Journal of Habitat Engineering 2011
Volume 3, Number 1, 101 – 110

Original Article

Robotic and Ubiquitous Technologies for Welfare Habitat

Thomas LINNER
Research Fellow, Department of Architecture, Chair for Building Realization and Robotics, Technische Universität München
Arcisstr. 21, 80333 Munich, Germany; Thomas.Linner@br2.ar.tum.de

Matthias KRANZ
Professor, Department of Electrical Engineering and Information Technology, Institute for Media Technology, Technische Universität München

Luis ROALTER
Research Fellow, Department of Electrical Engineering and Information Technology, Institute for Media Technology, Technische Universität München

Thomas BOCK
Professor, Department of Architecture, Chair for Building Realization and Robotics, Technische Universität München

The aging society requires novel approaches to facilitate in-home services and support for ambient assisted living. The transformation of an everyday home into a supportive environment is a challenging task, as costs and necessary efforts are preventing us to change normal homes into high-tech care units. We present an alternative solution, in between fully networked homes on the one hand and smart artifacts on the other end of the scale, applying research results from robotics. We elaborate on the multi-dimensional interdisciplinary challenges that need to be addressed for successful future pervasive and personalized healthcare systems, and present a prototypic robotic service unit which could be developed further for industrialized and affordable mass customization.

Keywords: *Ambient assisted living, Ubiquitous computing, Intelligent environments, Pervasive healthcare*

1. Introduction

An extended stay of elderly people in an appropriate with assistive technologies equipped home environment is less costly, and, in most cases, also more effective than a stationary stay in a care or nursing facility. The continuance of activity in naturally grown environments and social networks helps effectively to prevent somatic, motor, mental and social disorders, when customized personalized health environments meeting multiple requirements are installed around the care receivers. The seamless deployment of a set of sensors and telemetric applications to continuously monitor single disorders and patients showing "multimorbidity"[1)] could significantly enhance the quality of medical treatment, long-term therapies, medication and service provision in general. Advances in home automation technology, assistive mechatronics and service robotics promise service environments on a new level when interconnected, integrated properly in the home and linked to monitoring systems and related services. Moreover, government, society and industry are interested in elderly people living in their homes supported by integrated sets of classical methods and pervasive technologies in order to keep up the related value creation and to establish new value systems related to recurrent medical, care and household services. By our work, we wish to contribute to this important socio-technical and socio-economic issues. The challenges of facilitating independent living at home with integrated sets of methods and technologies require a holistic and interdisciplinary approach, including experts from the domains of medical science, architecture, design, robotics, computer science, electrical engineering, human-computer interaction and the housing industry.

ISSN: 1883-647X

2. Preparation Procedures

2.1 Geriatric and Medical Challenges

The geriatric profile of elderly people in general can be specified by so called “multi-morbidity”[1], which is defined as the co-existence of two or more chronic conditions. All “use cases” are a complex mixture of multiple geriatric requirements as support of daily physical activity, support of mobility, compensate deficits concerning hearing and seeing, support of cognitive abilities, support of emotional and psychological state, support of social interaction or emergency support also require a multiple set of technologies. Some of those requirements can be met with higher efficiency by “passive” (architecture and design), others by “active” systems (sensors, actors and integrated circuits, and pervasive computing applications). A carefully chosen and aware combination of both passive and active systems significantly enhances the ability of environments to holistically address geriatric challenges. Further, customizable and personalizable, multidimensional component-based systems are gradually becoming a basic requirement: upcoming “personalized healthcare” demands to guarantee the individual care receivers’ optimized physical and mental health. We do contribute to personalized, pervasive healthcare systems by applying robotics research to the domain of ambient assisted living proposing modular service units.

2.2 Architectural Challenges

When we talk about “assistive” environments incorporating pervasive computing technology, we do not talk about standalone health applications - such as a blood pressure measure system, emergency monitoring system or a “health phone” - which do not communicate. Without communication, the potential of the employed technologies is not used to its full extent. In “intelligent” or “assistive” environments, those components are networked - ideally interconnected amongst themselves, connected to home automation systems, including fire detectors, HVAC systems, care services and many more. But, how can we integrate pervasive computing technology into existing homes, where their deployment would be demanded, given that we start by an ordinary, non-connected home[2]? It can be assumed that people, who become “elderly” during the next decades in most cases, do not own a “networked” home providing the necessary infrastructure. Thus, new methods have to be found allowing an efficient transformation of existing homes into networked assistive environments for independent living.

