009.
- [17] T. V. Duong, H. H. Bui, D. Q. Phung, and S. Venkatesh. Activity recognition and abnormality detection with the switching hidden semi-markov model. In *Computer Vision and Pattern Recognition, 2005. CVPR 2005. IEEE Computer Society Conference on*, volume 1, pages 838–845. IEEE, 2005.
- [18] I. Duque, K. Dautenhahn, K. L. Koay, I. Willcock, and B. Christianson. Knowledge-driven user activity recognition for a smart house - development and validation of a generic and low-cost, resource-efficient system. In *The Sixth International conference on Advances in Computer-Human Interactions, 24 February - 1 March 2013, Nice, France*, pages 141–146. ACHI, 2103.
- [19] G. Englebienne and B. J. Kröse. Fast bayesian people detection. In *Proceedings of the 22nd Benelux AI Conference, BNAIC, 2010*.
- [20] Eurostats. Population projections. online database, April 2013. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Population_projections.
- [21] R. J. Firby. An investigation into reactive planning in complex domains. In *Proceedings of the sixth National conference on Artificial intelligence*, volume 1, pages 202–206. Seattle, WA, 1987.
- [22] J. Fischer, G. Arbeiter, R. Bormann, and A. Verl. A framework for object training and 6 DoF pose estimation. In *Proceedings of the 7th German Conference on Robotics (ROBOTIK 2012)*, Munich, Germany, May 2012.
- [23] J. Fischer, G. Arbeiter, and A. Verl. Combination of time-of-flight depth and stereo using semiglobal optimization. In *International Conference on Intelligent Robots and Systems (IROS)*, pages 3548–3553. IEEE, May 2011.
- [24] J. Fischer, D. Seitz, and A. Verl. Face detection using 3-d time-of-flight and colour cameras. In *Proceedings of the Joint Conference of the 41st International Symposium on Robotics (ISR) and the 6th German Conference on Robotics (ROBOTIK 2010)*, pages 112–116, 2010.
- [25] A. Georgiades, P. Belhumeur, and D. Kriegman. From Few to Many: Illumination Cone Models for Face Recognition under Variable Lighting and Pose. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 23(6):643–660, 2001.
- [26] J. J. Gibson. *The ecological approach to visual perception*. Psychology Press, 1986.
- [27] T. Goel, V. Nehra, and V. P. Vishwakarma. Comparative Analysis of various Illumination Normalization Techniques for Face Recognition. *International Journal of Computer Applications*, 28(9), 2011.
- [28] L. Goff-Pronost and R. Picard. Need for ict assessment in the health sector: A multidimensional framework. *Communications & Strategies*, (83), 2011.
- [29] T. Grundmann, W. Feiten, and G. Wichert. A gaussian measurement model for local interest point based 6 DOF pose estimation. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 2085–2090, May 2011.
- [30] S. A. Gudmundsson, H. Aanaes, and R. Larsen. Fusion of stereo vision and time-of-flight imaging for improved 3D estimation. *International Journal of Intelligent Systems Technologies and Applications*, 5(3/4):425, 2008.
- [31] U. Hahne and M. Alexa. Combining time-of-flight depth and stereo images without accurate extrinsic calibration. *International Journal of Intelligent Systems Technologies and Applications*, 5(3/4):325, 2008.
- [32] E. T. Hall and E. T. Hall. *The hidden dimension*. Anchor Books New York, 1969.
- [33] M. Heerink, B. Kröse, V. Evers, and B. Wielinga. Assessing acceptance of assistive social agent technology by older adults: The almere model. *International Journal of Social Robotics*, 2(4):361–375, 2010.
- [34] R. Helaoui, M. Niepert, and H. Stuckenschmidt. Recognizing interleaved and concurrent activities: A statistical-relational approach. In *Pervasive Computing and Communications (PerCom), 2011 IEEE International Conference on*, pages 1–9. IEEE, 2011.
- [35] R. Hg, P. Jasek, C. Rofidal, K. Nasrollahi, T. Moeslund, and G. Tranchet. An RGB-D Database Using Microsoft's Kinect for Windows for Face Detection. In *Proc. of International Conf. on Signal Image Technology and Internet Based Systems*, pages 42–46, 2012.
- [36] M. L. Hoffman. *Empathy and moral development: Implications for caring and justice*. Cambridge University Press, 2001.
- [37] N. Hu, G. Englebienne, and B. J. Kröse. Bayesian fusion of ceiling mounted camera and laser range finder on a mobile robot for people detection and localization. In *Human Behavior Understanding*, pages 41–51. Springer, 2012.
- [38] K. Isbister and C. Nass. Consistency of personality in interactive characters: verbal cues, non-verbal cues, and user characteristics. *International journal of human-computer studies*, 53(2):251–267, 2000.
