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Development of an Ambient Health Monitoring System for a Self-Sufficient and Independent Life in Old Age

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Zusammenfassung

Der demographische Wandel wird zum Zusammenbruch des Generationenvertrags führen. Die Konsequenz ist, dass die Rente der zukünftigen Senioren nicht ausreicht, um Gesundheitsleistungen bezahlen zu können. Allerdings nimmt der Gesundheitszustand im hohen Alter stetig ab, was zu chronischen Erkrankungen und schließlich zur Multimorbidität führt. Aus diesem Grund werden sich in Zukunft Pflegeinstitutionen und Gesundheitsversicherungen einer erhöhten, oder sogar überlastenden, Anfrage an Gesundheitsleistungen ausgesetzt sehen. Des Weiteren haben bereits heute Seniorenheime und Krankenhäuser schon Probleme ausreichend Pflegepersonal einzustellen. Dies liegt daran, dass die Arbeit in Pflegeeinrichtungen physisch und psychisch sehr herausfordernd ist, wobei die Bezahlung im Vergleich zu anderen Berufen schlecht ist. Der demographische Wandel wird voraussichtlich die Situation an Pflegeeinrichtungen zusätzlich verschlimmern. Daher müssen neue Konzepte entwickelt werden, die es Älteren und Erkrankten ermöglicht im hohen Alter unabhängig und selbstständig zu bleiben, da andererseits die Pflegeeinrichtungen überlastet werden. Da die Überlastung der Pflegeeinrichtungen und Pflegeversicherungen zum Problem führen wird, dass Senioren solche Systeme selbst finanzieren müssen, und unter Berücksichtigung des Faktes, dass mit Zusammenbruch des Generationenvertrags die Senioren weniger finanzielle Möglichkeiten haben werden, müssen diese Konzepte preisgünstig sein. Neben dem Aspekt der Kostengünstigkeit, muss auch die Nutzerakzeptanz berücksichtigt werden. Stigmatisierende Lösungen die das Gefühl einer permanenten Überwachung auslösen, oder das gewohnte Wohnumfeld zu drastisch verändern, führen zur Nutzerablehnung des Systems.

Aus diesem Grund wurde in dieser Thesis ein unauffälliges „Ambient Health Monitoring System“ Konzept entwickelt und umgesetzt. Das System ermöglicht unauffällig physiologische Parameter, wie die Körpertemperatur, das EKG, die Pulskurve und den systolischen Blutdruck zu messen. Des Weiteren ist das System in der Lage über Umgebungssensoren gefährliche Situationen zu erkennen, z. B. wenn jemand gestürzt ist und ohne Hilfe nicht mehr aufstehen kann. Um die Nutzerakzeptanz zu unterstützen, ermöglicht der modulare Entwicklungsansatz die verschiedenen Systemmodule in existierende Möbel unauffällig zu integrieren. Um den Senioren die Bedienung des Systems zu erleichtern, oder um die Daten anzuzeigen und zu speichern, wurde ein Tisch entwickelt der die Daten auf Basis von „Augmented Reality“ anzeigt. Über eine Gestenerkennung wurde eine intuitive Touchscreen-Anwendung entwickelt, die zugleich darauf abzielt, Ältere physisch und psychisch zu trainieren. Um den Erfolg des in dieser These entwickelten Systems zu untersuchen, wurden Nutzertests durchgeführt. In einem frühen Entwicklungsstadium der Systemmodule wurde ein Labortest durchgeführt, welcher ermöglichte die Verbesserung der Nutzerakzeptanz im Bezug zum Feldtest zu vergleichen. Beim Abschließenden Feldtest, bei dem 30 ältere Testpersonen das System testeten, wurde das vorgestellte System für eine Woche in einer Wohnung in Bozen Italien installiert. Unter Berücksichtigung des aus den beiden Tests gesammelten Feedbacks, wurde das „Ambient Health Monitoring System“ in der Versuchswohnung des Lehrstuhls für Baurealisierung und Baurobotik installiert. Dieses Vorgehen erlaubt in Zukunft die Genauigkeit und Zuverlässigkeit des Systems zu verbessern, sowie weiter Servicefunktionen und neuartige Module zu entwickeln und dem System nach und nach hinzuzufügen.

Abstract

The demographic change leads to the collapse of the intergenerational contract. The retirement funds available for the future elderly citizens prove insufficient as a consequence, and result in failure to pay health care services. Moreover, in old age the health status is continuously descending, which leads to chronic diseases and finally to multi morbidity. Therefore, the health care institutions and health insurances will face an increased, or even overtaxing, demand of health services. Even today care homes and hospitals have the problem to hire sufficient care staff. This is because the work in care facilities is physically and mentally very challenging, and the payment compared to other occupations is worse. Furthermore, the demographic change is expected to worsen the situation within care facilities. Therefore, new concepts have to be developed, which enable elderly and diseased to remain independent and self-sufficient in old age to avoid overtaxation of care facilities. Since the overtaxing of care facilities and care insurances will lead to the problem that seniors will most likely have to finance such a support system on their own, and considering the fact that with the collapse of the intergenerational contract, the elderly will have fewer financial opportunities, therefore the concepts have to be low-cost. In addition to the low-cost, the user acceptance has to be considered. Stigmatizing solutions, which triggers the feeling of permanent observation, or change the accustomed living environment too drastically, will lead to a rejection of the system.

For this purpose in this thesis, an unobtrusive "Ambient Health Monitoring System" concept was developed and realized. This system enables the user to measure physiological parameter unobtrusively like the body temperature, ECG, pulse curve and the systolic blood pressure. Furthermore, this system is able to identify by ambient sensors dangerous situations, e.g. in case someone has fallen and cannot stand up without help. To support the user acceptance, the modular development approach of this concept enables to unobtrusively implement these modules into existing furniture. To facilitate the seniors to control the system, or to see and store the measurement results, a table was developed, which displays the data on basis of "Augmented Reality". Via gesture recognition an intuitive touchscreen application was developed, which aims simultaneously to train people of old age both mentally and physically. In order to investigate the success of the developed system of this thesis, user tests were performed. A laboratory test was executed in an early development stage of the system modules, which enabled the developer to compare the user acceptance increase with respect to the final filed-test. At the final field test, the proposed system was installed for a week in an apartment in Bozen, Italy, where more than 30 elderly tested the proposed system. Under consideration of the feedback collected in both user tests, the "Ambient Health Monitoring System" was installed into the test apartment of the Chair for Building Realization and Robotics. This approach allows the developer to improve the accuracy and reliability of the system, as well as to develop and add gradually additional service functions and novel system modules in the future.

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1 Introduction

Ambient Assisted Living, also sometimes named as Active Assisted Living (AAL) [1] is a young research area, which tries to develop technologies for the elderly. Some people misinterpret AAL with Smart Home, since both topics are very closely related. However, both areas differ mainly in the objective and target group. Smart Home connects the key electrical applicants and services to a communication network, in order to enable remote control, access and monitoring [2].

AAL tries to increase the safety, independency and comfort of the elderly and sometimes builds upon smart home solutions [3]. The aspect of the comfort, especially, is a critical part in AAL. If an elderly person receives too much support, i.e. there is too much comfort provided by the system, senescence could be accelerated in the worst case. This phenomena occurs because of the medical law “use it or lose it” [4, 5], which means that inactivity results in fragility.

Additionally, according to Fratiglioni et al. [6], mental, physical and social activity enables deceleration of the progression of dementia. Therefore, AAL tries not only to increase the comfort like Smart Home solutions, AAL also tries to encourage the elderly both mentally and physically in order to train their fitness and sanity.

On the other hand, AAL systems have to support the elderly in their activities of daily living, when they are not able to do it alone. In old age, the human body becomes more fragile, which results in chronic diseases. Symptoms and impairments are usually tied to these chronic diseases. The AAL systems and products aim to support the elderly and people with special needs with respect to such symptoms and impairments, so that they can proceed safely and independently in their daily activities [7].

Nowadays, with the medical achievements of the last centuries, it is possible to enable even very ill or dying people to live without pain, owing to the palliative medicine [8]. The disadvantage is that mostly medical products are needed to support the elderly to live in dignity in old age. These products transform the apartment into a hospital room, which is stigmatizing for the user and reminds him or her of the currently poor health condition. Therefore, the aspect of the unobtrusive implementation is very important for AAL solutions, since stigmatization can lead to struggle in daily life [9].

However, someone may ask, why technology is the key to solving the problems of old age. To answer this question, it is necessary to understand the demographic change and its consequences for the healthcare system, which is written in section 1.1. Since the AAL is a very broad field of potential developments, where all natural science and engineering disciplines can sufficiently contribute, it was necessary to define boundary conditions, which are addressed by this thesis. These boundary conditions and objectives of this thesis are written in section 1.2. The corresponding methodology and structure of this thesis is summarized in section 1.3.

1.1 Problem Statement

The need of AAL solutions nowadays has its origin in the demographic change, which was triggered by the dropped mortality rate of children compared to the beginning of the nineteenth century. According to Uhlenberg [10], the survival rate of children (between the ages zero to 15) was 79 % in 1900. This means on the contrary that there was a 21 % chance of death before reaching 16 years old. According to Rosenbaum [11], between one third and one half of all children did not reach the adult ages at the end of the eighteenth and early nineteenth century.

Thus, in a family of seven to twelve children, no more than one or two of these children have grown up as adults. At this time, first medications against infectious diseases were found, like penicillin, which helped to defeat infectious diseases like tuberculosis. Infectious diseases at the time were the main cause for child mortality [12]. In the following years, hygiene and medical support improved, which lead to a reduced childhood mortality rate [13]. Already in 1940, the survival rate increased to 94 %, and in 1976 even to 98 % [10]. The survival rate of children between newborns and 15 years reached 99 % between the years 2007 and 2009 [14]. However, this medical success had a big impact on the family structures. According to Rosenbaum [11], children are very expensive due to high educational costs among other factors. Therefore, it is less surprising that there exists a negative relationship between family size and educational achievements [15]. This means, when from seven to twelve children suddenly all survive, then the family has to carry the costs for food and education for all children. This can be overtaxing for families and lead to the general change of the family size, where a family has only one or two children.

In response, countries experience a low birthrate (e.g. for Germany 1.50 children per woman [16]), which modifies the age distribution in the population. Therefore, the demographic change means that the low birthrate in combination with an increased life expectancy leads to a massively increased amount of elderly (65 years and older), as depicted in Figure 1.1.

a) **b)** **c)**

Figure 1.1: The age distribution of Germany. (a) The age distribution in 1900. (b) The age distribution in 2005. (c) The expected age distribution until 2050. [17]

Figure 1.1 of the demographic change, provided by Eisenmenger et al. from the Statistischem Bundesamt [17], shows that the population with an income eligible age will drastically reduce in the next years. According to Eisenmenger et al. [17], only 55 % of the population will fall between ages 20 to 64 in 2020. In 2050 (depicted in Figure 1.1 (c)) only 50 % of the population will be between 20 to 64 years old. According to Schneider and Sülber [18], this will have profound political, social and economic consequences for Germany.

The intergenerational contract, for example, will be in danger. The intergenerational contract describes that the younger generation with income finances the generations without income, i.e. the elderly and the children. This intergenerational contract worked with the age distribution in 1900 (see Figure 1.1 (a)), but it will not work with the predicted age distribution in the future. According to Ebbinghaus [19], the demographic change is the reason that the intergenerational contract will collapse and, therefore, the current generation has to finance the retirement of the elderly of today, as well as their own retirement in the future. In order to reduce the impact of the unavoidable collapse of the intergenerational contract, the politicians introduce a stepwise change [19]. The financial support for the retirement is probably not very high in 2050, which implies the private money of the elderly (e.g. for purchasing AAL solutions) is very limited.

However, primary consequences already have an impact on the healthcare sector today. The increased amount of elderly leads to an increased need in healthcare. The children of the elderly cannot care for their aged parents, due to career pressure. Additionally, hospitals and care homes suffer already under a shortage of care staff. This shortage has complex reasons, which are influenced by the individual staff, as well as relation with organizational factors [20]. In response, the demographic change will worsen the shortcoming of care staff [21]. This combination leads to an overtaxing of hospitals and care homes, especially. Health services could become a luxury in the future, which only the wealthy could afford.

Therefore, AAL solutions aim to increase the independency and self-sufficiency in old age, which will furthermore relieve care homes and hospitals. Considering the low support by the retirement agencies, the question arose, if AAL solutions should be paid by health insurances. According to Garlipp et al. [22], health insurances are very cautious in regards to overtaking the cost of AAL solutions in the future. Therefore, it is possible that AAL solutions have to be purchased privately. In order to avoid luxurious AAL solutions as an alternative for only the wealthy, researchers and developers have to consider the low-cost design factor from on the beginning, when developing novel AAL solutions.

1.2 General Requirements and Objectives

Systems are therefore needed in the future, which relieve the hospitals and care homes, and enables the elderly to stay independent and self-sufficient in old age. At the moment, several research groups are developing different prototypes (see section 2.3), which are mainly developed as standalone devices. Existing medical, Smart Home and AAL solutions, which are available on the public market, are mostly standalone devices that can also sometimes communicate with each other via an internet server. Presently, most research groups do not consider the environment (e.g. furniture, rooms or the apartment) as an important component of such a system. By unobtrusive and seamless integration of Information and Communication Technology (ICT) services and functions, the environment, e.g. the apartment, will be enabled to support automatically the inhabitant. This approach of a robotic room, aims to increase the independence and security of the inhabitant.

User acceptance for technological solutions is currently one of the biggest obstacles for researchers and developers of AAL solutions. Therefore, the system has to be developed in such a way that it can be integrated into existing furniture and apartments and are still as unobtrusive as possible. In case AAL solutions are obviously visible, everyone sees that the user is in need of such devices, which can be embarrassing. Furthermore, the user is always reminded of his or her own fragility, if the implemented AAL solutions are clearly visible. By the approach of unobtrusive implementation of ICT solutions into the environment, the stigmatization of the user is avoided. Consequently, this increases the user acceptance of AAL solutions because the apartment looks unchanged, while additional benefits, e.g. increased security, are implemented by such a system.

Generally, such a system can be separated into sensory and service modules. Sensory modules focus on capturing health related data, and have the objective to increase security and to relieve care staff, e.g. by automatically documenting the health condition. Service systems aim to support the elderly in order to keep them independent, e.g. via robotic assistance for dressing etc.

In this work, the focus is set to the sensory modules (e.g. on the health monitoring), in order to support especially the relief of hospitals and care homes. Additionally, such systems can be used by care homes alongside private apartments of the elderly. For instance, a module, which can autonomously track the fever, would relieve the nurse the burden to measure sporadically the body temperature of the seniors. The blood pressure monitoring is especially important yet time-consuming for nurses, which is more so inconvenient for some elderly. By automating such a task via novel concepts, which increase also the simplicity of such a measurement, the care staff can focus more on important tasks like the social interaction with the elderly. Additionally, the fear of being helpless push the elderly more often to call for help. Thereby, false alerts are most commonly triggered, which are a distraction for the care staff. A cost efficient and simple-to-install alert system (e.g. a fall detection) would enable the care staff to check for help only when necessary. Moreover, such a fall detection calms the elderly, since they are sure that help will come despite their consciousness if something happens.

Furthermore, if such a system is able to monitor the health status unobtrusively, the foundation is provided for future tele-monitoring applications and automated alerts. It is therefore important that the devices can communicate with each other, e.g. in a local network, which comprises several devices in one system. For this approach, one module has to be responsible for the data management of the entire system. An intuitive user interface with access to the stored data of the system modules can enable the user to use the personal health data at a physician consultation hour. Assuming that this approach will provide health data records over a long time, which documents the pathologically changes in the human body, the physicians are supported in their anamneses and diagnosis.

In addition, such system will provide an unpredictable benefit for social and medical research, since the user of such systems generate data. The data thereof shows the pathological change in health over years. For example, hospitals could be seen as a precious data treasure for studies and research, but due to the patient privacy, these data cannot be used for any study. Since noninvasive (or at least minimal invasive) data are collected in AAL, in addition to the lenient data privacy regulations, which are more lenient compared to the data privacy regulations in medical institutions, the collected data can be used more easily for research.

For this purpose, this thesis investigated the possibilities for developing such an "**Ambient Health Monitoring System**", with the focus on the health data monitoring network.

1.3 Research Methodology

To develop such a system, at the beginning a study was performed regarding the state of the art, which is provided in chapter 2. In this chapter the actual health related issues, diseases, and symptoms of elderly are provided, which are addressed by the proposed "Ambient Health Monitoring System". Pre-existing devices and ongoing research are provided as well. In section 2.4, the limitations of the state of the art are highlighted, in order to show how the proposed systems improve the state of the art.

The concept and its realization is described in chapter 3. The development of each single module, which has an individual subsection in chapter 3, always follows the same approach: First, a literature recherché was used to work out the technical concept, which was iteratively developed via functional test. Once a function was satisfactorily developed, user tests with the elderly were executed.

The user test execution and results are provided in chapter 4, which describes two user tests: A laboratory test in section 4.1 and the final field test in section 4.2. The laboratory test was the first test, which was executed in a controlled laboratory environment with the elderly. The results of the laboratory test were used to improve the so far developed prototypes. At the end, a field test showed which improvements were successful, and which modifications were less promising (see section 4.2). On grounds of the field test, the final implementation, which is described in section 3.4 was performed. By this approach, it was possible to consider the user opinion at an early development stage of the system and to compare the progress of the development in a later development stage. Thereby, it was feasible to ensure that the user acceptance of the proposed "Ambient Health Monitoring System" would be at least larger than 50 % of the participating test sample group.

The decision to document the tests and the implementations independent of the timeline in this work was made in order to provide the reader an easy impression of the progress of the user acceptance by comparing both tests (i.e. the laboratory test and the field test) directly with each other in chapter 4. Additionally, for someone who is more interested in the technical implementation, it is more convenient to read the implementation undisturbed by user evaluation in chapter 3. Nevertheless, the timeline is contained in this thesis, since cross-references allows the reader to see if an implementation happened before or after a test.

In chapter 5, a conclusion and an outlook are provided, which describes how the individual developments of the modules of chapter 3 are already under further development. Additionally, an outlook of the future AAL research topics and related research areas is provided in chapter 5.

2 State of the Art

In this chapter, the state of the art is presented, which proves the necessity and novelty of this work. The requirements of section 1.2 provide just a first idea what has to be developed. In order to develop such a system, it is important to understand the daily issues of the elderly, caused by age-related frailty. Therefore, in section 2.1 the age related diseases are listed, which are addressed by the developed "Ambient Health Monitoring System" in this thesis. The state of the art regarding commercially available devices, which are commonly used in health issues provided in section 2.1, are listed in section 2.2. In order to compare this work with the ongoing research, section 2.3 provides an overview of other research groups, aiming to support the age-related diseases mentioned in section 2.1.

Finally, in section 2.4 the current limitations of the commercial solutions of section 2.2 are highlighted and summarized, in addition to the ongoing research projects of section 2.3. The objective of this section is not to prove the bad quality of the existing solutions and research projects, but to show how the proposal of this work, especially the development of the "Ambient Health Monitoring System" (which is described in chapter 3) contributes to the existing market and research gaps.

2.1 Age related Symptoms, Diseases, and Issues

Health is one of the most precious possessions of someone. According to the World Health Organization (WHO), health is defined as follows: "*Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.*" [23]

These requirements are difficult to fulfill for most people, since even trivial health issues like overworking, a cold, or skin injuries lead to the conclusion of sickness according to the WHO definition. What is really meant by this statement is that health can be affected not only by diseases, but also by either mental or social issues. Additionally this phrase indicates the relationship between well-being and health.

Chronic diseases affect not only the mental and/or physical condition, but also the social interaction with others, e.g. when someone becomes too frail to meet with others. Chronic diseases are incurable diseases, and due to the age-related physiological changes, the probability that a disease becomes a chronic disease is greater in old age. This phenomenon is due to the telomeres. Telomeres can be seen as a protective extension of the DNA code at the ends of the chromosomes, where no significant messages are stored. After each cell segmentation, the telomeres become shorter until the telomeres are completely depleted and lead to segmentation inability of the affected cell [24]. Therefore, the WHO statement underlines the consequence of chronic diseases, since physical, mental and social well-being is permanently disturbed by chronic diseases.

Depending on the lifestyle and the genetic predisposition, each individual has a different exposure rate to a chronic disease. Therefore, AAL solutions are not addressing the "old age" as the problem, rather AAL solutions address the prevention and living support of chronic diseases. There is a very big variety of chronic diseases someone can experience in old age.

Therefore, in this section, only some selected chronic diseases and their symptoms and issues are provided. Although fever is not a disease, rather a symptom for countless different diseases, this symptom can be used to support the prevention of diseases in old age.