2.3 Design Challenges

It is important to introduce hierarchical modularity and platform strategies cutting cross all related disciplines, so that various assistive technologies or modules can be customized to a specific use case and further be exchanged or extended to meet the variety of possible use cases, even changing over time[3]. The individual modules of the system have to be pre-configurable, easy to install and have to integrate into an existing, presumably non-pervasive computing home. Maintenance, for care givers and receivers, has to be addressed by a designed-in serviceability.

Secondly, the distribution and arrangement of functionalities, as for example kitchen, bath, sleeping and related appliances and technologies have to be considered. We will show and discuss this combination and present a scale model facilitating research on this combination. Elderly people tend to have a restricted degree of freedom in mobility and the distribution of mostly needed or life supporting functionalities over several rooms as in most homes today is not compulsorily an optimal solution.

Thirdly, a sustainable technology enhanced environment has to hide the complexity of its subsystems[4] to a maximum extent to take mental load and stress from the users as care receivers and to motivate them for activity and interaction with the technology. Persuasiveness here is a key aspect: encouraging activity or a healthy way of living leads to more satisfactory experience. Pervasive health technologies have, following the vision of calm computing, to be integrated in the design of the environment seamlessly, working invisibly in the background. Further, for the communication of information to care receivers, accepted devices as televisions, should be used as primary interfaces, as they state perfect intersections between well known common environments and new pervasive technology overlays. Not many elderly people today are accustomed to the use of modern mobile phone technology, but they are very well experienced of using a TV set, thus presenting information as overlay (“Please take your pills”) seems a promising approach. Additionally, cultural backgrounds have to be acknowledged. While it is more common, e.g. to accept assistive robots in Asia, this may be different in Europe or the US. Similar, the extent of potential assistive functionality has to be carefully evaluated for the individual target groups of care receivers.

2.4 Pervasive Computing Challenges

Assistive environments need to be flexible and versatile to cope with the dynamically changing requirements of their inhabitants and support them, especially when health- and age-related disabilities arise. Components of a service unit might be exchanged to reflect the change in the health status, and therefore a pervasive computing middleware system is required to be able to deal with this change. While smart homes such as PlaceLab[4] have been subject to research, they exemplarily stand for the goal to instrument and equip the whole building or apartment and doing so at once. Our approach allows incremental addition and replacement of modules and components, not requiring an effort comparable to the augmentation of a complete home. This allows costs, as major factor when investigating real world deployment scenarios, to be kept within much lower boundaries.

While MIT's House_n also includes modular intelligent furniture, their approach is on a smaller scale: the cabinets do not necessarily have to form a dedicated ecology e.g. to holistically support a specific need, as proposed by our core service modules. While modular cabinets are of value for pervasive computing and AAL environments, it has to be considered as incomplete when it comes to support assistive or independent living. We therefore argue that a dedicated, targeted approach supporting incremental extension of assistive environments and their middleware is necessary.

While we focus on environmental based ambient assisted living and pervasive healthcare, the inclusion of external devices has to be accounted for. External means: external in the sense of physical space – that is outside of the service units such as wearable health monitoring devices – and external in the sense that they can come from other manufacturers, such as an activity fostering chair for elderly people or a kitchen tool supporting cooking activities[8][17].

2.5 Social Challenges

As the computer-human interface is putting the human at the center, the most crucial part regarding usability and acceptance of any system, the presentation of and interaction with information has to be integrated already in the development process at an early stage. So it is needed to include the simulation of the environment and of the environments physicality.