- [39] G. P. J., D. E. Karreman, and V. Evers. Contextual analysis of the needs of elderly for independent living : is there a role for robot physical therapy? In *Workshop on Motivational Aspects of Robotics in Physical Therapy. (IROS2012)*, 2012.
- [40] V. Jain and E. Learned-Miller. Online domain adaptation of a pre-trained cascade of classifiers. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pages 577–584, 2011.
- [41] K. L. Koay, D. S. Syrdal, M. L. Walters, and K. Dautenhahn. Living with robots: Investigating the habituation effect in participants' preferences during a longitudinal human-robot interaction study. In *Robot and Human interactive Communication, 2007. RO-MAN 2007. The 16th IEEE International Symposium on*, pages 564–569. IEEE, 2007.
- [42] K. L. Koay, M. L. Walters, A. May, A. Dumitriu, B. Christianson, N. Burke, and K. Dautenhahn. Exploring robot etiquette: Refining a hri home companion scenario based on feedback from two artists who lived with robots in the uh robot house. In *International Conference on Social Robotics, 27–29 October 2013, Bristol, UK*. ICSR, 2103.
- [43] M. Krainin, P. Henry, X. Ren, and D. Fox. Manipulator and object tracking for in-hand 3D object modeling. *The International Journal of Robotics Research*, 30:1311–1327, July 2011.
- [44] H. Lehmann, D. S. Syrdal, K. Dautenhahn, G. Gelderblom,

- S. Bedaf, and F. Amirabdollahian. What should a robot do for you?-evaluating the needs of the elderly in the uk. In *ACHI 2013, The Sixth International Conference on Advances in Computer-Human Interactions*, pages 83–88, 2013.
- [45] J. Li, T. Wang, and Y. Zhang. Face Detection using SURF Cascade. In *IEEE International Conference on Computer Vision (ICCV Workshops)*, pages 2183–2190, 2011.
- [46] P. Marti and J. Stienstra. Exploring empathy in interaction. scenarios of respectful robotics. *GeroPsych, Journal of Gerontopsychology and Geriatric Psychiatry*, 26(2):101–1012, 2013.
- [47] Z.-C. Marton, D. Pangercic, R. B. Rusu, A. Holzbach, and M. Beetz. Hierarchical Object Geometric Categorization and Appearance Classification for Mobile Manipulation. In *Proceedings of the IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, Nashville, TN, USA, 2010.
- [48] M. Merleau-Ponty. *Phenomenology of perception*. Motilal Banarsidass Publisher, 1996.
- [49] N. A. Mirza, C. L. Nehaniv, K. Dautenhahn, and R. te Boekhorst. Grounded sensorimotor interaction histories in an information theoretic metric space for robot ontogeny. *Adaptive Behaviour*, 15(2):167–187, 2007.
- [50] J. Modayil, T. Bai, and H. Kautz. Improving the recognition of interleaved activities. In *Proceedings of the 10th international conference on Ubiquitous computing*, pages 40–43. ACM, 2008.
- [51] R. Nair, F. Lenzen, S. Meister, H. Schäfer, C. S. Garbe, and D. Kondermann. High accuracy TOF and stereo sensor fusion at interactive rates. In *Proceedings of the European conference on Computer vision (ECCV)*, pages 1–11, 2012.
- [52] Z. S. Network. Zigbee sensor network. product database, August 2013. <http://www.digi.com/products/wireless-wired-embedded-solutions/zigbee/>.
- [53] N. J. Nilsson. Teleo-reactive programs and the triple-tower architecture. *Electron. Trans. Artif. Intell.*, 5:99–110, 2001.
- [54] G. E. Options. Green energy options. Company website, August 2013. <http://www.greenenergyoptions.co.uk>.
- [55] C. Overbeeke. The aesthetics of the impossible. 2007.
- [56] M. P., I. I., T. M., and S. J. Engaging through her eyes : embodying the perspective of a robot companion. In *Artificial Life and Robotics, AROB2013. the 18th International Symposium on*, 2013.
- [57] D. J. Patterson, D. Fox, H. Kautz, and M. Philipose. Fine-grained activity recognition by aggregating abstract object usage. In *Wearable Computers, 2005. Proceedings. Ninth IEEE International Symposium on*, pages 44–51. IEEE, 2005.
- [58] M. L. Patterson. *Nonverbal behavior: A functional perspective*. Springer-Verlag New York, 1983.
- [59] F. Pecora, M. Cirillo, F. Dell’Osa, J. Ullberg, and A. Saffiotti. A constraint-based approach for proactive, context-aware human support. *Journal of Ambient Intelligence and Smart Environments*, 4(4):347–367, 2012.
- [60] reablement. Demonstrating improvement through reablement. Welsh Social Services Improvement Agency, Dec 2012. www.ssiacymru.org.uk/reablement.