So, the "Ambient Health Monitoring System" needs an unobtrusive automated fever detection module. Why the fever is an important aspect for elderly is explained in subsection 2.1.1, whereas the concept and prototypical realization of the unobtrusive fever detection is described in section 3.1.

A more serious health threat are the cardiovascular diseases, which are introduced in subsection 2.1.2. The issues of the cardiovascular disease are addressed by the "Ambient Health Monitoring System" of the cuff-free blood pressure monitor module of section 3.2.

The fear to fall is mostly triggered by osteoporosis, which is explained in subsection 2.1.3. The concept and prototype realization of the novel module and related issues are described and addressed in section 3.3.

Finally, the user acceptance of the elderly regarding ICT solutions is discussed in subsection 2.1.4. This subsection is crucial in order to understand the development approach of the user interface of the "Ambient Health Monitoring System", which is described in chapter 3 under subsection 3.4.2.

2.1.1 Fever: An Important Symptom

According to Mackowiak [25], fever is mostly part of the immune response of the human body, which aims to defend the body against bacteria, viruses and other pathogens. Therefore, fever is not only assisting the diseased to recover, it is also a symptom of infections, which can be measured using medical thermometers (see section 2.2.1). However, fever also can become a life threat, e.g. if the temperature rises above 43 °C [26].

According to Persson [26], the physicians nowadays are still not sure if the fever is useful as an immune response, or rather is redundant. The fact is, fever is a regulated increase of the body temperature. In order to increase the temperature to become a fever, the body's target temperature is adjusted when the fever is triggered. This leads to a cold feeling and triggers chills (see Figure 2.1).

The chills increase the temperature by shivering, which consumes energy. In addition, fever between 39.5 °C and 40 °C are very exhausting for the metabolism and the cardiovascular system [26]. Therefore, especially for seniors and children, high fever can become life-threatening, because of the intense stress on the cardiovascular system. Painkillers, like paracetamol or aspirin, can normalize the target temperature (i.e. suppress the fever) and thereby reduce the physiological stress. In case the fever drops, whether a result of immunerecovery or the assistance of painkillers, the body feels hot and starts to sweat (see Figure 2.1). Expectedly, painkillers can trigger chills as soon as the effects vanish (e.g. after eight hours), in order to increase the body temperature to the target temperature.

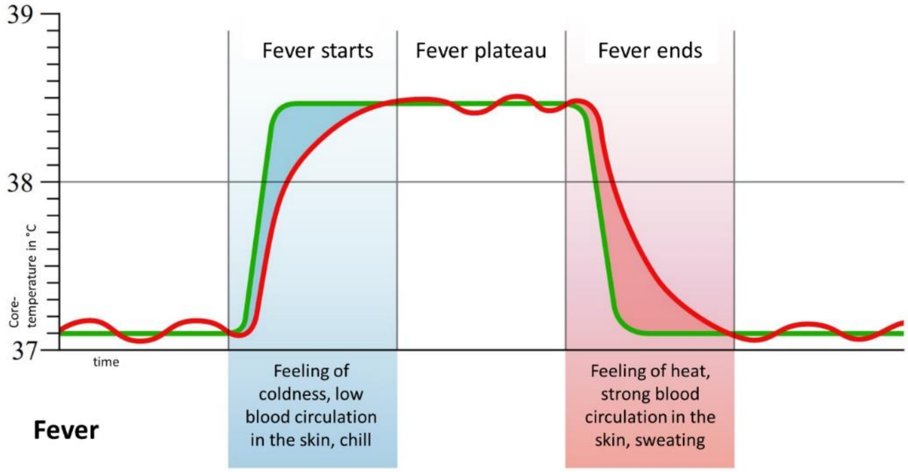


Figure 2.1: Usual progress of fever. The green curve shows the targeted temperature value of the body, regulated by the hypothalamus. The red curve shows the body temperature, regulated by chill and sweat. Picture based on Silbernagel and Lang [27, 28].

Therefore, the measurement of fever is not unimportant, since high fever must be treated especially in old age. However, the body temperature is not only of high interest for treatment, but also prevention. For example, typically viruses like the influenza or gastro-enteritis pathogens tend to trigger a fever [29]. Of course, this does not mean that by identifying a fever symptom alone such a serious disease can be diagnosed, but under consideration of further measurement results, the body temperature (or fever value) can support physicians in their diagnosis.

According to Whitley & Monto [30], children, pregnant women and the elderly belong to the risk group of serious influenza-related complications for the influenza. Even though vaccinations are a suggested prevention for this risk, they are especially limited for seniors because of the suboptimal antibody response [30]. Therefore, the elderly have to adjust their behavior, e.g. when having symptoms of an influenza to do less sport, and to spare oneself physically etc. In this case, the elderly person should not leave the apartment before recovering, especially in the scenario of bad weather conditions (e.g. cold, rain, snow etc.). Furthermore, fever can be a symptom occurring as a response to diseases not everybody knows, e.g. leukemia [31]. Acute myeloid leukemia is especially common amongst the elderly [32].

2.1.2 Cardiovascular Diseases and Hypertension

Cardiovascular diseases are one of the most often occurring chronic diseases in old age [24], wherein cardiovascular diseases can be seen as the summary term, which includes several dangerous diseases. The chronic ischemic heart diseases (also known as coronary artery disease), acute myocardial infarctions (heart attack), heart insufficiency (heart failure), hypertensive heart diseases (high blood pressure) and the stroke belong to the group of cardiovascular diseases. In Table 2.1 the mortality reasons in Germany from 2015 are listed, where these cardiovascular diseases rank within the top ten causes for death, which proves how dangerous cardiovascular diseases really are.

Table 2.1: The ten most often occurring reasons for death in Germany in 2015. [33]

Number	Death reason / Disease	Amount
1	Chronic ischemic heart diseases	8.0 %
2	Acute myocardial infarction	5.5 %
3	Lung cancer	5.2 %
4	Heart insufficiency	5.1 %
5	Other chronic diseases	3.1 %
6	Dementia	2.9 %
7	Hypertensive heart diseases	2.6 %
8	Breast cancer	2.1 %
9	Colon cancer	1.9 %
10	Stroke	1.9 %

Summing the percentages of the aforementioned diseases (i.e. number one, two, four, seven and ten) in Table 2.1, shows that 23.1 % of all deaths are related to cardiovascular diseases in general in 2015. The death rate in countries like China, Russia, or India is even worse, whereas there are many countries with similar mortality rates like Germany [34].

The reason why cardiovascular diseases occurs so often in these countries is because of the so-called metabolic syndrome (also known as disease of affluence). Physicians understand within the metabolic syndrome, the following four symptoms exists: Hypertension, obesity, insulin resistance, and a disorder of the lipid metabolism. The symptom of the disorder of the lipid metabolism can be divided into two subcategories: hypertriglyceridemia and a low HDL cholesterol [35].

Typically the metabolic syndrome occurs in countries where the citizens are quite wealthy (i.e. industrialized countries like USA, Germany, UK etc.), since here high age, inactivity and over consumption triggers the metabolic syndrome. This dangerous development of the metabolic syndrome can lead to injuries along the inner vessel wall (the endothelium vessel wall). In case a human vessel has any inner injury, where lipids can start to attach at this position, a stenosis starts to grow (i.e. a narrowing in the vessel) [36]. The resulting stenosis leads to an undersupply of blood to the affected tissue region behind the stenosis. Consequently, the blood undersupply leads to an undersupply of nutrition and oxygen for the cell of the affected tissue.

In case this pathomechanism is affecting the coronary artery, which is responsible to provide blood to the heart muscle, the so-called chronic ischemic heart disease is triggered. According to the Statisches Bundesamt [33], this was the leading cause of death in Germany in 2015 (see Table 2.1). As a result, the patients suffer a heart insufficiency. This can also be triggered by other factors, like a long-term hypertonia, myocarditis, myocardial infection, etc. [37].

Some patients develop a thrombus through the stenosis, which means that thrombocyte attaches to the lipids of the stenosis, which accelerate the narrowing process of the vessel. Thrombocytes normally have an important role in case of injuries, since they are responsible for the blood coagulation. If a thrombus obstructs a heart vessel so that the heart tissue behind the stenosis starts to die (i.e. a necrosis is triggered at the heart), then the physicians speak about (acute) myocardial infarct [36], which is the second most common cause of death as visible in Table 2.1.

In case the systolic blood pressure is chronically larger than 140 mmHg, or larger than 90 mmHg for the diastolic value [38], even without the other symptoms of the metabolic syndrome, physicians call this a hypertensive heart disease [39], which is the seventh most common cause of death in Table 2.1.

In case this pathomechanism is not affecting the coronary artery of the heart, but an artery of the brain, the physicians speak of a stroke, which is on place number ten under the mortality reasons in Germany (see Table 2.1). There are even more diseases, which can be triggered by the metabolic syndrome, e.g. the peripheral vascular disease, or the phlebothrombosis, which again lead to different sequelae. However, these diseases are not further discussed in this work.

Since hypertension heart disease, as well as the metabolic syndrome, address both the high blood pressure as a major symptom, it is important to monitor the blood pressure regularly, in order to intervene in time. Additionally, according to Wolf [40], hypertension is the major risk factor for strokes. However, who is measuring the own blood pressure without reason, e.g. a disease or because of a symptom? Especially high blood pressure is starting insidious and symptom free, and therefore a monitoring system is necessary for recognizing health threatening blood pressure changes early.

2.1.3 Osteoporosis and the Fear to Fall

Osteoporosis is a disease, which leads to a loss of bone substance, resulting in an increased fragility of the bones. Even minor falls can cause fractures because of the increased fragility triggered by osteoporosis.

According to Land and Murer [41], a 20 year-old human has the highest bone density, which starts to decrease after this age, continuously. Therefore, in old age osteoporosis is quite common. Furthermore, females are more likely affected than are males, because of the lack of the hormone estrogen. There are several studies [42, 43, 44], which prove that the mortality rate among the elderly is greater. The risk for a hip fracture is especially increased, as is the fear to fall for people who suffer from osteoporosis [45].

Furthermore, investigations showed that in Germany the amount of hospitalized individuals under 65 years old is decreasing, while the amount of hospitalized people older than 65 years old is increasing [46]. In addition, in 2010 the femur facture was the second highest reason for elderly females to stay in hospital [46], which further indicates the impact of osteoporosis and the related risk of fractures by simple falls.

Brownsell and Hawley [47] found out that in case an elderly has fallen, the fear to fall again is amplified. In addition, the fear is an important risk factor to trigger a fall accident. Therefore, even if a fall detection is not preventing directly a fall and related fractures, the fall detection increases the feeling of security according to Brownsell and Hawley [47], which can be seen as an improvement of the life quality. Furthermore, since the fall detection promises immediate help, the users feel more self-confident, which further induces the prevention of falls, since this suppress the risk factor of the fear.

According to Body [48], the general prevention management of osteoporosis is the avoidance of nicotine and excessive alcohol intake. Immobility, e.g. triggered by the fear to fall, is an important risk factor, too. Body [48] stated especially the importance to prevent falls for the elderly.

An additional complication of osteoporosis is that steel implants cannot easily be implanted into the bones of an osteoporosis patient, since artificial joints (e.g. at the hips) will loosen faster from the bones. The screws, which fix the artificial joint in place, will weaken with progression of the osteoporosis, since the bone structure around the screws is permanently reducing and leads to a weak screw-bone interface [49]. Furthermore, bone fractures need more time to heal, which can lead to a considerable morbidity, and may result to a decrease in life quality [50].

2.1.4 User Acceptance of Elderly and ICT Solutions

In old age, the human intelligence morphs from a so-called fluid intelligence to a crystalline intelligence [51]. This means that in old age, it is more difficult to learn something new, but it is easy to apply existing knowledge and experience. Therefore, the elderly have difficulties learning the use of new ICT solutions, especially when software updates change the Graphical User Interface (GUI) quite often, e.g. like the internet browser, text programs etc. However, according to Conci et al. [52] this does not generally mean that the elderly reject new ICT solutions, as long as the ICT solutions sooner or later meet the expectations of the elderly.

Furthermore, age-related diseases lead to problems when using ICT solutions, since most ICT solutions are targeting younger customers. For example, according to Hwangbo et al. [53], the size of buttons, including the related spacing, is important in order to achieve a good pointing performance of the elderly on smartphones. Diseases like Parkinson additionally affect the motor skills, which also is a factor that makes learning to use (or learning from) ICT solutions difficult. Therefore, Lam and Chung [54] demand that appropriate user-interfaces for the elderly have to be visual and interactive, and not only comprising sound and text.

As soon as the elderly see the benefits of ICT solutions, they are willing to learn the use of ICT applications and accept the new technology [55]. Therefore, the ICT solutions, or in this case, the user interface to the “Ambient Health Monitoring System”, has to be as intuitive as possible, in order to ensure a user acceptance.

2.2 Commercially Available Solutions

Today's medical solutions are limited; otherwise, chronic diseases like osteoporosis (see subsection 2.1.3) would be curable. However, since chronic diseases are not curable, the aim for research has been to develop systems, which support the user in daily activities, in order to sustain the individual's independence.

The possibilities for such systems are countless; however, this work focuses primarily on capturing health related data, like a novel fall detection system (see section 3.3), which increases the feeling of security (see subsection 2.1.3). Based on the results in this work, further developments are planned, which support the more active AAL systems, e.g. calling an emergency robot for help (see subsection 5.1.3). One approach to develop such AAL systems is to combine existing devices and solutions with something new.

Therefore, in this section, the commercially available technologies are discussed. There is also a discussion about how the available technologies presently enable the user to measure the symptoms, which were introduced in section 2.1. The different possibilities to measure the fever according to the state of the art are summarized in section 2.1.1. Current methods of the blood pressure measurement are described in subsection 2.2.2. Commercially available solutions for fall detections are summarized in subsection 2.2.3. Different possibilities to interact with ICT solutions using commercially available devices are listed in subsection 2.2.4.

2.2.1 Fever Measurements

Typical body areas used to measure the fever are the forehead, sublingual (i.e. under the tongue), rectal, or axillary [26]. The most accurate results normally can be measured rectally. Due to this inconvenient measurement technique, mostly sublingual or axillary are used.

According to Pearce [56], Galileo in 1592 already developed a rudimentary device, which was used for temperature measurements. Although there was no scale and the accuracy was also not given, the mechanics are the same as they are in the mercury thermometers.

The mercury thermometer, invented by Huygens in 1665, was one of the first thermometers, which was used in the clinical environment for a long time [56]. Since mercury tends to transform into a gas, which is toxic for humans when aspirated, soon it was replaced by galinstan [57]. Both devices work on the same principle. A small, very narrow glass tube is filled with the appropriate liquid (e.g. galinstan), which expands depending on the temperature increase. Thereby, a small glass thorn is moved up, which detaches, in case the liquid cools down, since mercury and galinstan tend to shrink when exposed to a colder environment. This allows the largest temperature to be captured by this device. Therefore, the thermometer has to be shaken so that the glass thorn can be lowered for a new measurement. Since the small narrow glass tube is protected by a larger glass tube, only the body temperature can affect the liquid via the test prod of the medical thermometer.

Even nowadays, the galinstan medical thermometers are used in hospitals, since they do not need any battery, unlike electronic medical thermometers.

Electronic medical thermometers normally use resistors, which adapt their resistance depending on the environment temperature (widely known as thermistors) [58]. These devices measures via a test prod the body temperature as long as the value is increasing. If the temperature value stops to increase within a given time, the thermometer stops the measurement and displays the result in a small digital window.

Both devices, the galinstan medical thermometer and the electronic medical thermometer, need some time to capture the body temperature. Therefore, there exist devices, which enable quick and remote measurements exploiting infrared sensors. These medical thermometers focus the infrared emission of a body via a lens on a sensor. There are devices, which measure on the eardrum or on the human skin via infrared [58]. The big advantage is the very short measurement time. However, to measure correctly it is important to aim carefully with the thermometer in order not to miss the measuring spot [59]. Also when measuring, there is still a small risk of missing the measurement spot (e.g. at the eardrum) with the infrared sensor, which will lead to false values.

Additionally, measuring on the eardrum makes disposal probe covers necessary, in order to avoid cross infections [60]. The disposal probe covers are not necessary in case of remote measurements. Thereby quick mass screenings are possible (e.g. in public area), but again the accuracy depends on how accurate the measurement point was met while measuring.

2.2.2 Blood Pressure Measurements

The human body possesses a high-pressure system, which affects mainly the arteries, and a low-pressure system, which affects mainly the veins. The methods and devices for capturing the blood pressure nowadays focus on the measurement of the high-pressure system [38].

The most common blood pressure measuring technique is named according to its inventor, Scipione Riva-Rocci [61]. In the Riva-Rocci method, the person who is measuring (normally a nurse) must find the pulse at the wrist. Via a cuff, pressure is applied to the brachial artery of the upper arm, which will stop the entire blood flow to the arm [62]. At the cuff is a valve and a manometer attached, which can be used e.g. by the nurse to open the valve and reduce slowly the pressure which is displayed on the manometer. In the Riva-Rocci method, the value of the manometer is the systolic blood pressure, where the person who is measuring first time feels the pulse again. This method just needs the arm cuff (without any battery or other power supply issues), and can be executed even in loud areas. However, the accuracy is very dependent on the experience and the subjective impression of the measuring person. Additionally, it is only possible to measure the systolic blood pressure, i.e. the maximal pressure in the arterial system, which occurs with each heartbeat.

The physician Nikolai Sergejewitsch Korotkow improved the method of Riva-Rocci by using a stethoscope. In the Korotkoff method, the one who measures places the stethoscope above the arteria at the crook of the arm. Here as well the cuff is used to stop the blood flow in the arm, as it is done in the Riva-Rocci method. When opening the valve and slowly reducing the pressure, the person will hear the turbulences of the blood flow, as soon as the systolic blood pressure is slightly larger than the cuff pressure (see Figure 2.2).

The sounds caused by the turbulence are called Korotkoff sounds [61, 63]. Since in unobstructed vessels a laminar blood flow exists, the one who measures cannot hear the Korotkoff sounds without any stenosis e.g. caused by the cuff (see Figure 2.2). Therefore, the last audible Korotkoff sound is the last pressure of the cuff, which is slightly larger than the diastolic blood pressure, which represents the minimum blood pressure. The advantage of the Korotkoff method is that next to the systolic blood pressure value, the diastolic blood pressure value can also be measured. On the other hand, a silent environment is necessary in order to measure accurately.

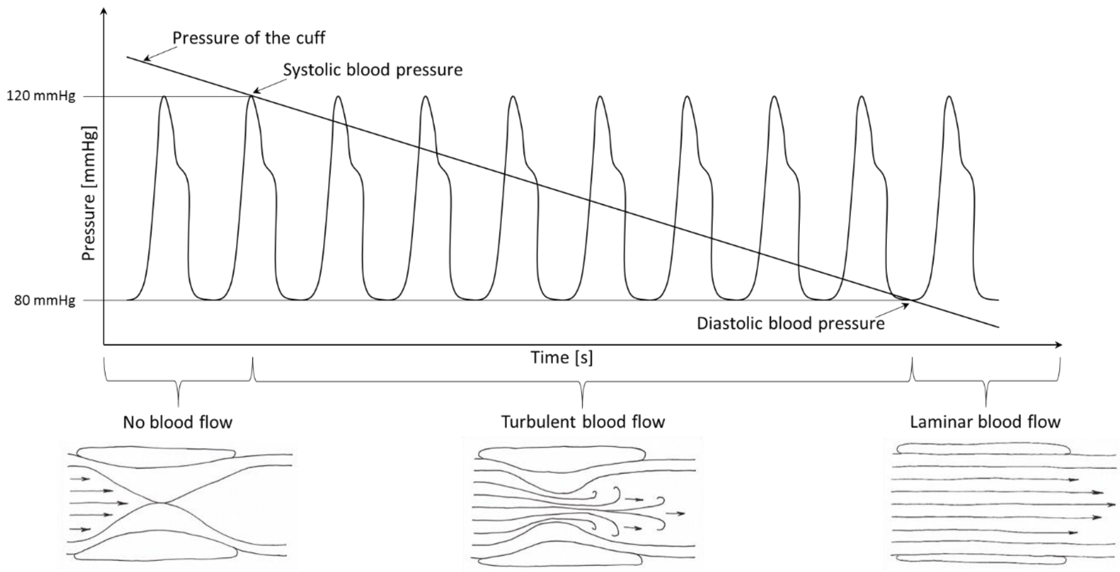


Figure 2.2: Schematic principle of the blood pressure measurement via the Korotkoff method.

Because of the subjective impression of the person who measures, the accuracy of both methods, the Riva-Rocci and the Korotkoff method, is questionable [64]. Based on cuff method also electronically blood pressure monitors, devices are working up to today. There are two measurement spots for electronic devices: The wrist and the upper arm.