Technology is normally considered as information source, but even human care givers and receivers provide lots of sensor data. Such an input is shown within CareNet[8], but also social networks like Twitter or the Internet of Things need to be considered. Ideally, a pervasive middleware not only connects devices to the Internet of Things, but also humans – care givers, care receivers and families – to a "web of support"[20]. Other middleware systems, such as GAIA[15] and MundoCore[10], have already been proposed and used in the relatively young research field of pervasive computing. The challenges of distributed multimodal information processing connecting heterogeneous input and output technologies and sensor-actor systems have very different demands towards the middleware. Unfortunately, reuse and final development in this domain is limited usually to the initial developers of a respective middleware and no community yet evolved to pursue the ambitious goal of a unified middleware. Existing systems, therefore, have not been designed for a long life cycle and future inclusion of upcoming technologies. We, therefore, consider the middleware as an extremely important issue towards deployable and working systems.

2.6 Cultural Challenges

In Japan pervasive technologies and especially service robotics have been accounted as basic and natural elements in addressing the problem of the ageing society. Therefore, currently several robots are under advanced development which can communicate, interact with humans or perform complex service tasks ("PaPeRo", "Emiew", "Hospi"). Moreover, obvious robotic subsystems as robotic hands, suits and control interfaces ("Tendy-One", "HAL", "Brain Machine Interface") are basic issues of both scientific and commercial research. A common characteristic of the Japanese efforts is that most service solutions are intentionally designed as "humanoid" or "mobile" systems as obvious robotic systems are widely accepted and demanded by care receivers as well as care givers. Yet, in Europe, different strategies to successfully introduce high-tech based services, health or rehabilitation technologies are necessary as "visible" robotic systems are strongly related to production and "dull, dirty and dangerous" tasks. Therefore, the robotic service unit has been distinctively designed as a seamless "Immobile Robot", distributed and integrated in the service environment as an invisible and highly customizable companion, supporting health- and age-related disabilities with a high degree of autonomy.

3. The Potential of Robotics in Ambient Assisted Living and Pervasive Healthcare

To guarantee a sustainable implementation of pervasive health technologies, a concept of scalable, compact, highly modular and customizable service units has been derived from the above discussed challenges, designed as alternative to fully networked homes and houses. Robotics, in the context of service robots and motorized systems, such as controllable beds or kitchen surfaces, are already known in care scenarios. By approaching assistive environments, offering services, applications and supporting their inhabitants based on distributed sensing systems - ranging from presence detection to bio-medical monitoring - we can significantly increase the development speed, development support and thereby deployment costs and obstacles, as respective pervasive computing applications exist. Yet, there have been no feasible ways of actually integrating them in today's homes.

Recently designed German prototypes of assistive homes are exemplarily equipped with a variety of networked pervasive technologies, integrated in modern and "expensive" design. Both these homes act as demonstrator and as technology probe, supporting and facilitating discussion, as does our functional scale model. Nevertheless, both approaches do not address topics as modularity or interoperability on physical, digital or service level - only architecturally. Afore mentioned approaches thus require houses to be built from scratch or requiring costly renovation. In contrast to the robotic service unit system, approaches presented by those prototypes do not allow gradual implementation and extension, simplified "upgrading" or continuous customization[21] of existing environments, which could be accounted as essential to deploy pervasive health environments as discussed before. Other examples for assistive homes[22] offer higher modularity, achieved through modular and open architectural concepts. Yet, they do not fully use the potential of that approach and still require basic parts of the building and its infrastructure to be built from scratch. The scalability of both systems is restricted to newly built environments; they are also not explicitly designed for implementation into existing and naturally grown environments. Although these modules are industrially mass customized unit boxes prefabricated by the so called "skeleton and infill"[22] approach, it is not foreseen that those preconfigured high-tech units could be added to an existing home.

Our approach addresses these issues integrating pervasive healthcare subsystems through a hierarchically structured and highly scalable prefabricated component system able to be installed as an adaptive continuously changeable subsystem in existing low-tech homes. The hereby integrated healthcare subsystems are part of an open and modular component system that could be configured, pre-installed or updated with sets of sensors for real-time monitoring of vital parameters, invasive and not-invasive medical sensing devices, medication dispensers, telemedical communication devices, intelligent and assistive appliances and actively and physically supporting mechatronic and robotic service devices. Only personalized, to a certain degree autonomic and integrated sets of sensors, assistive technologies and services are able to counterbalance the co-existence of two or more chronic conditions typically for in-home cre especially of elderly people[12].