- [61] U. Reiser, R. Klauser, C. Parltitz, and A. Verl. DESIRE WEB 2.0 - Integration Management and Distributed Software Development for Service Robots. In *Proceedings of the 14th International Conference on Advanced Robotics (ICAR)*, pages 1–6, 2009.
- [62] E. Rublee, V. Rabaud, K. Konolige, and G. Bradski. ORB: an efficient alternative to SIFT or SURF. In *International Conference on Computer Vision (ICCV)*, Barcelona, Nov. 2011.
- [63] R. B. Rusu, G. Bradski, R. Thibaux, and J. Hsu. Fast 3D Recognition and Pose Using the Viewpoint Feature Histogram. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2010.
- [64] R. B. Rusu, A. Holzbach, M. Beetz, and G. Bradski. Detecting and Segmenting Objects for Mobile Manipulation. In *Proceedings of the International Conference on Computer Vision (ICCV), S3DV Workshop*, 2009.
- [65] J. Saunders, C. L. Nehaniv, K. Dautenhahn, and A. Alissandrakis. Self-imitation and environmental scaffolding for robot teaching. *International Journal of Advanced Robotics Systems*, 4(1):109–124, 2007.
- [66] E. Schnelle and M. Thiersch. *The Metaplan-Method: Communication tools for planning & learning groups*. Metaplan, 1979.
- [67] D. A. Schön. *The reflective practitioner: How professionals think in action*, volume 5126. Basic books, 1983.
- [68] G. Singla, D. J. Cook, and M. Schmitter-Edgecombe. Recognizing independent and joint activities among multiple residents in smart environments. *Journal of ambient intelligence and humanized computing*, 1(1):57–63, 2010.
- [69] J. Stienstra, M. B. Alonso, S. Wensveen, and S. Kuenen. How to design for transformation of behavior through interactive materiality. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, pages 21–30. ACM, 2012.
- [70] J. Stienstra and P. Marti. Squeeze me: gently please. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, pages 746–750. ACM, 2012.
- [71] J. Stienstra, P. Marti, and M. Tittarelli. Dreamy eyes: exploring dynamic expression in human-system interaction. In *CHI’13 Extended Abstracts on Human Factors in Computing Systems*, pages 595–600. ACM, 2013.
- [72] J. Stienstra, P. Marti, and M. Tittarelli. What you do is who you are: The role of task context in perceived social robot personality. In *Robotics and Automation (ICRA13), International Conference on*. IEEE, 2013.
- [73] J. Stienstra, C. Overbeeke, P. Marti, P. Levy, and C. Hummels. Mapping the continuous to the discrete : Interaction aesthetics in complex products and systems. <http://www.tue.nl/en/publication/ep/p/d/ep-uid/266054/>, 2012.
- [74] L. Takayama and C. Pantofaru. Influences on proxemic behaviors in human-robot interaction. In *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, pages 5495–5502. IEEE, 2009.
- [75] M. Turk and A. Pentland. Eigenfaces for Recognition. *Journal of Cognitive Neuroscience*, 3(1):71–86, 1991.
- [76] V. Venkatesh, M. G. Morris, G. B. Davis, and F. D. Davis. User acceptance of information technology: Toward a unified view. *MIS quarterly*, pages 425–478, 2003.
- [77] P. Viola and M. Jones. Rapid object detection using a boosted cascade of simple features. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, volume 1, pages 511–518, 2001.
- [78] M. Walters, K. Dautenhahn, S. Woods, K. Koay, R. Te Boekhorst, and D. Lee. Exploratory studies on social spaces between humans and a mechanical-looking robot. *Connection Science*, 18(4):429–439, 2006.
- [79] M. L. Walters, K. Dautenhahn, K. L. Koay, C. Kaouri, R. Boekhorst, C. Nehaniv, I. Werry, and D. Lee. Close encounters: Spatial distances between people and a robot of mechanistic appearance. In *Humanoid Robots, 2005 5th IEEE-RAS International Conference on*, pages 450–455. IEEE, 2005.
- [80] M. L. Walters, K. Dautenhahn, R. te Boekhorst, and K. L. Koay. An empirical framework for human robot proximity. In *New Frontiers*

in Human-Robot Interaction, a symposium at the AISB2009 Convention, Heriot Watt University, 8-9 April 2009, Edinburgh, Scotland. SSAISB.

- [81] M. Weser, D. Off, and J. Zhang. Htn robot planning in partially observable dynamic environments. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 1505–1510. IEEE, 2010.
- [82] J. Wu, A. Osuntogun, T. Choudhury, M. Philipose, and J. M. Rehg. A scalable approach to activity recognition based on object use. In *Computer Vision, 2007. ICCV 2007. IEEE 11th International Conference on*, pages 1–8. IEEE, 2007.
- [83] J. Zhu, L. Wang, R. Yang, J. E. Davis, and Z. Pan. Reliability fusion of time-of-flight depth and stereo geometry for high quality depth maps. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 33(7):1400–1414, July 2011.