The reason for these specific locations is that the blood pressure monitor needs to be at the same height as the heart, since there the blood pressure level is not influenced by the gravity [38]. Therefore, the wrist device must be placed with relaxed muscles at the same height of the heart.

According to Langewouters et al. [65], the French physiologist, Marey, observed in 1885 that the pressure chamber of a cuff is fluctuating with the frequency of the pulse. These fluctuations behave exactly like the Korotkoff sounds and therefore are used as measurement input for the blood pressure via a piezo-resistive principle, as in Figure 2.3 depicted. Of course, this means that also electronic blood pressure monitors use a cuff in order to contract the arteries and cause the pulse oscillations.

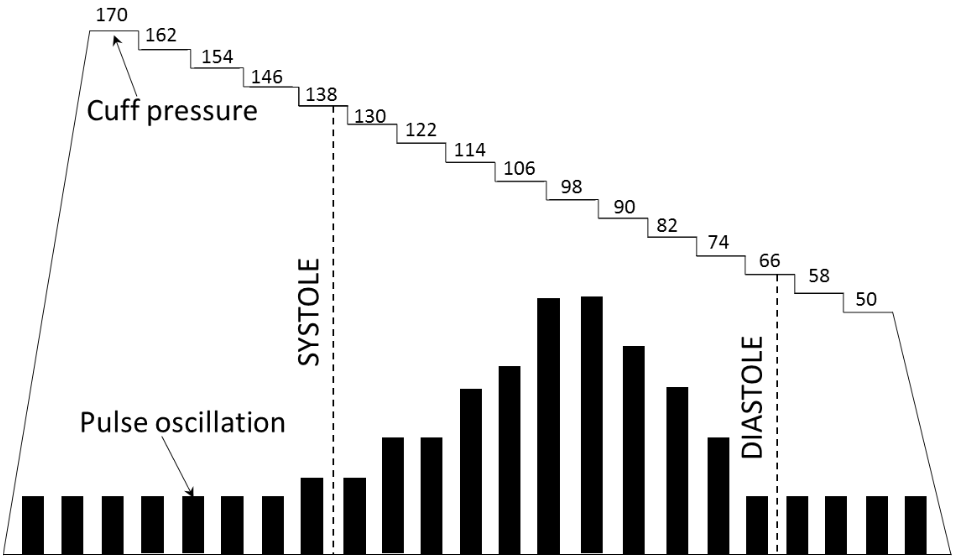


Figure 2.3: Schematic example how a blood pressure monitor detects the systolic and diastolic value via a microphone or a pressure sensor.

The resting blood pressure is interesting for medical purposes, especially the blood pressure while sleeping. In case the blood pressure is too high for too long, without appropriate physical conditions (e.g. sports), the development of cardiovascular diseases is supported (see subsection 2.1.2). In case there is a suspicion for a hypertension (high blood pressure), a person has to wear a blood pressure device for long-time monitoring (as depicted in Figure 2.4), which is automatically measuring blood pressure every 15 to 30 minutes [66].

Figure 2.4: Blood pressure monitor (at the belt) for longtime blood pressure measurement. [67]

Alternatively, it is possible to measure the blood pressure invasively, by interfacing a catheter, which is directly inserted into an artery and connected to an electronic transducer amplifier, which forwards the signal to a monitor. This method is the most precise in measuring the blood pressure. However, due to its invasive nature and related risks (e.g. infection), it is not applicable in the AAL field. For example, this method is used in order to evaluate the accuracy of different measurement methods, e.g. the accuracy of the pulse wave velocity method [68].

2.2.3 Fall Detection Systems

Because osteoporosis leads easily to fractures, which slowly heals and increases the morbidity of the affected (see subsection 2.1.3), there is a market that focuses on solely fall detection.

In the past, the forces and impact were mostly for research purposes of interest, when engineers tried to measure a fall. People, e.g. the elderly, were equipped with accelerometers and gyroscope sensors [69]. Since the mid ‘90s, the costs for MEMS IC sensor for gyroscopes and accelerometers purpose decreased and now these sensors can be found in countless devices. Smartphones, especially, nearly always possess these sensors. Therefore, fall detections are nowadays mainly an issue of software, i.e. interpreting the acceleration values correctly. In each app store, (e.g. from Windows, Google, or IPhone) applications (Apps) promise the user to detect a fall [70, 71].

Since additional add-ons entered the market, e.g. smart glasses (e.g. the Microsoft HoloLens [72], or Vuzix M100 [73]) or smartwatches, the apps can operate on several body parts. Fall detection Apps are therefore developed to detect falls, while capturing acceleration values at the hips or at the wrist [74]. However, these approaches need at least a smartphone, as well as access to the App store, which most elderly do not have. The other disadvantage is that even if an elderly owns a smartphone with an appropriate App, which was installed for fall detection, it is necessary to carry the smartphone (or smartwatch etc.) on the body the entire time.

Next to these software solutions, special wearable devices like “Medical Guardian”, “Bay Alarm Medical” [75] or “Philips Lifeline” for automated health alerts, which include fall and motion detection, are available on the market [76]. Here, additional sensors are used in order to increase the reliability of the fall detection, e.g. vibration and tilt sensor, barometer etc. However, these devices suffer under the same problems, like the smartphones and smartwatches; they have to be worn on the body. Additionally, according to Colón et al. [77] fall detectors like “Alert1”, or “Medical Guardian” need to be in range of a base unit, which reduces the movement space of the user.

Furthermore, these fall detections use wearable sensors, which are not always working in the home environment, e.g. in case someone takes off the wearable (for example when showering or sleeping in bed). Therefore, another approach, which is available on the public market, is the installation of a fall detection into the environment. The SensFloor [78] from Future Shape [79] advertise to install a fall detection in the floor. For this purpose, a capacitive grid is installed in the floor, which enables wireless communication with the fall detection system via a computer, to estimate the body surface size on the floor. Similarly to a smartphone, the capacitive grid is responding on capacitive changes on the surface, which are particularly triggered by water contained in the human body. Therefore, such systems have problems in environments where a lot water is present, e.g. bathroom or kitchen. Nevertheless this solution is already in use e.g. in care homes, where care staff is alerted in case a fall was detected by the SensFloor.

2.2.4 Human-Machine Interfaces

The human-machine interface is the part of a device or system, where the user can setup and interact with the device or system. The classical human-machine interface for a computer is currently the keyboard and the mouse. In this subsection, a short historical introduction about the development of the mouse and the keyboard is used to explain why these classical interfaces are not appropriate for AAL solutions, before alternative possibilities are introduced.

Using a keyboard, a user can control the computer and related ICT solutions. The keyboard, especially the layout, originates from the typewriters from 1873. The alignment of the different letters of the keyboard was in that way prepared by the Sholes brothers so that the type bars rarely jam [80]. However, the countless functions offered by computers and ICT solutions lead to the keyboards nowadays having even more keys, allowing operating the devices with different shortcuts.

Additionally and unthinkable to miss, the mouse complements the keyboard. The mouse was invented by Douglas Engelbart in 1963 [81] in order to provide a novel interaction possibility with machines. Before, computer and ICT solutions where operated exclusively only via keyboard. At this time, the use of the mouse was not given as the software were not prepared for such an interface device. Therefore, it needed approximately 18 years, before the mouse became interesting as a user interface. This was because of the “Xerox star”, which was the first computer with a GUI [81].

Even today, it is possible to control a desktop computer only by mouse, since virtual keyboards can be controlled using this intuitive interface. At the beginning, a mouse used a ball, which rotated two rollers that captured the x- and y-movement. Later, the ball mouse was replaced by the optical mouse, since the mechanical ball solution suffered from dirt accumulation over time [82]. One of the first commercial successes for personal computers was the “Apple Macintosh”, which entered the market in 1984. In the next years, several solutions with GUI and mouse entered the market [81].

Due to the “late” success of personal computers, the elder generations still have problems operating computers and similar ICT solution, even with the intuitive keyboard and mouse interface [83]. Prior to commercial use, computers were used mainly in appropriate occupations. Therefore, elderly have to get used to, or even learn to, control a computer or related ICT solutions via mouse and keyboard. This is difficult for elderly because of the changed learning behavior in old age (see subsection 2.1.4). Although the keyboard and mouse have already a long history, the use for people with physical or mental disabilities is very difficult and results in performance errors [84], which underlines the necessity to develop alternative human-machine interfaces.

That is why in the last years alternative user interfaces were developed, like the speech recognition. The software Siri, Google [85], Cortana or Alexa [86] enable to remotely control the smartphones, or even smart house applications. These software use audio files and speech recognition to simulate thereby a very natural communication between human and machine. The issue here for elderly is that a proper pronouncement is mostly necessary, since dialects (or speech impediments) cause problems for voice recognition [87].

Gesture recognition is another interface approach, which is nowadays also used and is quite intuitive, depending on the mechanics. Especially in the video game sector, this interface is of high interest. Devices like the Xtion Pro Live from Asus or the Microsoft Kinect [88], which are depth cameras, are potentially able to control computers with the appropriate software [89]. The depth cameras enabled new possibilities in the last years, e.g. improved motivation of rehabilitation training, since the rehabilitation games are working via gesture recognition [90].

Touchscreen and the Leap Motion sensors enable the user to operate computer applications by hand gestures [91]. It is even possible to control robots via hand gestures [92]. In addition, touchscreen monitors can be seen as a gesture recognition, which is very intuitive [93].

Furthermore, in the last years the augmented reality via Vuzix M100 [73] and HoloLens [72], or virtual reality devices like the Occuls Rift [94], or HTC Vivie [95] entered the market, and offer both (head) position tracking via accelerometers and gesture recognition techniques, which enables the user to trigger specific functions. However, when elderly wear such devices, cyber sickness is easily triggered [96]. Cyber sickness, also known as simulator sickness, is a specific type of visually induced motion sickness [97]. Therefore, such applications are less promising than main user interface for the elderly.

2.3 Research Proposals and Solutions

Although there are already several commercially available solutions (see section 2.2), which address the mentioned symptoms, diseases and issues of section 2.1, the efficiency is momentarily suboptimal. Therefore, several research groups search for new or alternative technologies and approaches to improve the independence and life quality of the elderly.

Therefore, in this section an overview of current research proposals and projects is provided. Ongoing research about thermal imaging for fever detection and its use for health care applications is provided in subsection 2.3.1. For cardiovascular diseases, the electrocardiogram (ECG) is one of the most powerful tools for research and treatment. Therefore, the actual research regarding the ECG and alternative methods in comparison for investigating cardiovascular diseases can be found in subsection 2.3.2. The actual research about fall detection is provided in subsection 2.3.3, and an overview of research for human-machine interfaces for the elderly and AAL applications is provide in subsection 2.3.4.

2.3.1 Research of Thermal Images

Thermal images are used in research mostly for investigating environmental heat distribution, e.g. looking for hotspots on solar panels or batteries [98] or investigating thermal isolations in facades [99]. However, more exotic research for thermal images also exists, e.g. thermal images for agriculture [100]. Recently a big research area is the medical use of thermal images. For example, Godoy et al. [101] investigated the possibility to detect cancer via thermal imagining. In addition, investigations for the use of thermal imaging exist, which are more basic e.g. the investigation for the accuracy of thermal imaging for fever detection [102, 103, 104, 105].

The medical interest in thermal images is related with the risk of pandemics. Due to the easy possibility to travel over the world via airplanes, diseases can spread nowadays much faster than they did in the past. Therefore, the risk of epidemics or even pandemics, like the first influenza pandemic in 2009, is increased [106]. According to Simonsen et al. [107] mostly the elderly are dying due to an influenza infection. In order to diminish the risks, e.g. of influenza pandemics, quick screens are introduced e.g. at airports via thermal cameras [108].

Since the measurement principle is very similar to the infrared thermometer device of subsection 2.2.1, it is not surprising that the studies confirmed that thermal images could be used for identifying fever. Additionally, the studies also investigated the best measurement position for a fever detection via a thermal camera. According to Ring et al. [102] two positions are very promising: the forehead and the eyes, whereas the forehead is an easy target, but lacks in the accuracy [104]. The eyes are very accurate (with the same accuracy as the measurement on the eardrum), but it is very difficult to meet the eye with the infrared measurement point [102]. Therefore, the studies request to automate this process.

The automated fever detection would have a prevention aspect, since it can warn the user and thereby support the user's habits to be more cautious and reduce the risk of infection, e.g. by rescheduling the daily activities or journeys to other countries.

2.3.2 Electrocardiography: A Cost Efficient Tool for Curing and Research.

Along with the long time blood pressure measurement, the ECG is a common tool for investigating the health condition for cardiovascular risk patients [109]. However, the ECG nowadays is mostly not implemented in AAL applications or home environment, since the interpretation of the ECG requires experience and medical education. More typical than AAL implementation, the pulse sensors, or blood pressure monitor count the pulse next to the blood pressure measurement.

However, the ECG delivers more than the pulse. Educated physicians can interpret an ECG and diagnose the stage as well as the area of a heart problem, e.g. caused by the cardiovascular diseases (see subsection 2.1.2). Therefore, this application belongs more to the research section, since the ECG is used nowadays by physicians for both curing and researching [109]. The ECG measures the electrical signals of the heart (i.e. the electrical sum of all myocardia cells [110]). In addition to the health problems, physicians research the impacts of medicine [109], habits and lifestyle issues [111], fitness [112], stress level [113] etc. via the ECG.

The ECG was developed by Augustus Waller in 1887, but the success of the ECG is credited by Einthoven's modification of the string galvanometer [114]. Einthoven defined thereby the measurement method via the Einthoven triangle [110, 115] (see Figure 2.5).

Since Einthoven defined the ECG measurement, the depicted leads in Figure 2.5 are named Einthoven I, II and III. The amplitude of the leads I – III (see Figure 2.5 (c)) depends on the electrical heart vectors alignment to the measurement vector of the electrodes.

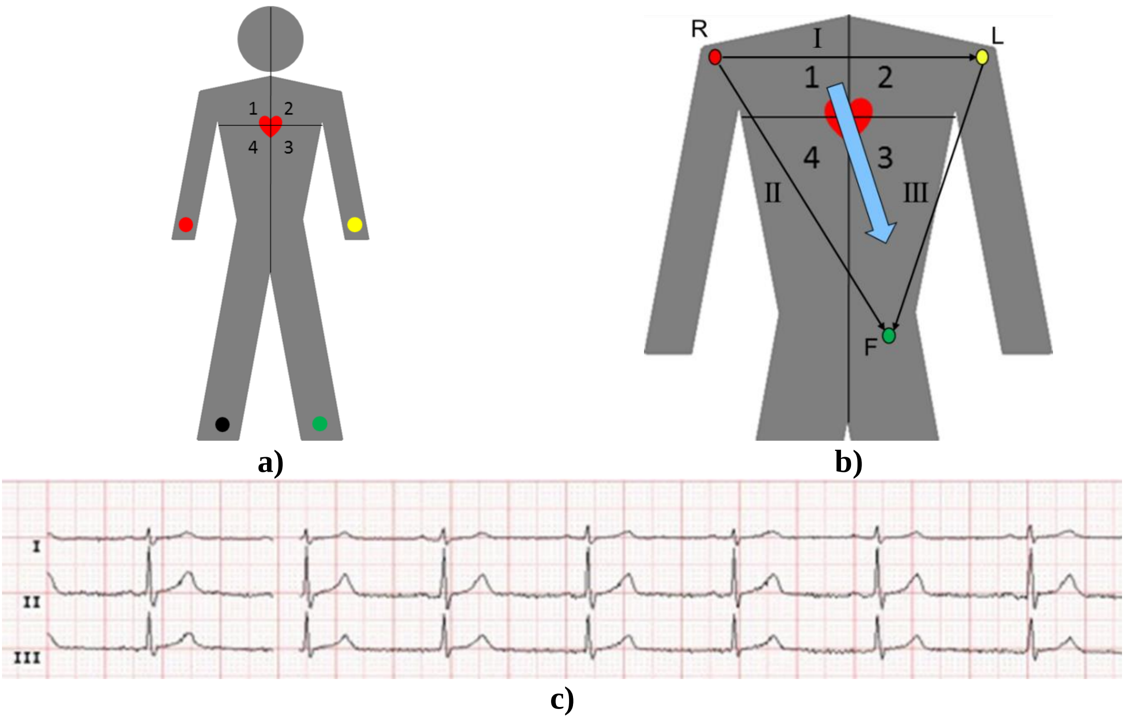


Figure 2.5: The ECG according to Einthoven. (a) The possible four sectors where the electrodes can be placed. (b) The unipolar measurement vectors in relation to the electrical heart vector, depicted in the "Einthoven Triangle". (c) An ECG measurement of the Einthoven I, II and III lead.

Only a few years later in 1942, Emanuel Goldberg published [116] his improved method for measuring three additional leads (aVR, aVL and aVF) by connecting two of the three electrodes to a virtual electrode and then measured this against the third (see Figure 2.6).

In Figure 2.6, the leads aVR and aVL are flipped. This is because the angle to the electrical heart vector is larger than 90°.

The leads aVF and Einthoven II have nearly the same amplitude, since the measurement vector is again nearly parallel to the electrical heart vector (see Figure 2.6 (c)). Goldberger`s development enabled the measurement of up to six ECG leads, with three to four electrodes, wherein the fourth electrode is normally used as ground.

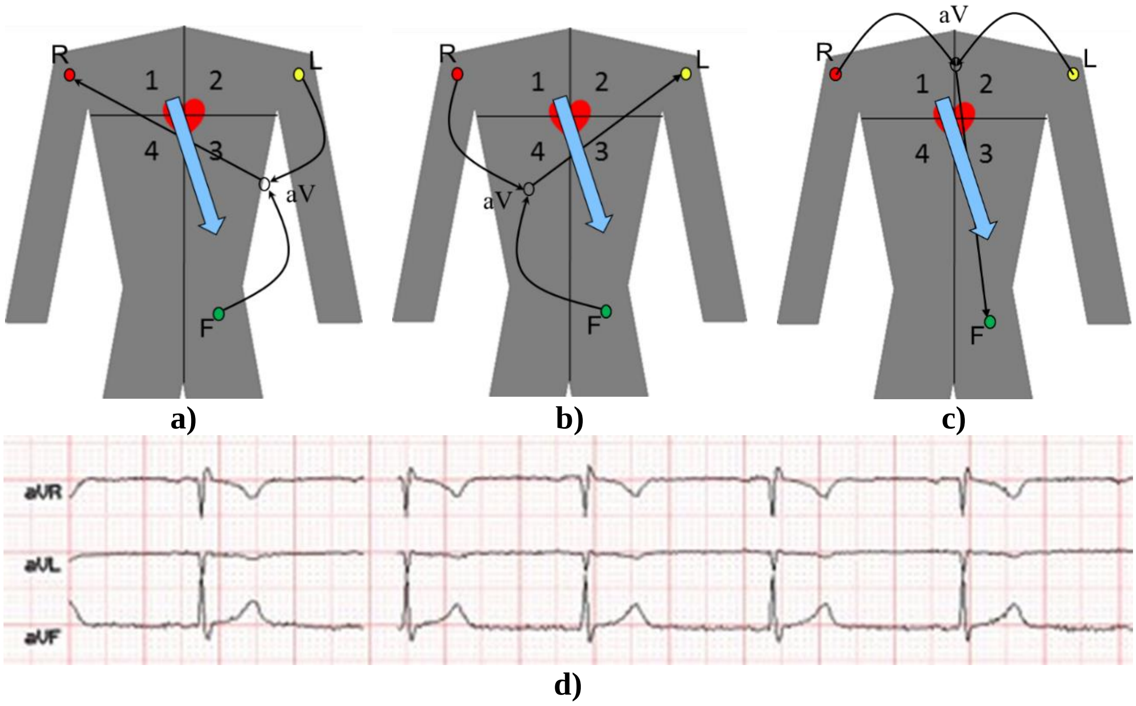


Figure 2.6: ECG leads expansion according to Goldberg. (a) Electrode placement and measurement vector for the augmented Voltage to the Right (aVR). (b) Electrode placement and measurement vector for the augmented Voltage to the Left (aVL). (c) Electrode placement and measurement vector for the augmented Voltage to the Foot (aVF). (d) The recorded augmented voltage measurements.

This currently enables the measurement of the heart`s electricity from different angles, i.e. twelve leads when using Einthoven, Goldberger and Wilson leads. In case of a healthy person, the measurement shows the typical PQRST complex, as depicted in Figure 2.7.

Figure 2.7: The PQRST-Complex of a 12 leads ECG. The atrium contracts at the P-wave, the signal delays at the PQ-line at AV-node, in order to keep the mechanical function of the heart, the main contraction of the ventricles takes place at the QRS-group, the heart contraction ends at the ST-line and the heart is repolarizing at the T-wave.