3.1 System Components

The robotic service unit consists of two basic system blocks. First, different service unit frames serve as platform or "chassis" in a physical and digital sense. Secondly, sets of compatible subsystems integrated with pervasive technologies allow customizing the service unit to different needs and multidimensional health- and age-related disabilities as discussed before. The fundamental transition from a normal home to a pervasive healthcare environment is depicted in Fig.1.

1) Service Unit Types as Integrating Platform

Independent living in a conventionally designed and low-tech home is in many cases impossible. Especially when entering a later stage of life, changes of habits and lifestyle - in comparison to previous stages of life – are

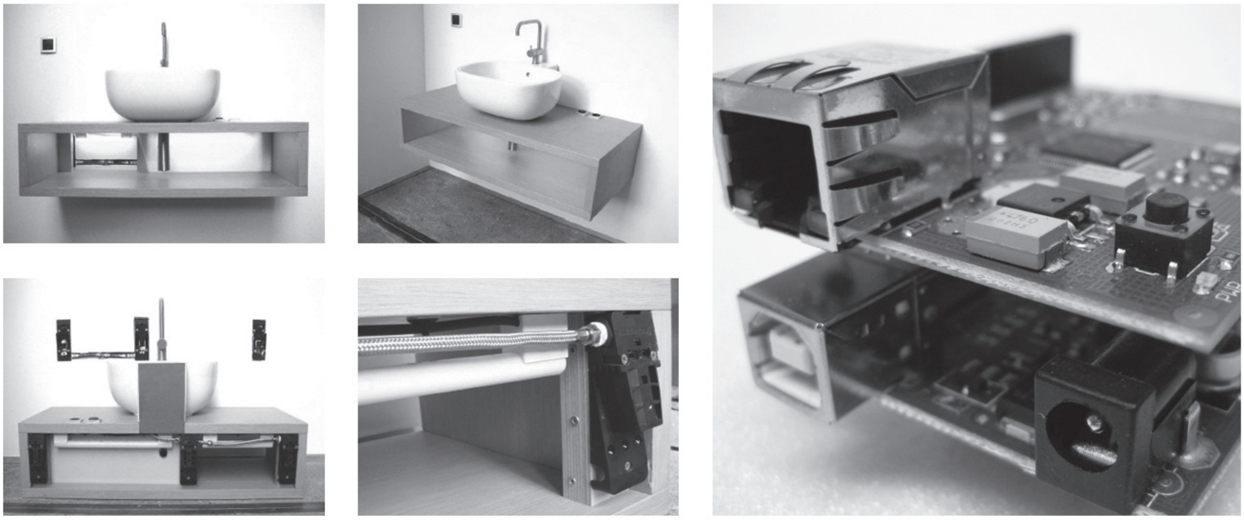

Fig. 1 Fully functioning, experimental 1:1 Models of Service Functions as Subsystems, which are connected via Plug-and-Play Connectors to the Service Units physically and on the Information Level.

Fig. 2 Types of Service Units. Left: Central Type Unit Placed in the Center of an Apartment to Organize Functionalities around the Unit Right: Room-in-Room Type Unit implements a new "Room" as an independent Sub-entity into existing Environments.

more dramatically. A possibility for re-configuration of the existing home or the addition of new assistive technologies would be needed. Today, this is a complex, costly and time consuming matter, often forcing elderly people to move. We aim to leverage the current situation. The presented approach simplifies this process, providing a compact, modular and adaptive service unit equipped with exactly the needed assistive technologies. The service unit is a highly compact entity which could be implemented in existing flats or homes as an independent sub-module instantly and with minimal efforts. It can be seen as an reconfigurable integration framework for technologies. As the service unit is expected to be integrated into a care receivers home, his/her well-known and comfortable environment is largely maintained, while required assistive pervasive healthcare technology is added the care receiver home. So he can stay in his well-known environment. The modular approach allows substituting and adding additional functionality later if and when needed.