In case of a heart attack, the shape of the ECG deforms. Depending on which lead is affected (as well as on the shape of the ECG), physicians are able to estimate the position of the heart attack (i.e. the progress of the ischemia or scars in the myocardium) [110].

The big advantage of an ECG measurement is the high cost-efficiency compared to other solutions like angiography. In angiography, a computer tomography (CT) is detecting a marker, which shows the blood flow in the vessels. Thereby stenosis and occlusions become visible, but the user suffers from large doses of x-ray. Also, the cost of an angiography is higher than the ECG and therefore this possibility should be used only for patients with middle to high risk for an acute coronary syndrome [117].

Nevertheless, physicians confirmed the improved performance of the angiography, compared to the ECG [118]. Consequently, ECG application possibilities have to be researched regarding the increase in accuracy of the cardiovascular disease prediction. Equally important, further research should provide non-medical professionals the ability to interpret the results of an ECG.

2.3.3 Fall Detection Systems under Development

In addition to the commercially available wearable solutions for fall detections, and the in-floor integrated fall detection providing as indoor solution (see subsection 2.2.3), fall detections for the public domain are still under research. Since in the public domain the personal privacy is not such a delicate issue as in the home area, e.g. in the bathroom, research groups investigate the possibility to identify falling pedestrians via cameras [119].

Nevertheless, due to the big benefits of camera systems, there are also research groups researching camera-operated fall detection systems for private apartments [120]. According to Blöcher et al. [121], it is possible to cover the entire AAL scope via optical sensors, if the stakeholder (i.e. the elderly) would accept such technical solutions. This proves once more that the user acceptance has to be considered from the beginning when developing AAL solutions.

Another new approach regarding the fall detection is to use the wireless local area networks (WLAN) (using IEEE 802.11n standards). It may be possible to accurately detect a fall based on the signal reflection and scattering on humans [122]. However, this approach is still very new and momentarily suffers in accuracy.

Concurrently with fall detection, motion detection is a focus mostly of other research groups [123]. Both commercially available solutions (wearables, as well as the SensFloor) try to predict the motion of the user in order to receive additional information. E.g. de Lime et al. [123] developed a fall detection system, which also provides tracking for the freezing gait symptom of Parkinson’s disease. According to Godfrey et al. [124] accelerometers are also used in research to detect human movements, e.g. when suffering from back-pain, Parkinson, obesity, stroke etc.

Solutions that integrated the fall detection directly into the floor, e.g. the SensFloor, focus more on identifying pets via motion analysis. According to Steinhabe et al. [125], pets (e.g.

cats or dogs) are a source of false alerts and it is not possible to distinguish between a fallen person and the pet with respect to only the capacitive surface.

Currently, however, there is no research aiming to develop alternative fall detection system solutions, which are more cost-efficient or easier to install than the integration of an in-floor fall detection. This is probably not necessary at moment, because of the weak amount of competitors on the public market. Alternatively, since small mobile devices like smartphones and smartwatches always have nowadays accelerometers installed, the cheapest solution is still to download the fall detection Apps.

2.3.4 Human-Machine-Interfaces for Elderly

According to Häikiö et al. [126], the touchscreen is an intuitive possibility to enable elderly to control ICT solutions. However, since they worked mainly with smartphones in their study, it was noted that the small size of the touchscreen is a big problem. Therefore, large surfaces with big buttons are necessary, which are intuitive and easy to tap via touchscreen technology.

Other research groups try to implement the user interface more naturally into furniture, e.g. Poh et al. [127] displays the results directly in a mirror. Another approach is the interactive table "Samsung SUR40 with Microsoft PixelSense", which offers already a large screen across the tabletop [128]. However, here the amount of services is so comprehensive that the elderly may reject this table. While thinking about dementia, additionally, the table plate could be damaged by accidents, which would lead to a dysfunctional interactive table.

Alternatively, robots are also possible in enabling the elderly to control AAL and ICT solutions more intuitively [129]. For example, the robotic ALIAs interacts by speech and a GUI, which is accessible at the chest of the robot, and serves as a social service robot [130]. In case the elderly suffer from cognitive impairments, e.g. because of diseases like dementia, therapeutic companion robots like Paro [131] are used. These robots simulate the social interaction with the behavior of a pet, which enables multi-sensory behavioral therapies. The advantage compared to real animals is the reduced injury risk for the elderly and the pet (e.g. by animal bites).

Another novel possibility for human-machine interface for the elderly is the noninvasive brain computer interface (BCI). The BCI works via the electroencephalography (EEG), which tracks a specific marker in the EEG channels, in order to trigger specific actions. Since the EEG is very inconvenient and difficult to attach, dry electrodes or capacitive electrodes are nowadays used for the noninvasive BCI interfaces [132]. According to McFarland and Wolpaw [133], studies are focusing on invasive and noninvasive BCI to control robotic arms. However, the issue at the BCIs seem to include the establishment of a fast, reliable and accurate signal control. Therefore, nowadays BCIs are still focusing more on basic research and less on the AAL research area.

Nevertheless, researchers are already investigating potential applications of BCIs, which would also fit to the AAL research area. For example, Mitsukura and Nomura [134] use a noninvasive BCI to detect the emotion of the user, which proves that the BCI can be used next to control ICT solution, as well as analyze the EEG. Therefore, also signs for epilepsy, e.g. the sharp wave, could be tracked in future BCIs use [135]. However, this research is still very young and at moment not applicable as human-machine interface for AAL solutions, especially for the elderly. Nevertheless, in the future when the BCI become more reliable and precise, they will become a very intuitive human-machine interface option for the elderly.

2.4 Limitations of the State of the Art

This section contains the technical limitations of the state of the art, which are briefly mentioned in section 2.2 and highlighted in section 2.3 in order to show how the conceptual realizations of chapter 3 contribute to the current existing market and research gaps. The highlighted limitations lead to the special requirements (listed in Table 2.2), which have to be considered when developing the "Ambient Health Monitoring System" (see chapter 3), in order to ensure the development will have an appropriate user acceptance.

Table 2.2: Special requirements of the "Ambient Health Monitoring System".

Prototype	Requirements of the prototypes
Unobtrusive Fever Detection	– The prototype must measure quickly – The operation of the prototype has to be simple – The prototype has to be unobtrusive implemented
Cuff-Free Blood Pressure Monitor	– Cuffs used for blood pressure measurements have to be avoided – The prototype must be safe and noninvasive – Monitors both the single value and other relevant medical values, e.g. the ECG curve – The interpretation of the raw data has to be automated.
Novel Fall Detection	– The prototype should be low-cost – The installation efforts of the prototype should be minimal – The system concept of the prototype must be absolutely reliable – The prototype must be operable permanently
Main User Interface	– The prototype must be low-cost – The prototype must be robust regarding strikes, pitches and stabs – The prototype has to be intuitive with respect to the control for the elderly, e.g. by gestures – The GUI must have large letters and buttons, and avoid fast actions like double-clicks

As mentioned in subsection 2.1.1, the **fever** is a symptom of the immune response [25], whose value is mostly underestimated. The reduced interest to measure the fever is linked to its shortcomings. Mercury thermometers are not typically used anymore due to the risks associated with mercury [57]. The replacement of mercury with galinstan reduced the risk, but did not improve the other shortcoming, e.g. long measurement time, preparation via shaking and measurement on inconvenient body parts.

Digital thermometers are even easier to use, since they do not need to be shaken for preparation. However, the digital thermometer is not addressing the issues of the long measurement time or the measurement on inconvenient body parts. Therefore, new devices exploit infrared radiation technology, which enables very fast measurements. However, cautious handling hereby is of utmost importance [59]. In case someone is holding the device wrongly, the measurement results will be false. Therefore, automation is desired to monitor quickly the body temperature at any given time without any additional efforts by the user (see Table 2.2).

Cardiovascular Diseases are insidious and life-threatening diseases, which sequelae are in industry nations like Germany the primary death cause (see subsection 2.1.2). One of the main symptoms of cardiovascular diseases is hypertension [35]. Even today, it is common to measure hypertension via the Riva-Rocci and/or the Korotkoff method (see subsection 2.2.2). Due to the subjective nature of both methods, as well as the need of the person who is able to measure according to Riva-Rocci and Korotkoff method, automated devices were developed to enable the user to measure the blood pressure independently and objectively.

However, the cuff of the blood pressure monitor can trigger mental stress. Relatedly, mental stress, panic and anxiety again can be seen as risk factors for developing hypertension [136]. An improved solution is therefore necessary. The solution must not need any cuff pressure, or invasive methods as used in hospitals in order to predict the blood pressure in the AAL field (see Table 2.2).

Along with the blood pressure, the ECG is an important tool used to identify cardiovascular diseases (see subsection 2.3.2). However, the interpretation of the ECG requires medical training. Additionally, physicians prefer the CT based angiography because of the improved performance compared to the ECG [118]. However, the angiography exposes the patient to a large amount of x-ray and therefore needs a controlled and safe environment (e.g. a hospital). The development of novel ECG applications is also important to enable users without a proper medical background to interpret results from the ECG. Moreover, the device should automatically analyze the results, and/or provide additional information for the physicians (see Table 2.2).

The **threat to fall** and age related diseases make the fall prevention an important aspect for AAL solutions. Currently, fall detections offer security to the inhabitant, and by result, contribute to the prevention and intervention of falls (see subsection 2.1.3).

Nowadays everyone can install fall detection software on a smartphone, or smartwatch. Additionally, alternative professional medical fall detection solutions can be purchased, which mostly use accelerometers and gyroscopes (see subsection 2.2.3). These solutions are only efficient, however, if the user is wearing the device on the body. The inhabitant sooner or later will put away the smartwatches, smartphones and other wearables, particularly in the bedroom or bathroom, which leads to a function gap of the fall detection systems.

Despite the shortcomings of many fall detection systems, some professional solutions, e.g. the in-floor SensFloor, fill the aforementioned function gap. Compared to the smartphones, this solution enables a permanent fall monitoring, but needs much greater installation efforts.

At the moment, research primarily focuses on implementing motion and posture analysis into the existing fall detection systems (see subsection 2.3.3). Regarding the SensFloor, additional research is executed in order to make the SensFloor able to distinguish between human and pets [125].

The use of WLAN networks is a new approach for fall detection. However, the reliability of this solution is currently not competing with existing solutions. Therefore, the desirable solution must be cost-efficient and easy to install to fulfill the research objectives. Furthermore, the concept must support a 100 % reliable and continuously running fall detection (see Table 2.2).

A proper **main user interface** for the elderly is a big research area. As mentioned in subsection 2.1.4, the challenge arises from the elderly having a different learning behavior compared to younger people. In old age, the use of existing knowledge is easier than to learn new skills. Even the mouse and keyboard, which are still the most used human-machine interface today, are mostly rejected by the elderly (see subsection 2.2.4). Therefore, most elderly have problems operating computers or other ICT solutions, which is the reason that there is a lot of ongoing research about new user-friendly and intuitive human-machine interfaces for the elderly.

Robots can be a big help for the elderly, especially if speech recognition enables a very intuitive human-machine interface (see subsection 2.3.4). Cost, alongside functionality, usability, and safety are important design factors for robotic solutions. A proper design is important to avoid user rejection [137]. Due to the mostly high costs of robots, the user-oriented implementation of such solutions is quite difficult in the AAL research area. A new application proven useful by AAL researchers show optimistic therapeutic applications via companion robots. However, these robots are very limited in their interactions and a therapist is still needed for the complete therapeutic success [131].

Eventually, future BCIs will enable the interface directly between machines (e.g. computer or robots) and the human brain. Much research is done today regarding the BCI, and even mood detection is possible via specially designed EEG devices with dry or active electrodes [134]. Nevertheless, at the moment, the BCI response time and accuracy is not sufficient enough for someone to use a BCI without training. Therefore researchers investigate possibilities to develop BCIs that need no or very minimal training [138]. Considering the learning behavior of the elderly (see subsection 2.1.4), BCIs at the moment are too complex for the elderly as a human-machine interface.

Virtual reality devices, e.g. the Oculus Rift, are mostly too heavy for long time use for the elderly. On the contrary, augmented reality devices are lightweight, but provide only a small display. For both applications, cyber sickness is equally problematic [96]. This issue must be solved efficiently, before these human-machine interfaces become interesting for the AAL field.

Touchscreens proved to be intuitive and applicable even for seniors. However, most touchscreens are implemented in smartwatches and smartphones, which offer only a small display due to the limited size of the device. Characters and buttons have to be large so that the elderly can efficiently use touchscreens. In addition, the GUIs of most applications are nowadays not intuitive enough for the elderly.

A human-machine interface is therefore needed for this system, which allows user control via gestures (e.g. by touch), including a substantial GUI surface, and large characters and buttons. Fast actions, like the double-click, have to be avoided to support the user intuition of the interface. The GUI has to be simple; multi-touch features and high-end graphics are less interesting for the elderly. Considering the elderly may also suffer from cognitive impairments (e.g. Dementia), the prototype has to be robust against strikes, punches and stabs, e.g. caused by forks or dishes (see Table 2.2).

Generally, the identified issues relate to the fever measurement, is the difficult and time-consuming measurement. Blood pressure monitors have similar issues in addition to the issue that these devices trigger mental stress in some people, which can lead to false measurement results. For fall-detections, most solutions need wearables, which are not operable when the sensors are not carried by the elderly. Other solutions, which are installed in the apartment are both expensive and difficult to install, or less accurate. User interfaces, especially GUIs are nowadays less considering the requirement of simplicity and intuitiveness, because they are mainly addressing younger people, which are more interested in functionality.

Therefore, it is important that the components of such an “Ambient Health Monitoring System” are developed modularly, unobtrusively, and with the ability to be installed in existing furniture and apartments. Already while developing such a system, the aspect of low-cost and simplicity (regarding installation) have to be considered. For controlling such a system, a novel human-machine interface has to be developed, which enables elderly to operate the proposed high-tech system with simplicity and intuition.

3 System Concept Implementation

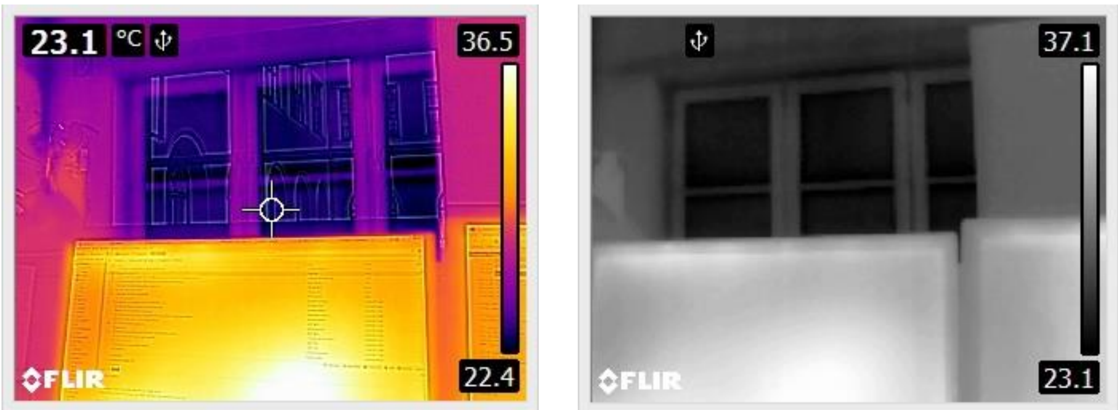
The requirements mentioned in section 1.2 and section 2.4 are addressed by several system prototypes (i.e. system modules). In the following sections of this chapter, the different system modules are introduced in terms of operation and functionality. Additionally, the used hardware is described, in order to prove that the low-cost aspect was successfully considered for the proposed system modules.

The overall system consists of four modules, where the first three modules focus on the sensing aspect and the fourth module represents the main user interface. In section 3.1, the concept of the unobtrusive fever detection is explained, whereas in section 3.2 the cuff-free blood pressure monitor and in section 3.3 a novel concept of a fall detection is described. At the end of the chapter in section 3.4, the concept of the interactive table, as well as the overall system communication are described.

3.1 Unobtrusive Fever Detection

The content presented in this section is partially published in the Sensors Applications Symposium of IEEE [139]. Deviations to the already published content are results of further improvements of this module since the publication.

The concept of the unobtrusive fever detection is based on a thermal camera. This module uses the thermal camera in order to identify a person, for which fever values are monitored via the thermal images. Thereby, the user has to stand only in front of the module in order to measure the body temperature, since it is fully automated, which addresses the simplicity requirement of this module (see section 2.4). Thermal cameras produce thermal images, which contain all temperature information in a picture. Usually, such images are presented as depicted in Figure 3.1 by using “pseudocolor” images.



a) **b)**

Figure 3.1: Display of the thermal camera FLIR E6 [139]. (a) Shows the image, which is displayed with the standard settings of the thermal camera, using a measurement point and “pseudocolors”. (b) Shows the display of the thermal camera after setting up the camera appropriately, i.e. displaying the raw thermal image as grayscale image.

This is because original thermal images are normally grayscale images, which support up to 255 different gray color intensities. However, the human eye cannot distinguish the different grayscale intensities with the same accuracy as with different colors. Therefore, thermal cameras use "pseudocolor" in order to enable an improved subject recognition by means of thermal images [140].

The accuracy of a thermal camera depends on the settings, i.e. the emissivity coefficient ε. Depending on the substance, which is expected to be measured with the thermal camera, ε has to be adapted. Otherwise, the accuracy of the thermal measurement suffers. According to FLIR [141], the emissivity coefficient ε has to be set to 0.98 [141] in order to measure on human skin. From this point on, the main issue is how to identify the correct pixel(s), which contains the appropriate thermal information. Since a thermal image represents a matrix containing a large amount of thermal information, a prototype was developed, which can track a person and identify the appropriate measurement position.

This section is divided into two subsections. The hardware realization is described in subsection 3.1.1; the software implementation is described in subsection 3.1.2.

3.1.1 Hardware Composition and Setup

Since an unobtrusive implantation is the design target, as already explained in section 1.2 and section 2.4, a lightweight and compact solution is necessary. The general working principle is that a computer is streaming and evaluating the data of the thermal images using image recognition tools. Therefore, the most compact solution is the use of single board computers (e.g. Raspberry Pi, or Banana Pi etc.) [142], since these computers are very small, but still powerful enough for the calculation-intensive tasks of image recognition. For this module, a BeagleBone Black (BBB) is used (see Figure 3.2), because this computer supports a variety of peripheral attachments (as touchscreen displays etc.), Debian as the operating system and already has some libraries of OpenCV installed.

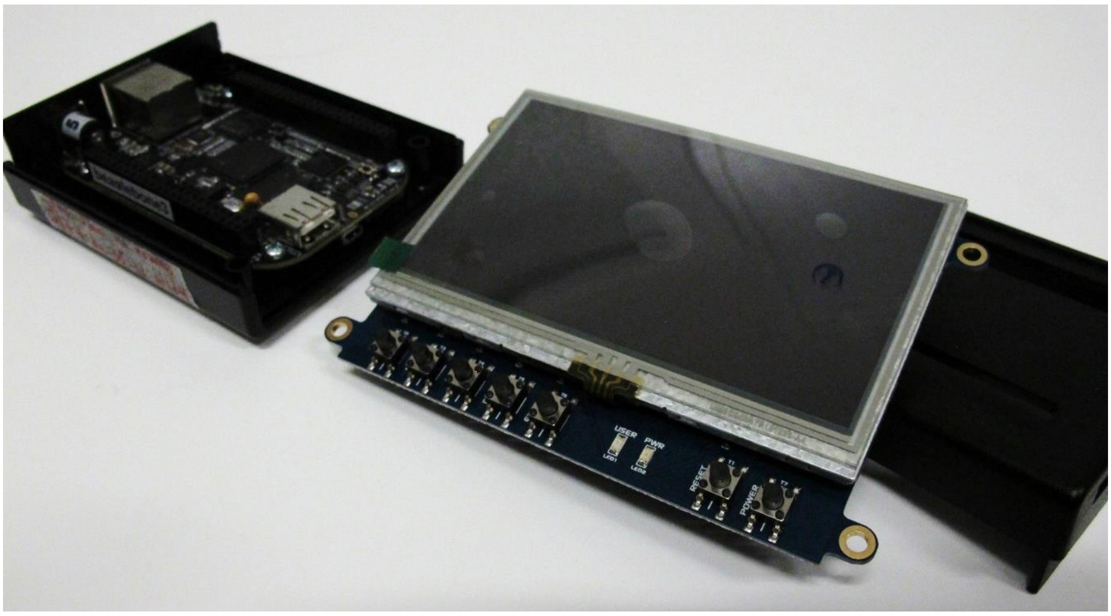


Figure 3.2: The BeagleBone Black, including its casing and the touchscreen cape.

The pre-installation of OpenCV especially has major advantages, since OpenCV is a powerful open source library collection of image recognition tools [143]. Due to its large storage space, which OpenCV needs, the installation of OpenCV on single board computers can be challenging. More details regarding OpenCV and the related implementation can be found in subsection 3.1.2.

The BBB has an AM3358BZCZ100, 1 GHZ processor with 512 MB DDR3L RAM and a 4 GB on-board eMMC memory chip. This allows direct programming on the BBB without the need of installing the operating system on a SD-Card, as it is necessary e.g. on a Raspberry Pi. For displaying the measurement results, a touchscreen 4DCAPE-43 cape was used [144], as depicted in Figure 3.2. Due to the hardware limitation of a single core processor of 1 GHZ, as well as privacy security reasons, it was never thought to display images on the screen or to save images on the BBB. Thereby, the available hardware resources can focus on the image recognition and the risk of privacy attacks by hackers is reduced. According to Chernbumroong et al. [145], it is important to consider the privacy of the user, especially for the elderly and Ambient/Active Assisted Living Solutions.

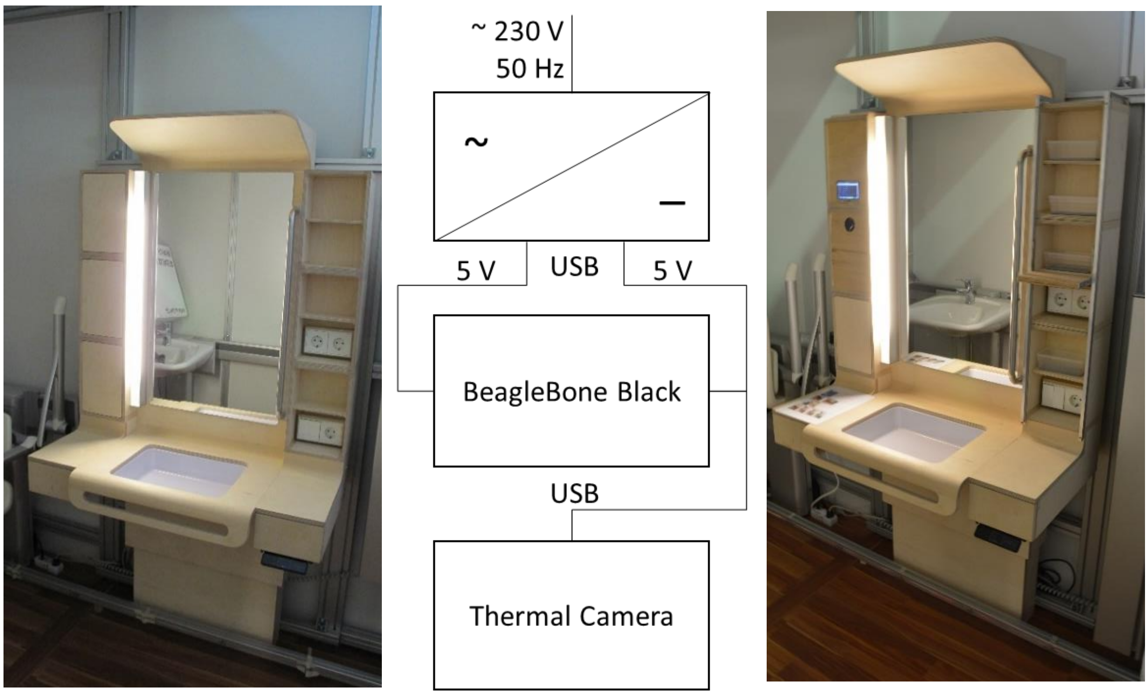
The final issue of this prototype was the power supply. The thermal camera possesses a battery, whereas the BBB is normally supplied via a power socket. One solution was to use a power bank to power the BBB instead of a power socket. This solution allows installation of this module, due to the small size of the components and unobtrusiveness in existing furniture (e.g. over the bed, or next to a mirror at the sink [146, 147]), where the fever measurement can be executed automatically.

For a functional test, a power bank with 2 A, 5 V, and 12.000 mAh output was used (see Figure 3.3).

Figure 3.3: Functional test, where the proposed prototype is power supplied only by batteries.

As can be seen in Figure 3.3, a Y-USB cable was necessary to sufficiently supply this solution with current. Using a normal USB cable was sufficient to start the BBB and keep it operational, but when the image recognition was executed, the program crashed due to a lack of power supply. The Y-USB cable approach successfully avoided the lack of the power supply, but led to the disadvantage that the power bank was discharging too fast. Functionality tests revealed that the power bank was already discharged after ~ 4 hours. Therefore, the battery approach was not used for the final implementation.

This prototype was for testing unobtrusive implemented into a piece of furniture - a mockup of a modern washbasin (see Figure 3.4 (a)). For the power supply of the BBB, a hole was drilled into the backside of the furniture, so that it was possible to attach a power cord to the BBB. Thus, it was feasible to execute the laboratory test for the user evaluation (for details see section 4.1), since now the prototype was operable for several days in a row. However, functional tests proved that the battery of the thermal camera was discharging, although the BBB was attached to a power socket. The USB wire, which connects the thermal camera and the BBB, was not able to stream the data and supply sufficient power to the thermal camera at the same time.



a) b) c)

Figure 3.4: The unobtrusive fever detection integration into the washbasin mockup in the laboratory apartment. (a) The mockup before the installation. (b) Schematic of the interface of the different components. (c) The same mockup including the prototypical implementation.

The concept requirements on this module (see section 2.4) made it necessary that this solution will run 24 hours continuously (since the thermal camera has to identify a person standing in front of this module), in order to recognize a user which is e.g. using the sink and to perform the fever detection unobtrusively and automatically. Therefore, the concept depicted in Figure 3.4 (b) was realized.

A power socket, which enables two USB wires to interface, was used to power the BBB and the thermal camera at the same time. Since the thermal camera has only a micro USB interface, the power supply can disturb the data stream. Functional tests proved that a stable stream of the camera data was only provided, in case the data stream exists, before the power supply of the thermal camera was active. The setting depicted in Figure 3.4 was tested for a few months, which proved that the thermal camera is not discharging, and therefore stays operable for long-term measurements.

For the data exchange, a Wi-Fi module was used, which enabled the prototype to communicate via a router to the entire system (see section 2.4 for more details). Unfortunately, the BBB has only one USB interface and no onboard Wi-Fi module. In order to interface the BBB to the whole system, a USB Wi-Fi module “EW-7811 Un” from Edimax [148] was attached. In order to also connect the USB-Wire for the data transfer, a USB-dispenser was used, which enabled the simultaneous interface of the Wi-Fi module and the thermal camera. The power supply was attached to the Micro-USB interface of the BBB and the thermal camera at the same time (see Figure 3.4).

3.1.2 Software Implementation

Since it was possible to integrate the thermal camera unobtrusively into a furniture, and to stay operable for weeks, it was conceptually possible to permanently monitor the body temperature of a person. In order to enable the BBB to measure automatically the body temperature, a software algorithm, which is presented in this subsection, had to be developed and implemented into this module.

The program was developed as a console program using “QT 4.8” [149]. By using “QT”, a quick and simple transfer of the source code to different operating systems was possible. This approach is necessary, since the entire QT IDE is too large for the limited storage space of the BBB. Therefore, the first source code was developed on a “Windows 10” computer. After the source code was successfully developed and tested regarding its functionality, the source code was transferred to the BBB. Although the BBB uses “Debian 7.8” as the operating system, the source was possible to compile using the “qmake” command of QT.

The overall concept of this prototype is depicted in the flowchart of Figure 3.5. The concept operates on the idea of a thermal camera running in the background. As soon as a person is recognized, a fever detection via the thermal image can be triggered following the algorithm of Figure 3.5.

As visible in Figure 3.5, the algorithm can be split into two parts. The first part of the algorithm focuses on retrieving the thermal value of the forehead. The second part of the algorithm analyzes the measurement in order to identify false measurements and increase the measurement reliability.

For the **basic forehead measurement,** the use of image recognition was necessary. For this purpose, the library “OpenCV 2.4.11” was used [143]. OpenCV provides so-called “haar-cascade” files, which enables the detection of faces, eyes, nose, mouth, hands, etc. However, these cascade files were developed for RGB cameras. Therefore, the different tracking methods were tested with the thermal camera at the beginning.

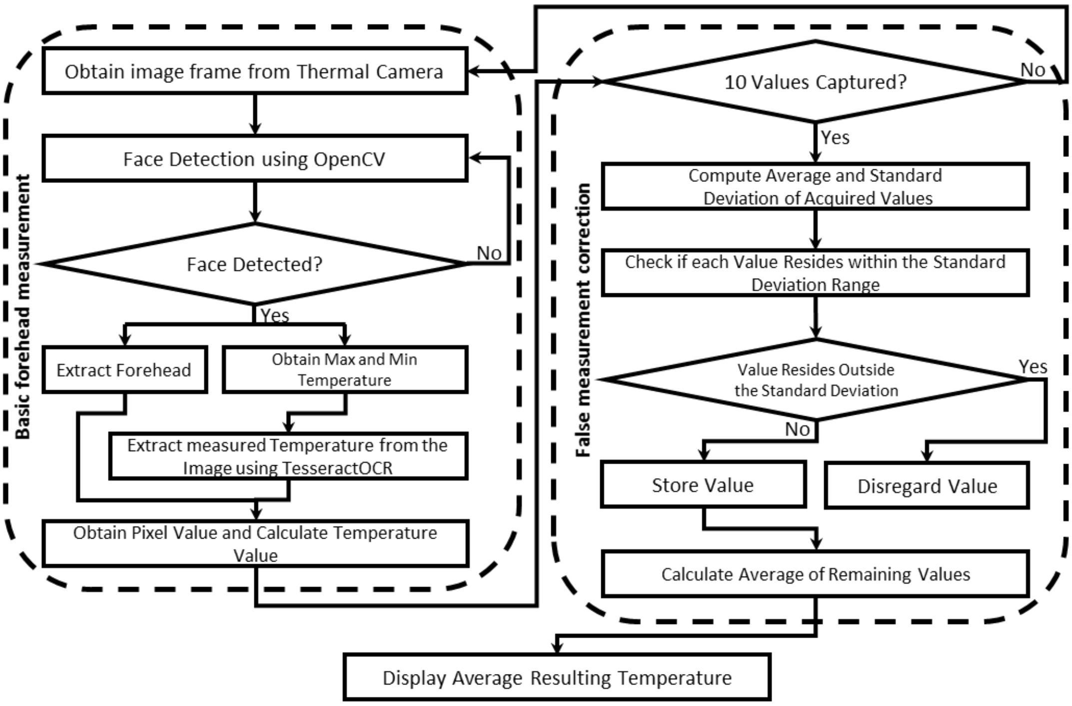


Figure 3.5: Measurement concept for an unobtrusive automated fever detection. The left part of the algorithm focuses on finding the measurement point, whereas the second part of the algorithm focus on ensuring the measurement quality.

Due to the weak contrast of the face (see Figure 3.6), especially for the mouth, nose and eyes, the “haar-cascade” files were unable to operate properly. Only faces were possible to track sufficiently using the appropriate “haar-cascade” file.

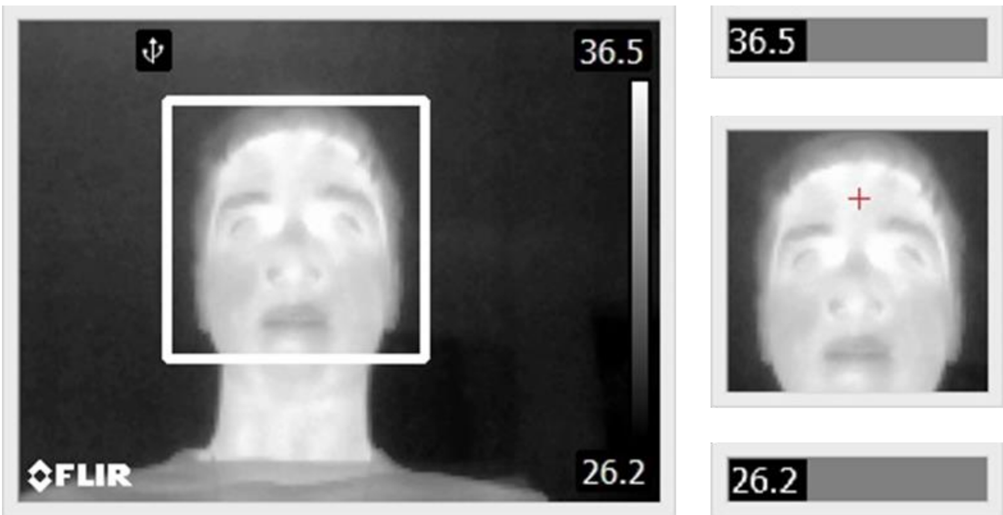


Figure 3.6: Thermal image of the thermal camera, which shows the tracked area of the face. The identified face was cut out of the original image matrix and transferred to an analysis matrix, which is plotted in a second frame where the measurement point is marked by a red cross. Additionally, the maximum and minimum temperature caption were cut as well into separated frames for a character recognition.

According to Ring et al. [102], appropriate measurement positions for thermal camera are the forehead (because of the easy access to this body region), as well as the eyes. The measurement on the eyes especially provides a high accuracy, but because of the small area and the issue of tracking the eyes in the thermal images, the measurement accuracy was not given. Fortunately, the forehead is a large area on the face, which is less difficult to track. Once a face was recognized by the prototype, the face area of the original image matrix was copied into an analysis matrix, were a fixed measurement point within the face area was used for the fever measurement (see Figure 3.6). The position of the measurement point on the forehead was identified via simple geometric relations of the face.

Finally, the pixel value has to be interpreted in order to receive the thermal value. For this purpose, the scale on the right side of the image, including the maximal and minimal value, are necessary. The maximal value of 36.5 °C (see Figure 3.6) corresponds with the highest pixel of the scale, as does the 26.2 °C (see Figure 3.6) with the lowest pixel of the scale, and the temperature relation of the two pixels is known. By using equation (1), the corresponding temperature T (which represents the body temperature or the fever value) of the forehead pixel p can be calculated by using these two input values:

$$T = p \cdot \frac{T_{\max} - T_{min}}{p_{\max} - p_{min}} + T_{\min} \tag{1}$$

In equation (1), the variables $T_{\max}$ and T_{min} represent the maximal and minimal temperature value of the thermal scale, respectively, whereas $p_{\max}$ and p_{min} are the corresponding pixel values. In case the pixel values would be 255 (for the white top of the scale) and zero (for the black bottom of the scale), the denominator would be 255. Analysis of the values of the scale showed that the minimum and maximum values of the maximal and minimal temperature are never exactly 255 and zero. Since the scale is always at the same position of the thermal image, no complex tracking mechanism was needed to receive the pixel values of the maximal and minimal temperature.

The first approach was to define fixed maximal and minimal temperature threshold values at the thermal camera for $T_{\max}$ and T_{min}. Thereby, these two variables would be constants. However, since these settings are not stored at the thermal camera, these settings get lost e.g. after a reboot of the thermal camera. In order to reduce the start efforts of the module, a text recognition library was implemented into the program using the library "TesseractOCR" (Version 3.01) [150]. This library has functions to enable image-to-text interpretations. Because of the reduced storage capacity of the BBB, only the numeric data of "TesseractOCR" were installed on the BBB, since only the translation of the thermal values $T_{\max}$ and $T_{\min}$ were of interest. To assure an accurate text recognition, the matrix pixel belonging to the values $T_{\max}$ and T_{min} have been extracted into two individual frames (see Figure 3.6). After interpreting both images into a double number via "TesseractOCR", both values can be used in equation (1) in order to identify the temperature on the forehead as proposed in the follow diagram of Figure 3.5.

An alternative approach would be the use of the Software Development Kit (SDK) of the FLIR E6, which allows to program personal software applications. It also provides full control to the thermal camera on source code level. However, this approach was not possible in this case, because the SDK provided by FLIR is only compatible with Windows operating systems. Since the common single board computers (Raspberry Pi, BeagleBone etc.) did not support Windows operating systems at this time, the value interpretation using equation (1) was essential. Therefore, the use of the existing SDK from FLIR was waived.

The second part of the program, **the false measurement correction**, is important, since fast user movements can lead to false measurement samples. In addition, false tracking can happen sometimes and lead to a pixel, which belongs e.g. to the hairs of the user. The temperature of the hair differs significantly from the true body temperature (e.g. more than 5 °C). According to the flow diagram of Figure 3.5, the identification of such false tracked values is executed in three steps:

1. Calculating the average and the standard deviation (STD) to define dynamical thresholds.
2. Using the dynamical thresholds for identifying false measurement values.
3. Calculating from the remaining values the average as final result.

For this purpose, the average temperature T_{average} is calculated out of at least 10 forehead temperature values T, by using equation (2):

$$T_{\text{average}} = \frac{(\sum_{i=1}^{N} T_i)}{N} \tag{2}$$

Once the average temperature is calculated, the standard deviation T_{STD} of T_{average} has to be calculated using equation (3):

$$T_{\text{STD}} = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{10} \left(T_i - T_{average}\right)^2} \tag{3}$$

With T_{average} and T_{STD}, an upper temperature threshold value $T_{\text{average}} + T_{\text{STD}}$, as well as a lower threshold value $T_{\text{average}} - T_{\text{STD}}$, is calculated. Each single value of the captured forehead temperatures are checked, whether they are smaller than the upper threshold or larger than the lower threshold. Only temperature values within this range will be used for the second average temperature calculation to obtain T_{fin} using equation (2) again. Figure 3.7 demonstrates this approach visually on a measurement series, which was captured as a functional test.

The average temperature T_{average} would be 35.224 °C, because of three false measured values via on-hair measurements. The new defined upper threshold of 37.172 °C and the lower threshold of 33.276 °C lead to the exclusion of these three wrong measurement points and thus improved the average calculation to 36.491 °C, which represents the final result T_{fin}. The accuracy can increase depending on the amount of used temperature samples. For this prototype, ten samples per measurement were used, because of the limited hardware capacities of the BBB. The BBB needs ~ 30 seconds to receive the final result, which was seen as the maximal acceptable time in order to consider the requirement of a fast measurement speed for this module (see section 2.4). A more powerful computer was used to test the analysis speed. More than 100 temperature samples were analyzed and the final result was calculated in less than 30 seconds.

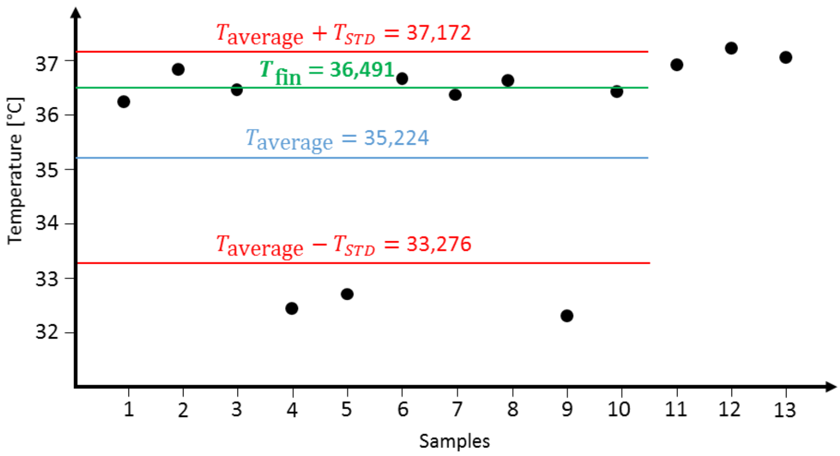


Figure 3.7: Exemplary false measurement detection using average values and standard deviation.

The result T_{fin} is displayed in the command window marked by a frame (see Figure 3.8), as well as transferred to the main user interface of the "Ambient Health Monitoring System" (see section 3.4) using the Wi-Fi module attached to the BBB.