Using the Central Type Unit various assistive scenarios as well as bath and kitchen functions could be arranged compactly around the service core (Fig.2.(l)). The Room-in-room Type Unit outlines an even more extreme and compact variant and implements a new "room" as an independent sub-entity into existing environments (Fig2.(r)). Both types provide – in contrast to conventional, existing homes the advantage that all functions needed for independent living can be organized on a minimal space, reducing the activity efforts of the elderly to a minimum, meanwhile activity and health condition are monitored with high precision.

2) Service Functions as Subsystems

For addressing the discussed design challenges, arising when conventional functions should be supplemented with pervasive technologies to an integrated assistive environment, the common practice of environmental design has to be rethought. Any kind of architecture or architectonic space can be defined by hierarchies[24]. In conventional architecture, this means that the function of a room is defined by all the rooms' subsystems (walls, furniture, doors, appliances, devices …), their positioning and the synergies they create. A level above, the house can be defined as an organization of rooms and floors working together as subsystems to build up the system 'house' as a whole.

The neighborhood area, the houses themselves, streets and other components would then state subsystems which in combination build up the whole system. Thus, in architecture, a systemic method to define functions and spaces exists. Recently micro systems technology becomes part of our living environments. Walls can be equipped with interface technologies, sensors, actors, assistive technologies, healthcare and wellness systems (Fig.1) and a many more of such high-tech systems are under development at the moment - and even more will be developed in the future. To control this new complexity, the above described method of defining spaces or modules or components by their subsystems should not only cover physical entities (walls, windows, doors, etc.), but also a new variety of embedded ICT enabled functionalities and services related to pervasive computing, such as location and context-aware services[14]. The current common practice is still that architecture defines the physical space, which is then later and often by somebody else outfitted with "loose" and not-integrated assistive and pervasive technologies and/or home automation components. The final functionality, which actually would be built up by an integrative combination of traditional "passive" systems and new pervasive "active" systems, is not foreseen and explicitly controlled, as no accepted framework or knowledge about this exists yet.

3.2 System Performance

Moreover, the service unit, as a system including both platform and compatible service functions has been designed as an invisible and "immobile" robotic system. The use case specific subsystems are not only networked and controllable, but technology works seamlessly, calm and to a high degree autonomously and pro-actively in the environment's background. The robotic service unit makes use of the concept of distributing and embedding robotic systems into environments, allowing distributed systems to interact on behalf of the care receiver. Environments enriched with distributed sensor-actor-systems, certain autonomy, and able to control their complex internal and external functions are considered as "ImmoBots": Immobile Robots[16].

A common characteristic of "ImmoBots" is that they are able to control their internal subsystems autonomously for achieving certain goals, thus reducing mental stress of human beings interacting with them. The concept of the robotic service unit is taking up this approach of autonomous and mental load reducing self-control of complex networks of subsystems. Our goal is to support elderly people with case specific sets of subsystems of pervasive technologies in their home. Through the approach of distributing and integrating robotic systems into environments, the goal of the robotic service unit is both outperforming the conventional smart home approach requiring still multiple control efforts and obtaining a higher acceptance of robotics as we have discussed.

3.3 Development Process

For the creation of a value system that brings pervasive health and service technologies into the range of care receivers, their relatives and care givers, a multidisciplinary team for research and development is required. During the development of the service unit concept, a main issue has been the continuous balancing of the requirements of the participating research fields derived from those challenges. In a second phase, design rules for modules and technology sets of the service unit component system have been formulated to simplify the implementation of knowledge of the participating research fields in the future. Moreover, the robotic service unit states a first step to a cross faculty initiative for the creation of modular, scalable and ambient integrated pervasive health environments which aim at bringing a set of high quality care, medical treatment technology, telemedical services and high-tech assistance technology in an affordable way into existing low tech homes giving access to care givers, care receivers and doctors.

3.4 System Integration

As we have argued, middleware, while an important topic, in short has not finally been addressed in pervasive computing. By treating service units composed of distributed sensing and actuation components as ImmoBots we took the view of a robotic systems developer on distributed, heterogeneous, and communicating pervasive computing systems. Following the interdisciplinary approach that we argued for, we investigated the current state of the art of distributed sensing and actuation. The successful transfer and application of a robotics middleware Player[13] in the domain of pervasive computing has been already been shown[17]. The successor middleware of Player is ROS (Robot Operating System)[19] - which is downward compatible - includes many modern concepts of distributed architectures, as decentralized peer-to-peer networking, publish-subscribe information distribution or bi-directional services between components. The middleware further to variety of sensing and actuation systems includes visualization and simulation, both the information flow but also the physical space using e.g. OGRE (Open Source 3D Graphics Engine) and ODE (Open Dynamics Engine) open source engines. This allows designing 3D objects in a CAD style manner investigating their interaction and sending the very same information as the deployed sensor-actuator system would do - well before any physical prototyping is done[11]. This reduces the time needed for iterative development and refinement and also costs. Also, the physical paths a human would have to take in such an environment can also be predicted, calculated and optimized already during the development phase in the middleware. This also has an impact on the prediction of the interaction times with the different digital systems. The inclusion for real world simulation capabilities originates from e.g. robotic SLAM where algorithms have to be re-tested often but a real experiment is quite expensive. The presented service units have first been designed by an architect, together with a domain expert from assistive living, as CAD models. They would then be developed as virtual model using the proposed middleware and then be implemented as a physical scale model to allow and foster discussion with care receivers as end users. It thereby supports thereby the development of “product configurator”-like tool to individualized components and functionality, prior to any deployment.

3.5 System Overview

We present the current state of the implementation and development process towards modular service units for independent living. We built a physical scale model allowing us to verify the utility and usability with care receivers, using it as technology probe[17,21]. The functionality of the service unit is introduced with the example of the scale model. While the sensors for a future service unit will be different given the requirements on certification for health care technology, their data and generated events will, by the employment of ROS[20], be the same and finally, so will be the applications that can remain untouched. This is important to reduce the necessary efforts needed for the transfer of knowledge from model to the real world and it allows for parallelization of the development. Assistive applications can be developed while designers, architects and care givers discuss amount, size and human-exposed functionality. It is again important to state that the middleware allows substitution of sensors (from scale model to real world unit) without touching the application as long as the interface of the sensor drivers is kept[19].

The scale model (Fig.3) contains 12 modular motorized units for on demand available service functions, a touch sensor for each compartment, PIR sensors for general presence detection, and a ceiling mounted functional color camera for fall detection, tracking, and activity recognition, several RFID readers and embedded tags in everyday objects, a wave sound output module for audio feedback, a scale model touch screen TV for convenient audio/visual communication with the care receiver, using multi-modal human-computer interaction accounting for potential deficiencies of the inhabitants. In the scale model various computer-human-interface devices have been experimentally implemented to test their applicability and to define solution spaces for fundamental communication challenges discussed[17].

Fig. 3 Fully Functional Experimental Models of Intelligent Service Units (Room-in Room Type) The model scale is 4:1. It implements the functionality shown in Fig.1

Bathroom, kitchen andsleeping room. The bed is hidden in the back wall, bath room functionality is on the left wall behind and below the mirror, and cooking functionality is in the left compartment of the left wall.

The middleware contains, besides drivers and abstraction layers from the specific instances of sensors and actuators, the control logic. Illegal states and actions are prohibited: the cooking plate cannot be hidden in the wall if there are pots present. This complements other supportive systems as intelligent knifes or kitchens[7)8)17)]. Similar logic prevents systems to open if the care receiver is in too close proximity, or the bed hidden in the back wall (Fig.3.), where the right hand is currently updating the system) cannot be extended if the sink on the left wall is used. This basic safety assessment is calculated based upon rules, such as the extent of a component into the room and an additional safety distance. In case of erroneous user requests, the system will either automatically retreat or close conflicting modules if the sensory systems detect no usage, or issue audible or audio-visually warning and give supportive output. Besides automatic rule checking, manual rules can be added by the designers, architects or system developers. The rules always will focus on maximum safety, as the target user group might not in all cases be aware on the consequences of their actions.

3.6 Current Progress

Currently we are setting up a test bed. The test bed simulates a compact flat (32 m^2), consists of modular and flexible wall systems and can be equipped with sensors, actors and other devices from all dimensions. The goal of the test bed is to simulate and evaluate the efficiency of different layouts and configurations of smart environments. It differs from other test beds as it is completely flexible and rearrangeble in order to be able to do research on the impact of technology and configurations on living processes. The service unit described in this paper will state a first use case simulated in the environment. The deployment in the test bed will help the authors to detail the concept of the modularity and to connect it closely with various scenarios taking place in a real living environment.