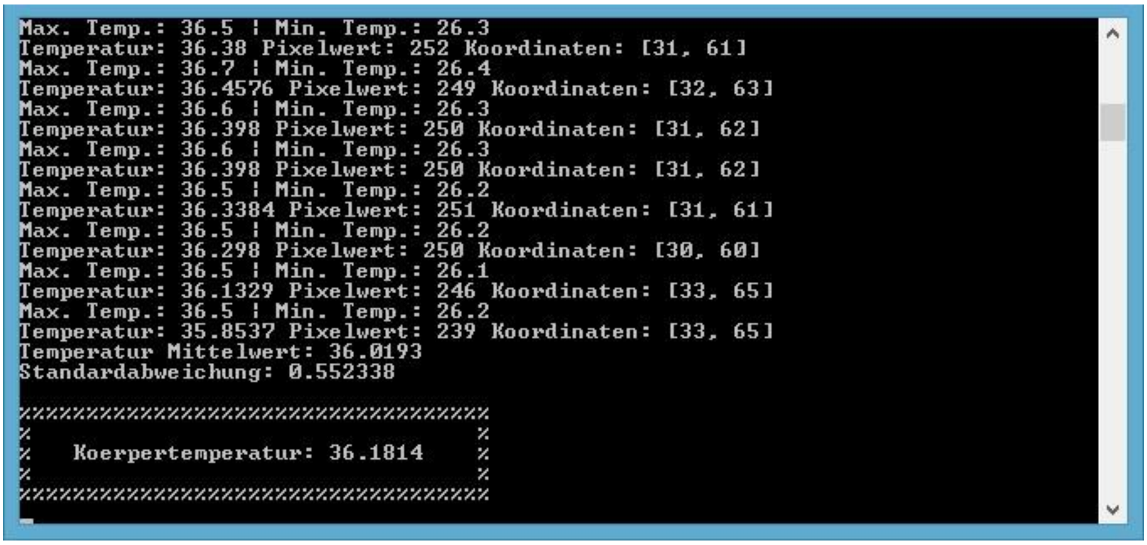


Figure 3.8: Command window of the program, which evaluates the body temperature on the forehead of the user. Each sample is displayed (with the appropriate coordinates), including the maximal and minimal temperature, which belongs to the same picture of the thermal sample. The value T_{fin} is the final value marked in the box at the end of the command window.

Nevertheless, the small size of the BBB allows an easy, cheap, and unobtrusive implementation. The implemented face recognition enables a permanent update of the tracked temperature, whenever the user is in reach of the device. Therefore, the BBB was used for the laboratory and field tests (details can be found in chapter 4).

The final product was evaluated in its function by using a commercial medical thermometer (see Figure 3.9). Further tests showed, although the temperature is properly tracked, the forehead temperature is less reliable in case the person is coming from a cool environment. A proper environmental temperature is necessary for a proper operation of this module. Therefore, the program can be started with an offset using system commands. This was realized by using the C++ argument variable “char *argv[]”, which was setup to expect a float input for adding the offset to the final result (e.g. for a 0.5 °C offset). For automation of the start, an icon was created, where the offset temperature can be saved at the command call of the program. However, in the presented laboratory and field test results, this parameter was set to zero, which means no offset correction was used.

Figure 3.9: Measurement results of a medical thermometer and the thermal cam, measured automatically in a functional test.

3.2 Cuff-Free Blood Pressure Monitor

The content presented in this chapter is partially published in the Journal of Robotics and Mechatronics [151], as well as at the conference Mechatronics REM [152]. Any differences to the already published content are results of improvements on the system, which have been done for this work.

As mentioned in section 1.2, the objective of this work is to develop a system, which monitors health relevant data simply and conveniently, in order to relieve care staff and to increase the independence of the seniors. Furthermore, the importance of the blood pressure was explained in section 2.2.2. Therefore, a prototype was developed, which can unobtrusively detect the blood pressure without using any cuff (according to the requirement of section 2.4) based on a sensor fusion between a pulse sensor and an ECG. The implementation as proposed in this chapter focuses on a chair (see Figure 3.10), since here the user is expected to sit several times a day, e.g. while watching TV, working, etc.

a) **b)**

Figure 3.10: The cuff-free blood pressure monitor and its implementation into a furniture. (a) The prototypical implementation for the laboratory test. (b) The prototypical implementation at the field test.

The advantage of the blood pressure measurement via the proposed module is that this method offers an alternative way to measure the blood pressure without any physical forces. Compared to the invasive blood pressure measurement, this method does not harm the human skin at all, which makes this method safe (regarding infections); it is also noninvasive according to the requirements of section 2.4. Especially people suffering from anxiety of blood pressure measurements benefit by this alternative approach, since only the body contact to the electrodes is necessary, which are attached at the chair of Figure 3.10, in order to measure the systolic blood pressure. To realize this module, the device is calculating the blood pressure by means of the ECG and pulse curve via the pulse transit time (PTT). Thereby, this prototype records and stores the systolic blood pressure and the ECG curve, and automatically calculates via the ECG and pulse curve the systolic blood pressure, according to the requirements of section 2.4.

In subsection 3.2.1, the general concept of a cuff-less blood pressure detection is explained. After the introduction of the general measurement, the concept of capacitive electrodes is described in subsection 3.2.2, then the hardware setup of this module is explained in subsection 3.2.3. Finally, the software functionality for obtaining the ECG curve, pulse curve and systolic blood pressure value is provided in subsection 3.2.4. Additionally, results of the functionality test are summarized in subsection 3.2.5, in order to prove that this novel method for blood pressure measuring is sufficiently accurate.

3.2.1 General Concept of the PTT

As already mentioned in subsection 2.2.2, the state of the art to measure the blood pressure is currently via the Korotkoff sounds [63]. However, Inajima et al. [153] published the fact that the pulse wave velocity (PWV) behaves linearly to the blood pressure change. In order to receive the PWV, Davis and Struthers [154] proposed equation (4):

$$\mathrm{PWV\ (cm/ms)} = \frac{\mathrm{BDC \cdot height\ (cm)}}{\mathrm{PTT\ (ms)}} \tag{4}$$

However, since the PWV is dependent on the body correlation factor (BDC), the body height, as well as the PTT, Gesche et al. [155] investigated the potential direct use of the PTT for the blood pressure estimation. Additionally, several research groups in the past [156, 157, 158] examined the use of the PTT for estimating the blood pressure, instead of using the more complex, but therefore more accurate PWV as input for the blood pressure detection.

Therefore, for this prototype, also the PTT was used to identify the systolic blood pressure. To capture the diastolic blood pressure as well via the PTT/PWV, several proposals have been published, e.g. from Poon and Zhang [159]. Unfortunately, functional tests using the published proposals failed with the proposed hardware of this module. As no reliable solution was found for additionally capturing the diastolic value, the module described in this section is exclusively capturing the systolic blood pressure, in additions to the ECG curve and the pulse curve (see Figure 3.11).

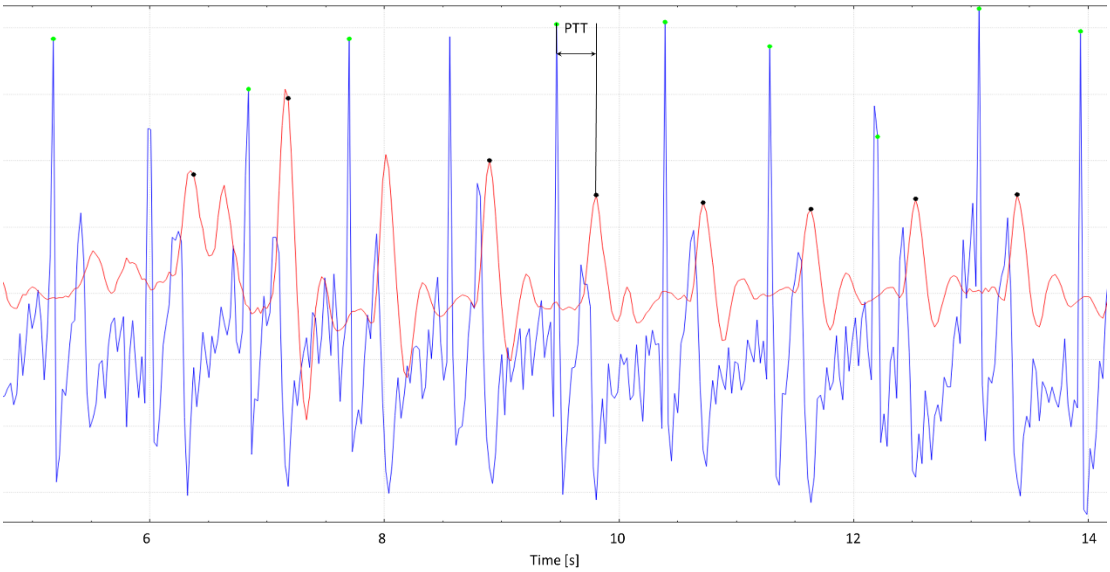


Figure 3.11: An exemplary marked PTT between an ECG curve and a pulse curve, which was measured on a finger.

Figure 3.11 represents the PTT, which is the time difference between the main contraction of the heart, i.e. the R-Peak of the ECG (see subsection 2.3.2), and the detected pulse wave at the periphery of the human body (e.g. at a finger). The shorter the PTT is, the higher the blood pressure becomes. In order to interpret the corresponding blood pressure to the appropriate PTT, the device needs to be calibrated.

The calibration process (see section 3.2.4 for more details) needs to measure the corresponding PTT (i.e. PTT_1 and PTT_2) for two different blood pressure values (BP_1 and BP_2). As a result, the average PTT is plotted by the prototype on the GUI, which enables the user to measure and compare the actual blood pressure manually with the detected PTT. The blood pressure values and the appropriate related PTT values are stored in an external text file, which is used as input information for the prototype upon program start. Thereby, the device can be calibrated without modifying the source code.

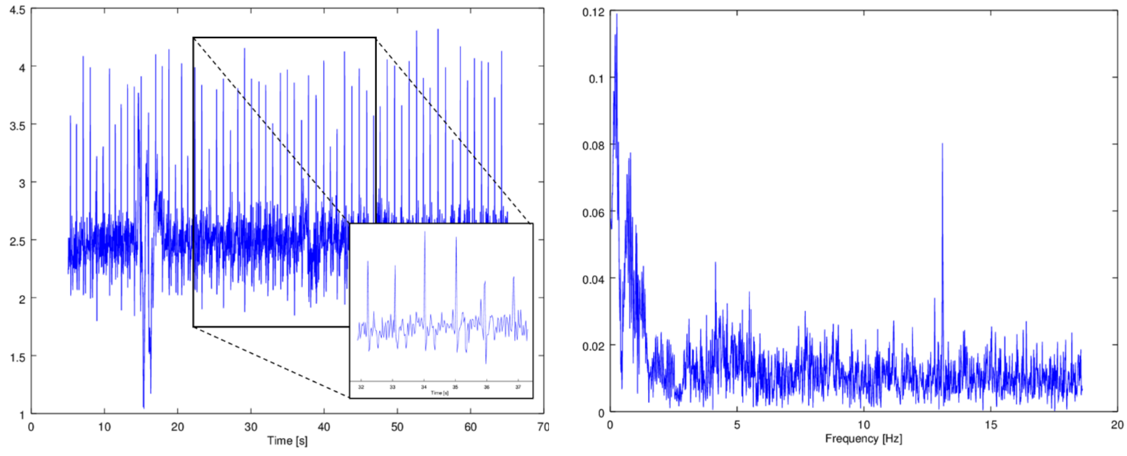
To capture the ECG curve and the pulse curve, an ECG device and a pulse sensor are necessary. The ECG device is especially not applicable for the home use according to the state of the art (see subsection 2.3.2), mainly because of the electrode gel. In order to have a strong R-Peak, which can be measured even through cloths, capacitive electrodes are used [160].

Thereby, the electrodes can be theoretically installed into furniture like a chair (e.g. into the backrest of a chair) in order to unobtrusively measure the ECG. Such approaches have been confirmed in the past e.g. by the car industry [161]. Since only one ECG lead is necessary for this implementation, the electrodes were arranged according to the “Einthoven I” definition (see subsection 2.3.2).

3.2.2 Capacitive Electrodes

For this module, capacitive electrodes were used, instead of normal electrodes. This is because of the potential application to measure without any contact gel or even through cloths, which enables an unobtrusive implementation of this application into furniture. In this subsection, the reason to why capacitive electrodes have the potential to measure the ECG even through cloths is introduced.

A relaxed person has normally 60 – 80 heartbeats per minute, which is equal to a frequency of 1 Hz – 1.2 Hz. The ECG signal itself possesses frequencies of 0 Hz to 15 Hz and higher (see Figure 3.12).



a) **b)**

Figure 3.12: The captured ECG curve and its frequency domain. (a) An ECG record of 70 seconds as input signal. (b) The related frequency domain from 0 Hz to 20 Hz.

As can be seen in Figure 3.12, the human ECG has a very low frequency domain. For instance, the QRS complex has a frequency domain of 0 Hz - 20 Hz [162]. However, capacitive electrodes (also sometimes called active electrodes [163]), can be seen as a capacitor, where one side consists of the human tissue and the other side the sensor surface of the capacitive electrode (see Figure 3.13). Unfortunately, capacitors are high-pass filters of first order, which prevent the ECG signal from becoming captured because of its low frequency domain.

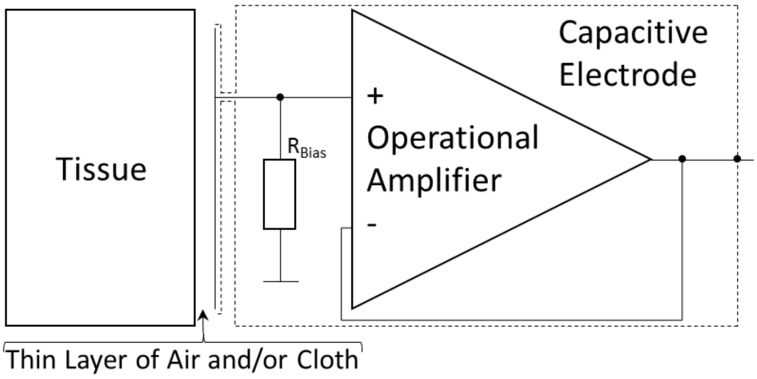


Figure 3.13: Basic schematic of the capacitive electrodes.

The schematic capacitive electrode of Figure 3.13 shows the general structure of such an active electrode, where the electrode surface is attached to a very high input impedance of an operational amplifier.

The operational amplifier is implemented as a voltage follower, because the high input impedance is the main reason for its use. Nevertheless, mostly the active electrodes have a pre-amplification implemented, in order to measure the ECG. The common input impedance for capacitive electrodes is around 10^{14} Ω, which can only be achieved by using these specific operational amplifiers like the OP124 [164].

The reason why such high input impedances are necessary for the capacitive electrodes can be explained via equation (5):

$$f_c = \frac{1}{2 \cdot \pi \cdot \mathrm{R} \cdot \mathrm{C}} \tag{5}$$

In equation (5), the dependency of the cutoff frequency f_c of the resistance R and the capacity C of the active electrode is visible. The larger the capacity C or the resistance R becomes, the larger the dominator will be, which results in a small cutoff frequency f_c. Therefore, it is necessary to have a large sensor surface to receive a large capacity C, or alternatively a very high input resistance R, in order to shift the border frequency f_c down so that the ECG curve can pass the high pass filter. Since the sensor surface is difficult to adapt and limits the implementation possibilities, the solution to use the ultra-high input impedance of specific operational amplifier is preferred. On the contrary, this approach leads to a very high sensitivity for noise.

3.2.3 Concept of the Hardware Implementation

This module can be split into three components: 1. the Sensors, 2. the Processing Unit, and 3. the User Interface. In this subsection, the task of each component is explained which led to the development of this module. Additionally, the interface between the different components is described as well, since without the developed interface presented in this subsection, the different components of this module are not compatible with each other.

For **the sensors,** capacitive electrodes were used in combination with a Driven-Ground-Leg circuit electrode and a pulse sensor. Since the development of capacitive electrodes is quite well researched, as well as capacitive electrode chips are commercially available, this component was purchased from Plessy Semiconductors. The chips have four pins, which need to be interfaced with an ECG device. From Plessey Semiconductors, the capacitive electrode chip PS25203B and PS25201B were purchased. The main difference between the sensor chips is mainly the amplification factor of both electrodes. Tests revealed that the PS25203B is more noise resistant because of the lower amplification factor compared to the chip PS25201B. The disadvantage is that the electrode chip PS25201B is potentially better in capturing the ECG signal through cloths. However, the PS25203B was used in this module for the laboratory test, as well as the field test.

In order to interface the capacitive electrode chips with a single board computer, e.g. the BBB via an Arduino and appropriate shield (like the Olimex or e-health shield), a unique interface had to be developed as depicted in Figure 3.14.

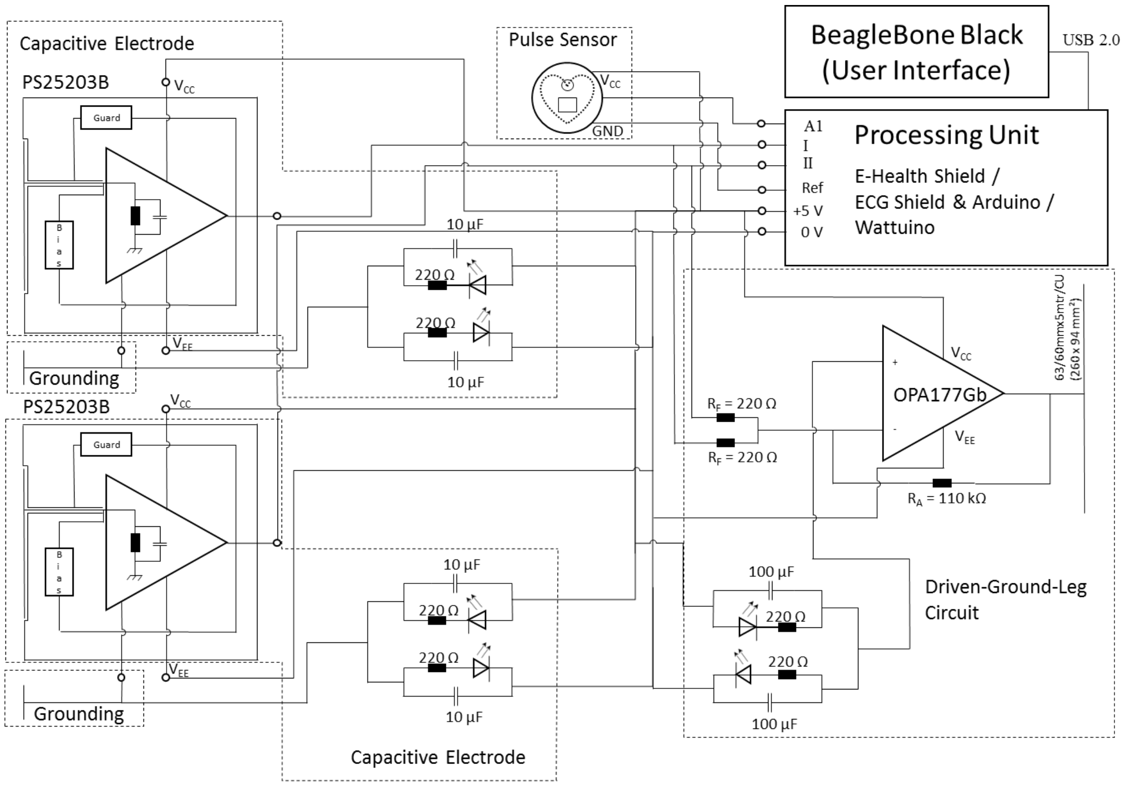


Figure 3.14: Interface schematic of the capacitive electrodes from Plessey Semiconductors and the Pulse Sensor, as well as the Dirven-Ground-Leg circuit.

Furthermore, also the modularity at this level was already considered. The capacitors and protection LEDs, which are used to stabilize the power supply (see Figure 3.14), are directly attached to the sensor board, where the capacitive electrodes chips were embedded (see Figure 3.15). Thereby, it was possible to investigate the performance of the PS25203B and PS25201B in this module.