4. Potential for Mass Customization of Personalized Pervasive Homecare

The service unit concept presented aims at the implementation of mass customized, performance added, reliable and affordable ambient assisted living environments through making use of the latest strategies in component system based building architecture and fabrication, as well as customer integration strategies. Basic "chassis" can be customized on factories to customer needs. Similar to automotive industry service units are kits which concentrate complexity on a compact unit or wall thus allowing for industrialized high quality and low-cost manufacturing in a highly-controlled factory environment[12]. Similar to desktop computers the robotic service unit presented can be customized and personalized through scalable modular sets of standardized sensors, medical devices, home automation components, intelligent appliances, high-tech mechatronics and robotic service devices to efficiently meet multiple requirements and counterbalance the co-existence of two or more chronic conditions specifying multimorbidity. Following the course of disease and medical treatment, robotic service units support fluent updates and easy reconfigurations by service providers, doctors, relatives or care receivers. System architecture and components on hard- and software level have been designed to allow customization and fluent updates.

5. Conclusions

We have discussed the multi-dimensional interdisciplinary challenges involved in the development and design process of pervasive healthcare technology. We have introduced the concept of modular service components as alternative approach to fully networked homes and discussed the advantages of the proposed approach. The design process pursued has been reported on, and the relevant medical and technological issues and challenges were discussed and situated in the body of related work. By the discussion of the employed middleware, facilitating simulation of both physical and digital operational sequences and workflows, and allowing for the separation and parallelism of sensing and actuation development, application development and deployment, we have highlighted the potential of robotics for future assistive pervasive healthcare environments from a very interdisciplinary perspective - from architecture to systems development. We also investigated the actual potential for mass manufacturing service units based on the presented concepts, allowing customized and personalized pervasive healthcare systems to be integrated in future homes.

Future work includes the modeling of human as “robots” in the middleware system, including the human motor apparatus. This will allow us to estimate interaction and movement times more precisely especially of physically handicapped persons and include this information in the development process to optimize computer-human interaction. This will include the modeling of reduced sensitivity and mobility models of elderly people and allow for the provision of more supportive and inclusive interactive systems[24] – as they are needed by future connected cooperative systems. As part of our future work, we will investigate how much and which information can be embedded into physical artifacts to support “embedded cognition”, allowing in-place, in-situ task and health support for care receivers.

Acknowledgement

This work has been funded in parts by the German DFG funded Cluster of Excellence “CoTeSys - Cognition for Technical Systems” and the BMBF funded project “GEWOS - Gesund wohnen mit Stil”.

References

1) Van den Acker, M., Buntinx, F., Metsemakers, JF., Roos, S., Knottnerus, JA. (1998). *Multimorbidity in general practice: prevalence, incidence, and determinants of co-occurring chronic and recurrent diseases*, Pub Med J. Clin Epidemiol, ***51***(5), 367-375
2) VanderHart, GP. (1998). *The Housing Decisions of Older Households: A Dynamic Analysis*. Journal of Housing Economics, vol. *7*, Issue 1, 21-48
3) Linner, T., Bock, T. (2009). *Continuous Customization in Architecture: towards customizable intelligent buildings*. Proceedings of MCPC2009 Conf. on Mass Customization, Personalization and Co-creation, Helsinki
4) Bock, T., Linner, T. (2009). *Service Oriented Design*. Proceedings of 2nd German AAL Congress,
5) Initlle, S., Larson, K., Tapia, EM., Beaudin, J., Kaushik, P., Nawyn, J., Rockinson, R. (2006). *Using a Live-in Laboratory for Ubiquitous Computing Research*. Intl. Conf. on Pervasive Comp., 349-365
6) Larson, K., Intille, S., McLeish, TJ., Beaudin, J., Williams, RE. (2004). *Open Source Building – Reinventing Places of Living*. BT Technology Journal, vol. ***22***(4), 187-200
7) Kranz, M., Holleis, P., Schmidt, A. (2005). *DistScroll - A New One-Handed Interaction Device*. 25th IEEE

Intl. Conference on Distributed Computing Systems Workshops, Washington, USA, 499-505

8) Consolvo, S., Roessler, P., Shelton, BE., LaMarca, A., Schilit, B., Bly, S. (2004). *Technology for Care Networks of Elders*. IEEE Pervasive Computing, vol ***3***(2), 22-29.

9) Kranz, M., Schmidt, A., Maldonado, A., Rusu, BR., Beetz, M., Hörnler, B., Rigoll, G. (2007). *Context-Aware Kitchen Utilities*. Intl. Conference on Tangible and Embedded Interaction, 213-214.

10) Aitenbichler, E., Kangasharju, J., Mühlhäuser, M. (2007). *MundoCore: A light-weight infrastructure for Pervasive Computing*. IEEE Pervasive and Mobile Computing, vol ***3***(4), 332-361.

11) Kranz, M., Schmidt, A. (2005). *Prototyping smart objects for ubiquitous computing*. Proceedings of the Intl. Workshop on Smart Objects at the 7th Intl. Conf. on Ubiquitous Computing

12) Linner, T., Kranz, M., Roalter, L. (2010). *Compacted and Industrially Customized Ambient Intelligent Service Units – Typologies, Examples and Performance*. Intl. Conf. on Intelligent Environments 2010

13) Collet, T., MacDonald, B., Gerkey, B. (2005). *Player 2.0: Toward a Practical Robot Programming Framework*. Proc. of the Australasian Conf. on Robotics and Automation (ACRA).

14) Kranz, M., Holleis, P., Schmidt, A. (2006). *Ubiquitous Presence Systems*. Proceedings of the 2006 ACM symposium on Applied Computing (SAC '06), Dijon, France, 1902-1909

15) Román, M., Hess, C., Cerqueira, R., Ranganathan, A., Campbell, RH., Nahrstedt, K. (2002). *Gaia: A Middleware Platform for Active Spaces*. ACM SIGMOBILE, ***6***(4), 65-67

16) Williams, BC., Nayak, PP. (1996). *Immobile Robots: AI in the New Millenium*. AI Mag., ***17***(3), 16-35

17) Kranz, M., Schmidt, A., Rusu, RB., Maldonado, A., Beetz, M., Hörnler, B., Rigoll, G. (2007). *Sensing Technologies and the Player-Middleware for Context-Awareness in Kitchen Environments*. Intl. Conf. on Networked Sensing Systems, 179-186

18) Kranz, M., Linner, T., Ellmann, B., Bittner, A., Roalter, L. (2010). *Robotic Service Cores for Ambient Assisted Living*, 4th International Conference on Pervasive Computing Technologies for Healthcare

19) Quigley, M., Gerkey, B., Conley, K., Faust, J., Foote, T., Leibs, J., Berger, E., Wheeler, R., Ng, A. (2009). *ROS: an open-source Robot Operating System*. Intl. Conference on Robotics and Automation.

20) Roalter, L., Kranz, M., Möller, A. (2010). *A Middleware for Intelligent Environments and the Internet of Things*. Ubiquitous Intelligence and Computing. 267-281

21) Hutchinson, H., Mackay, W., Westerlund, B., Bederson, BB., Druin, A., Plaisant, C., Beaudoin-Lafon, M., Conversy, S., Evans, H., Hansen, H., Roussel, N., Eiderbäck, B. (2003). *Technology Probes: Inspiring design for and with families*. Intl. Conf. on Human Factors in Computing Systems, 17-24

22) Larson, K., Stephen, I. (2003). *MIT Open Source Building Alliance – A house_n initiative*. MIT

23) Shimizu, N. (2005). *A House of Sustainability: PAPI - Intelligent House in the Age of Ubiquitous Computing*, Architecture and Urbanism (AU), Special Issue

24) Habraken, NJ. (2000). *The structure of the ordinary: form and control in the built environment*,

25) Kranz, M., Holleis, P., Schmidt, A. (2010). *Embedded Interaction: Interacting with the Internet of Things*, IEEE Internet Computing, vol. ***14***(2), 46-53