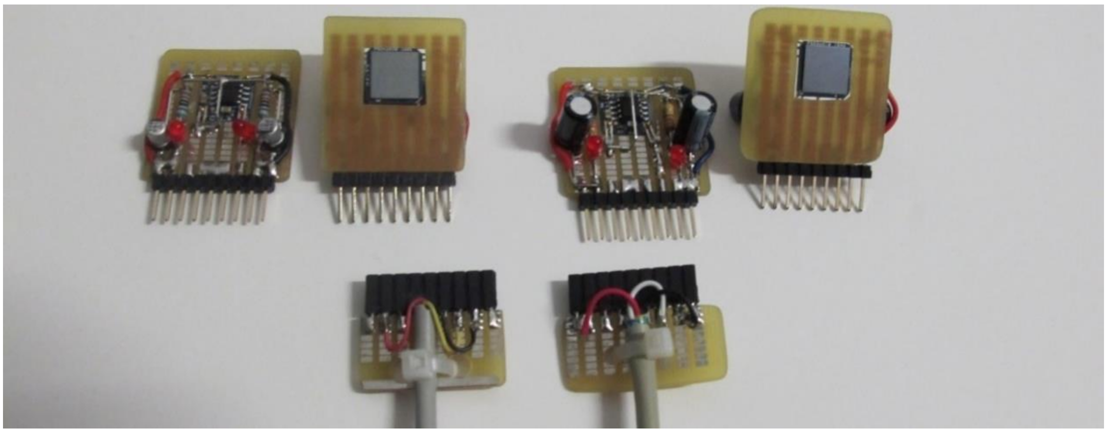
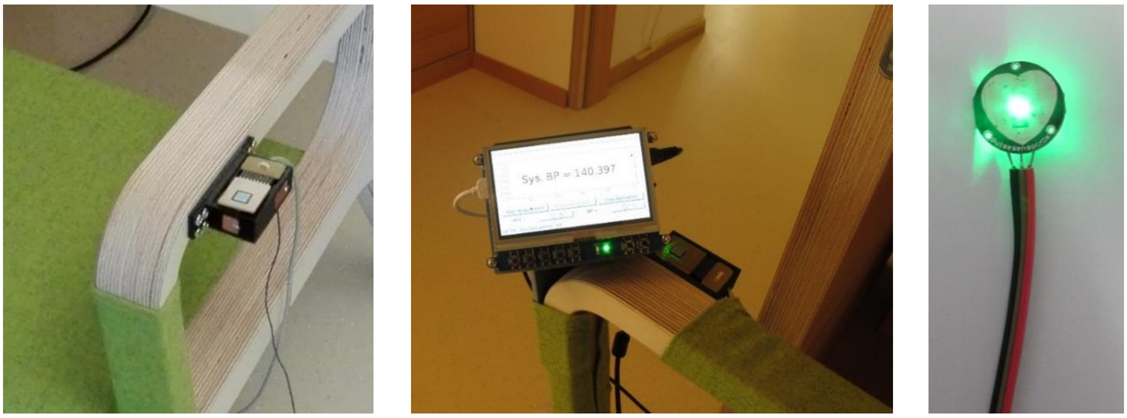


Figure 3.15: The modular interface of the capacitive electrodes, which are embedded on circuit boards and can be easily exchanged due to the modular interface.

As the electrode for the Driven-Ground-Leg circuit, a copper mesh was used on the sitting surface of the chair (see Figure 3.10 (a)). At the time of the laboratory test, this implementation focused on the ECG measurement itself. However, this implementation aimed to measure not only the ECG, but more the systolic blood pressure via sensor fusion and the PTT (see section 3.2.1). In order to receive the systolic blood pressure from the ECG, the necessary additional pulse sensor (see Figure 3.16 (c)) had to be implemented into the handles of the modules (see Figure 3.16 (b)). By this chance, also the Driven-Ground-Leg electrode was implemented into the handles of this module (see Figure 3.16 (a)). Thereby, for the field test, a better design was achieved, which is much more robust compared to the laboratory test version of this module.



a) **b)** **c)**

Figure 3.16: Design adaptions of the in-chair implemented cuff-free blood pressure monitor. (a) The electrode for the Driven-Ground-Leg circuit is directly embedded in the handle, and the ground electrode is placed at the front of the handle. (b) The BBB is directly attached to the chair, and a pulse sensor was installed on the handle next to the monitor. (c) The used pulse sensor, which was directly attached to the analog input of the Arduino Uno board.

The pulse senor was directly interfaced to the analog input of the processing unit (as depicted in Figure 3.14) and can be cheaply purchased as a ready product [165]. This solution is also used by other research groups, e.g. by Kemis et al. [166]. It consists mainly of the photo diode APDS-9008, a green LED and an amplification circuit including an active filter for the noise. In order to stay as cost efficient as possible, an Arduino Uno board [167] was used for the analog-digital conversion, which acts as the processing unit of this module (see Figure 3.17).

The task of **the processing unit** is to capture and forward the data to a computer interface. Of course, an Arduino Uno board does not have an ECG instrumentation amplifier onboard. Therefore, an ECG instrumentation amplifier was attached to the Arduino Uno board by using appropriate shields. In this work, two potential shields have been investigated, which were the e-health shield from Cooking Hacks [168], and the ECG/EMG-Shield from Olimex [169].

Both shields were designed for normal electrodes and showed the same performance during the functional tests. The main differences between the shields are that the e-health shield offers additional interfaces for other sensor systems and is much more expensive. Therefore, the results presented here were developed using the Olimex ECG Shield (see Figure 3.17 (c)). For the Driven-Ground-Leg circuit, which was implemented according to the proposal of Aleksandrowicz et al. [170], the OPA177Gb was used as depicted in Figure 3.14. In order to protect the electronic components of the processing unit, a casing was developed using FreeCAD, and printed using a 3D-Printer (see Figure 3.17).

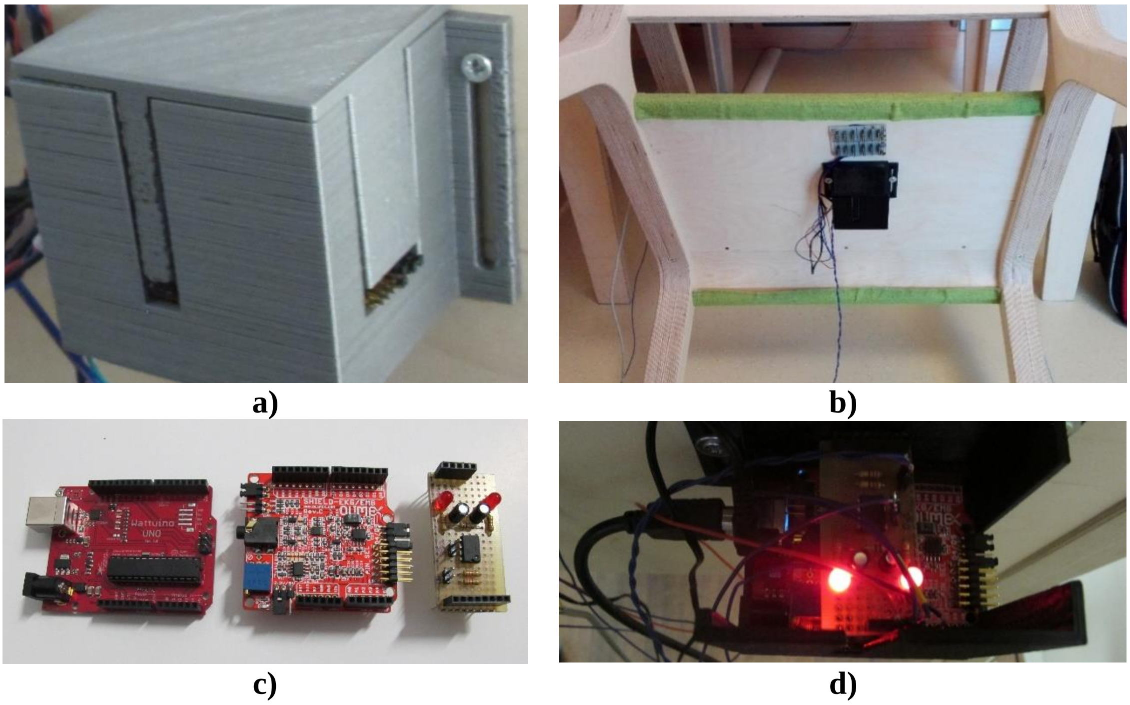


Figure 3.17: The processing unit of this module implemented unobtrusively into a chair. (a) The 3D printed casing of the processing unit, attached to the backside of the chair. (b) The processing unit while being installed under the sitting surface for the field test. (c) The inner life of the processing unit, which consists of an Arduino Uno, ECG shield from Olimex and the Driven-Ground-Leg circuit. (d) The inner life assembled and running in the background of the chair.

For **the user interface,** a similar approach was used as described in subsection 3.1.1. Instead of interfacing a normal desktop computer, which would be difficult to embed into a furniture in order to be as unobtrusive as possible, a cost efficient single board computer BBB was used, with the touchscreen cape 4DCAPE-43. Also this BBB used Debian 7.8 as the operating system and QT 4.8 was used to compile the software directly on the prototype.

3.2.4 Concept of the Software Implementation

For this module, the software had to manage the data transfer between the processor unit and the user interface of this module. The software for this prototype was developed on an Ubuntu 14.06 computer using QT 5, with the difference that here a GUI was in the foreground. The aim was to develop a very simple and intuitive GUI for the user (see Figure 3.18), which was ported afterwards to the BBB and finally compiled using the “qmake” command. Therefore, only libraries of QT 5 were used, which were compatible with QT 4.8.

In order to start the measurement, the user has to press the “Start Measurement” button on the touchscreen of the prototype in order to activate the sensors attached on the chair. After starting the program, the user grasps both handles on the armrest. As soon as 25 systolic blood pressure values are collected, the final result will be calculated and plotted. The program stops its execution automatically as soon as the final result is plotted. In case the user wants to abort the measurement, the button “Stop Measurement” can be used for this purpose. The button “Close Application” allows the user to return to the operating system of the BBB, which enables the use of the BBB for other research applications. In a final product, this button would be disabled, and the GUI would automatically start, so that the monitor would behave like a pure blood pressure monitor. At the very bottom of the GUI (see Figure 3.18) the detected average PTT and the corresponding blood pressure are plotted, which is necessary for the calibration process (see subsection 3.2.1).

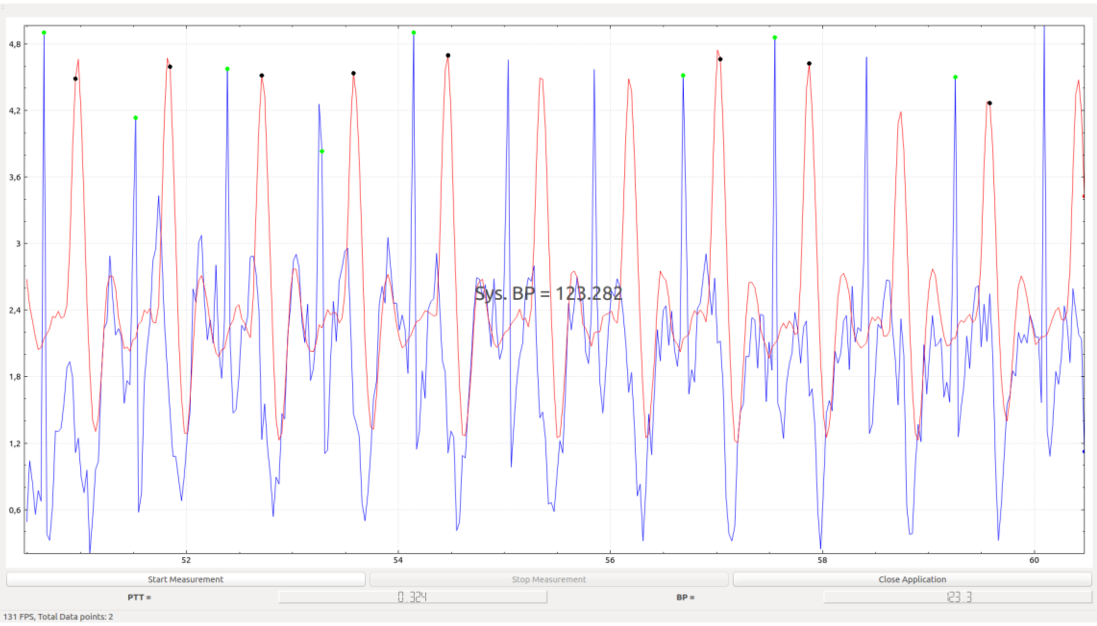


Figure 3.18: The GUI of the prototype, which consists of a large display for plotting the captured ECG and pulse curves, and the result of the blood pressure measurement. Next to the display, the GUI has only three buttons for starting, stopping and terminating the application.

The algorithm is split into two threads, which are the “Main Thread” and the “Sub thread”. The “Main Thread” is responsible for the GUI inputs as well as plotting the results and calculating the PTT and blood pressure from the curves. The “Sub Thread” deals with the data reception from the Arduino, data storage on the hard drive of the BBB, and data forwarding to the “Main Thread”. The “Sub Thread” and the Arduino Uno program (which is compiled and running on the Processor Unit) communicates via the serial interface via a

USB wire with each other. The overall algorithm and communication between the "Main Thread", "Sub Thread" and the Arduino is depicted in Figure 3.19.

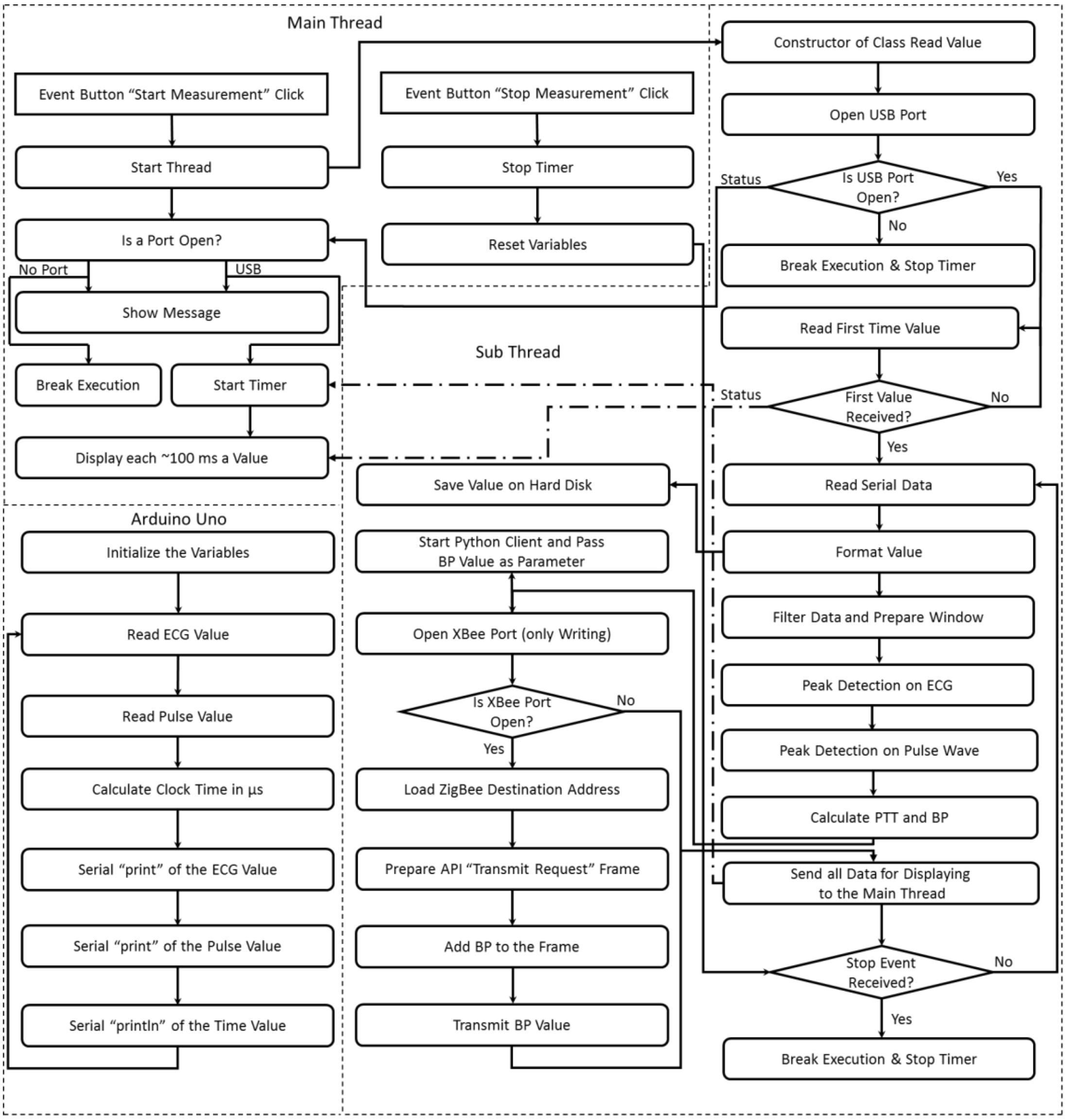


Figure 3.19: The software flow diagram of the "Main Thread", "Sub Thread" and the Arduino Uno. The Arduino Uno thread communicates with the "Sub Thread" via the USB port.

For plotting the ECG curve and Pulse curve, the Arduino Uno reads the analog input A0 and A1, which are the analog interfaces of the ECG shield and the pulse sensors, sequentially (wherein the ECG sample is always first captured, followed by the pulse sample). After recording the ECG and pulse sample of both sensors, a relative time value is calculated (in µs), before all three values (ECG, pulse and time) are transferred via the USB wire to the BBB. The BBB reads the incoming samples in the "Sub Thread" continuously and stores them on its hard drive in a text file. The "Main Thread" uses a clock, which ticks each 100 ms and grasps the incoming value of the "Sub Thread" for plotting. This means that the plotted ECG curve has a lower accuracy then the stored data. By this approach, graphical issues do not affect the raw data on the computer with limited resources (e.g. a single board computer).

In the “Main Thread”, the PTT is calculated using the transferred sample time difference of two samples, which are identified by a peak detection. The peak detection in the program is programmed according to the proposal of Pan and Tompkins [171] and is applied for the ECG curve as well as the pulse curve. In order to reduce the false detection rate, a security mechanism was implemented. If the program detects an ECG peak, the next incoming peak on the pulse curve marks the partner sample, which will be used to calculate the PTT (as depicted in Figure 3.11, in subsection 3.2.1). However, in case a new ECG maximum is detected, before the corresponding pulse curve maximum, then the old ECG maximum is replaced with the new ECG maximum. Furthermore, after successfully detecting a pulse wave peak, no further pulse wave peak will be considered for the PTT calculation, before an ECG peak was detected. This approach sufficiently decreased the impact of motion artefacts and noise when calculating the PTT.

After detecting the PTT, the blood pressure BP is calculated according to equation (6):

$$\mathrm{BP} = \mathrm{B} \cdot \mathrm{PTT} + \mathrm{A} \tag{6}$$

In equation (6) the values A and B are absolutely depending on the user and differ from user to user. The calibration process, which was mentioned in subsection 3.2.1, is used to calculate the user-dependent values of B and A by using equation (7):

$$\mathrm{B} = \frac{\Delta\mathrm{BP}}{\Delta\mathrm{PTT}} = \frac{\mathrm{BP}_1 - \mathrm{BP}_2}{\mathrm{PTT}_1 - \mathrm{PTT}_2} \tag{7}$$

The input values BP_1 and BP_2 represents both measured blood pressure values, which should be different, whereas PTT_1 and PTT_2 are the corresponding PTTs of the respective blood pressure. Once the value B is known, value A can be calculated by substituting value B into equation (6). Alternatively, substituting equation (7) into equation (6) results in equation (8), which was programmed in the source code.

$$\mathrm{A} = \mathrm{BP}_1 - \frac{\mathrm{BP}_1 - \mathrm{BP}_2}{\mathrm{PTT}_1 - \mathrm{PTT}_2} \cdot \mathrm{PTT}_1 \tag{8}$$

The two blood pressure values (BP_1 and BP_2) and their corresponding PTTs (PTT_1 and PTT_2) are stored in an external text file, which has to be updated depending on the user. When the program starts, these values are loaded, and the variables B and A are calculated using equation (7) and equation (8). During the measurement, the detected PTT will be calculated corresponding to the appropriate systolic blood pressure using equation (6). Both values (the PTT and the calculated corresponding blood pressure) will be immediately plotted on the bottom of the GUI (see Figure 3.18 on page 46). The text file, which was used to store the captured curves on the hard disk, includes the final results of the blood pressure as well, which will be automatically transmitted via a Python script to a server at the end of the measurement (see subsection 3.4.3). For this purpose, the Python script is called in the source code of the C++ application via system commands. As seen in Figure 3.19, the program also checks for an XBee interface (see subsection 3.3.2). In case there is an XBee antenna available, the data can be transmitted via XBee modules in parallel. However, tests revealed that the transition rate is worse compared to Wi-Fi. Therefore the curve samples, as well as the result of the blood pressure are transmitted only via Wi-Fi, and the option to use the XBee antenna was disabled for the proposed “Ambient Health Monitoring System”.

3.2.5 Reliability Tests of the Cuff-Free Blood Pressure Monitor

Since this module is very sensitive to noise and captures the blood pressure via sensor fusion, several functionality test were used, to confirm the reliability of this novel approach. In this section, the different functional test and their results are provided.

Because of the high sensitivity of the capacitive electrodes, noise can lead from time to time to false results. Therefore, the same approach of a false measurement detection was applied as already proposed in subsection 3.1.2 via equation (2) and equation (3) (see Figure 3.7 on page 37). The only difference here is that instead of 10 values, 25 values are collected. The prototype proved that depending on the noise while measuring, the final result can be calculated within 30 s – 60 s, when 25 blood pressure values are collected. In order to prove the impact of the false detection algorithm, functionality tests were executed. The algorithm included defining dynamic thresholds, using the STD of an average value, to correct the average calculation. In these tests, a test person measured his/her systolic blood pressure with the prototype, one time with a clear signal, and with nearly no noise and no motion artefacts. Afterwards, the measurement repeated, but this time the test person caused some false recognized blood pressure values by disturbing the ECG and pulse curve detection via motion artefacts. The individual blood pressure results for the false detection analysis of this functionality test are listed in Table 3.1 [151].

Table 3.1: Functionality test measurement values of the detected systolic blood pressures. Measurement one was with minor disturbance, whereas measurement two suffered under heavy motion artefacts, which led to a high STD. At the end of the false measurement algorithm, both results show similar values.

BP ID	Result of measurement 1	Result of measurement 2	BP ID	Result of measurement 1	Result of measurement 2
1	123.68 mmHg	227.73 mmHg	15	102.55 mmHg	144.01 mmHg
2	114.11 mmHg	217.76 mmHg	16	133.64 mmHg	133.64 mmHg
3	138.03 mmHg	138.03 mmHg	17	123.28 mmHg	133.64 mmHg
4	118.10 mmHg	216.57 mmHg	18	112.91 mmHg	112.91 mmHg
5	108.13 mmHg	206.20 mmHg	19	102.54 mmHg	133.64 mmHg
6	98.17 mmHg	81.821 mmHg	20	133.64 mmHg	123.28 mmHg
7	112.91 mmHg	19.629 mmHg	21	133.64 mmHg	112.91 mmHg
8	102.54 mmHg	9.264 mmHg	22	112.91 mmHg	71.46 mmHg
9	92.19 mmHg	0 mmHg	23	133.64 mmHg	61.09 mmHg
10	81.82 mmHg	81.821 mmHg	24	123.28 mmHg	123.28 mmHg
11	123.28 mmHg	237.30 mmHg	25	112.91 mmHg	112.91 mmHg
12	112.91 mmHg	237.30 mmHg	**Threshold**	**115.48 +/- 14.02 mmHg**	**133.11 +/- 71.64 mmHg**
13	123.28 mmHg	237.30 mmHg			
14	112.91 mmHg	154.37 mmHg	**Result**	**114.25 mmHg**	**118.41 mmHg**

Comparing the first average values of Table 3.1 shows that the first measurement resulted in a systolic blood pressure of 115.48 mmHg, whereas the disturbed measurement detected a much higher systolic blood pressure with 133.11 mmHg. The STD indicates already which measurement is more accurate. However, by applying the false measurement algorithm from subsection 3.1.2, the false measured samples were successfully detected and the systolic blood pressure of 133.11 mmHg was corrected to 118.41 mmHg.

The systolic blood pressure measurement with 115.48 mmHg had only a minor correction to 114.25 mmHg. The result at the end of the table is the value displayed in the center of the GUI as the final result as depicted in Figure 3.18 on page 46.

Additionally, the prototype was tested for 34 hours, in order to make sure that the calibration is not valid for only a short time. For this purpose, a test person measured the systolic blood pressure several times with a few hours difference with the prototype, as well as with a wrist blood pressure monitor “tenso-comfort” from the company Biocomfort Diagnostics GmbH [172]. The results of the systolic blood pressure, as well as the time difference between each measurement are listed in Table 3.2 [151].

Table 3.2: Comparison of the results between the proposed module and a commercial blood pressure device (for the wrist), in order to investigate the calibration accuracy over 34 hours.

Time difference of the wrist device [hh:mm]	Sys. blood pressure [mmHg]	Time difference of the prototype [hh:mm]	Sys. blood pressure [mmHg]
00:00	122 mmHg	00:04	120.925 mmHg
03:15	127 mmHg	03:16	128.152 mmHg
07:11	118 mmHg	07:12	123.407 mmHg
09:49	120 mmHg	09:51	117.063 mmHg
25:34	119 mmHg	25:37	118.100 mmHg
28:24	118 mmHg	28:25	122.715 mmHg
28:42	125 mmHg	28:43	127.534 mmHg
33:44	118 mmHg	33:46	120.468 mmHg
34:00	118 mmHg	33:59	122.937 mmHg

In Figure 3.20, the measurement series of Table 3.2 are plotted against each other, which make the detected blood pressure fluctuation of the test person visible. As it can be seen, both devices are able to follow the different blood pressure levels only with minor deviations to each other. This proves that the proposed module is able to record the blood pressure change of a person over a longer time and the reliability is given. Therefore, the unobtrusive implementation into a bed could be a future application, where this module captures the blood pressure changes e.g. while someone is sleeping, (see section 5.1.2).

Finally, in order to assure that the developed sensor method is working accordingly, the functionality has been tested on three different test people. For this purpose, all three test people first calibrated the prototype by measuring their PTT and the corresponding blood pressure with the prototype and the wrist blood pressure monitor. Once the values of BP_1 and PTT_1 were noted, the test person performed some sit-ups to cause a different blood pressure for BP_2, which was recorded with its corresponding PTT for PTT_2.

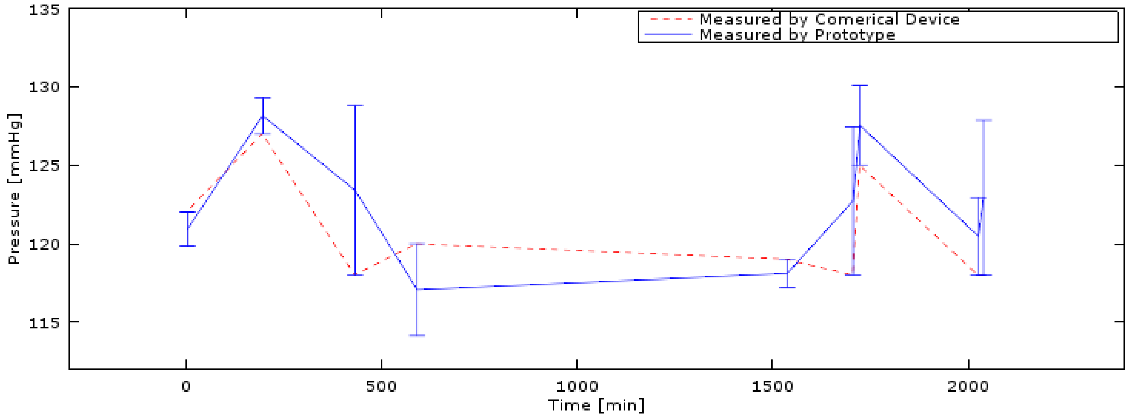


Figure 3.20: Systolic blood pressure measurement (nine in total) of the proposed module in direct comparison with a commercial blood pressure monitor.

After setting up the blood pressure device for each test person with their individual BP_1, PTT_1, BP_2 and, PTT_2 values, each person (see Table 3.3) measured the blood pressure using the cuff-free blood pressure module. Directly after the blood pressure measurement with the proposed module, the comparison measurement was performed, using the blood pressure monitor ("tenso-comfort" from the company Biocomfort Diagnostics GmbH) on the left wrist. The systolic value of both devices are noted in Table 3.3. This procedure has been redone three times for each of the three test people.

Table 3.3: Measurement results of different test people in direct comparison with a commercially available device.

Test subject	Calibration data	Result of the Prototype	Result of the commercial device
Male; 37 years	BP_1: 132 mmHg; PTT_1: 0.108 s BP_2: 113 mmHg; PTT_2: 0.223 s	111.882 mmHg 115.755 mmHg 112.497 mmHg	112 mmHg 117 mmHg 110 mmHg
Male; 30 years	BP_1: 148 mmHg; PTT_1: 0.260 s BP_2: 117 mmHg; PTT_2: 0.325 s	113.301 mmHg 118.096 mmHg 123.355 mmHg	113 mmHg 117 mmHg 122 mmHg
Female; 33 years	BP_1: 132 mmHg; PTT_1: 0.210 s BP_2: 121 mmHg; PTT_2: 0.313 s	113.256 mmHg 126.411 mmHg 115.717 mmHg	117 mmHg 124 mmHg 112 mmHg

The largest deviation between the two presented measurements of Table 3.3 was 3.7440 mmHg, which proves that the proposed prototype can detect the systolic blood pressure independently of age and sex. The largest deviation to the commercial blood pressure device during the long-time measurement, presented in Table 3.2, was 5.4 mmHg. Additionally, the prototype is following the blood pressure trend over the measurement time (as seen in Figure 3.20), which confirms the system is also working appropriately over a longer period.

3.3 Novel Fall Detection

As mentioned in subsection 2.1.3, the fear to fall is one of the biggest issues in old age. In some cases, the fear to fall increases the chance to fall [173]. Sequelae e.g. osteoporosis, increase the fear to fall, since the consequences are more fatal in case of a fall. Additionally, the fear to fall and to be in need of help, lead to the resignation of living independently and self-sufficiently at home regarding single households in old age. In order to reduce the fear and to support the ambulance to interfere as fast as possible in case of a fallen person, fall detections become more and more important.

Therefore, it is less surprising that several fall detection systems and concepts already exist on the public market (see section 2.2.3). However, their main weak point is either the necessity to wear something all the time, or the increased expenses for installing the systems. Therefore, it was an objective to develop a novel fall detection system for the elderly, who live alone. The cost efficiency and unobtrusive implementation, which is operating permanently and reliably, are the requirements for this module according to the request of section 2.4.

The concept developed and described in this section is partially published in the journal of IEEJ Transactions on Electrical and Electronic Engineering [174]. The development consisted of three steps. The first step was to build the necessary hardware setting, which is described in subsection 3.3.1. The related software development is documented in subsection 3.3.2. After the laboratory test, which is described in section 4.1, some improvements have been implemented, in order to prepare this concept for the field test (see section 4.2). These improvements lead to the final development stage of this module, which is described in subsection 3.3.3.

3.3.1 Initial Functionality Concept

The basic concept of the novel fall detection was inspired by a light barrier. Normally a light barrier consist of a light emission source, which transmits light at least collimated or coherent, and a light sensor, e.g. a photo resistor or photo semiconductor. When the light source is scattered in one dimension, e.g. by using a line laser instead of a laser pointer, several sensors can be addressed at the same time. Thereby, two or three light sources can cover an entire room sufficiently to track for blocking obstacles (see Figure 3.21). By implementing the light barrier as close as possible to the ground, the light barrier can transmit its light under most objects (like beds, chairs, tables etc.).

Depending on the amount of blocked light sensors, the size of the obstacle can be estimated, which helps distinguishing between objects e.g. table legs and chair legs, or pets e.g. cats and small dogs, and a fallen person, because a human laying on the ground has a much larger contour compared to pets and most furniture. As the bathroom is the area with the most accidents in an apartment [175], the proposed concept is aimed to be developed into the bath environment. According to section 2.4, the proposed solution aims to be a cost-efficient module, which can be installed fast and easily into a bathroom.

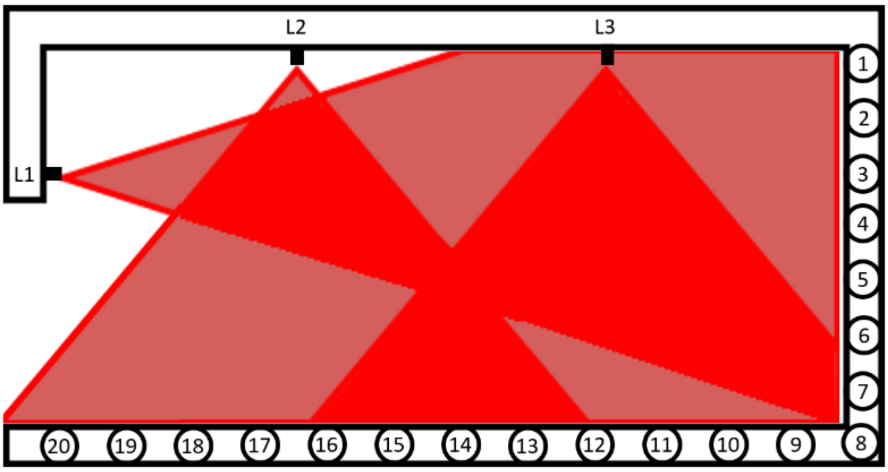
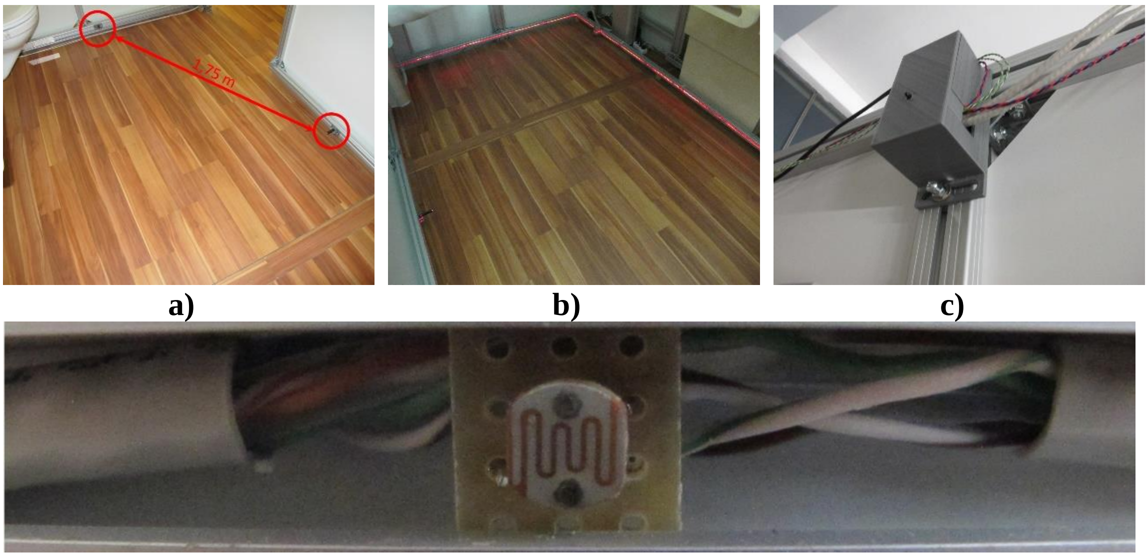


Figure 3.21: Schematic of the light barriers in a room for a fall detection. L1, L2, and L3 represent the laser source, the numbers 1 through 20 the appropriate potential photo sensors.

In order to hide the lasers as well as the light sensor, it is thought to implement this concept into a baseboard, i.e. the fall detection is implemented unobtrusively at the edge of a room (see Figure 3.22).



d)

Figure 3.22: The fall detection module. (a) The two line laser, with a distance of 1.75 m. (b) The baseboard implementation in the bathroom of the test apartment. (c) The Arduino Mega 2560 attached at the ceiling of the bathroom, covered by a self-developed and 3D printed casing. (d) One of the 14 photo resistors, which is parallel, set to the other photo resistors according to Figure 3.23.

The depicted system in Figure 3.22 was implemented in a ~ 6 m² bathroom of a test apartment. For research purposes, aluminum profiles from MayTec [176] were used as the baseboard element (see Figure 3.23). In order to have a sensor grid dense enough for identifying a fallen person, 14-photo resistors were used. The schematic in Figure 3.23 shows that the different photo resistors were attached to the analog inputs A0 to A14 via a voltage divider to an Arduino Mega 2560 board [177]. By using the analog input of the Arduino Mega 2560, the values for each photo resistor can range between 0 and 1023. The lasers were controlled over the Arduino Mega 2650, by the digital output D7 and D8. The IMM-63/07-Line, which have a 100° open angle and emit light at 630 nm – 690 nm [178], were used as line lasers.

By using this specific wavelength, the laser emission is recognizable as red light, which helps to calibrate the system. The later concepts foresee the use of infrared emitting light sources.

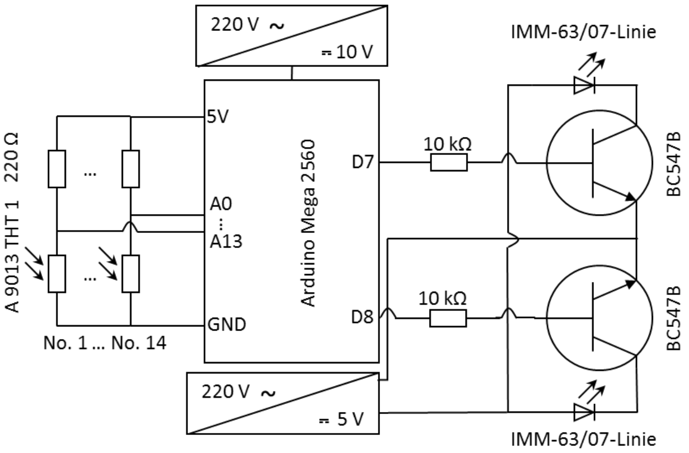


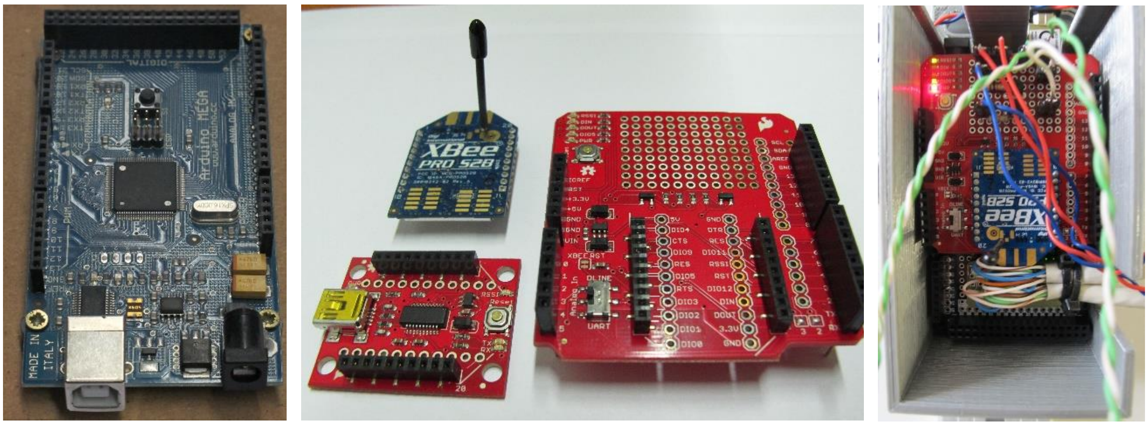
Figure 3.23: Schematic connection diagram of the prototype. At this development stage, two different power supplies are needed, one for the Arduino board and the photo resistors, and one for the line lasers.

Since the used line laser IMM-63/07-Linie are consuming too much current for interfacing the power supply directly to the Arduino Mega 2560 board, an external power supply for the line lasers was necessary. To interface the lasers with the digital outputs of the Arduino Mega 2560, in order to enable the control of the lasers via the Arduino Mega 2560 board, the NPN transistor BC547B [179] was used.

The distance of 1.75 m to the two light sources (see Figure 3.22 (a)) assures that even if one laser is fully blocked by an obstacle (e.g. someone is standing directly in front of the laser) the other laser still hits enough photo resistors so that the fall detection is still able to distinguish between an obstacle and a fallen person. The Arduino Mega 2560 was used to steer the entire system and to decide, whether a fallen person was detected in the room or not (see section 3.3.3 for more details). However, the Arduino Mega 2560 is not a single board computer as used in the modules described in section 3.1 and section 3.2. By definition, the Arduino Mega board is a microcontroller board, which enables the developer to program microcontroller application using C++ with an Arduino IDE.

For this purpose, the XBee antenna “XBee PRO Series 2” [180] was used, which enabled a wireless data transfer in order to forward the information of the Arduino Mega 2560. In order to interface the XBee antenna with the Arduino Mega 2560 board, a special “XBee Shield” from Sparkfun [181] was used (see Figure 3.24).

The XBee modules were chosen for this prototype because of their benefits. When using a Wi-Fi network, a Wi-Fi router is necessary. In an XBee network, there is one XBee module functioning as the coordinator, where other XBee modules join by an appropriate network ID [180]. In this prototype, the computer consisting of the XBee module for receiving the information from the Arduino Mega 2560 was defined as coordinator, which means that the XBee module depicted in Figure 3.24 was used as an “end device”.



a) b) c)

Figure 3.24: The hardware configuration of the fall detection. (a) The Arduino Mega 2560. (b) The XBee antenna module and the XBee shield, which is necessary to interface the antenna with an Arduino board, and an XBee development board, which allows interfacing the XBee antenna to a computer. (c) The Arduino Mega 2560 interfaced with the laser, photo resistor and the XBee module, covered in a casing.

This paring approach is very similar to Bluetooth, except Bluetooth has a lower range and does not easily support the communication of more than two devices. By using an XBee network, it is possible to interface several fall detections with the same computer or server.

3.3.2 Software Functionality of the Initial Concept

The software of this module aims to work automatically and unobtrusively in the background. For this purpose, the algorithm steering this module was developed via the Arduino IDE using C++. The algorithm running on the Arduino Mega 2560 board is depicted in Figure 3.25.

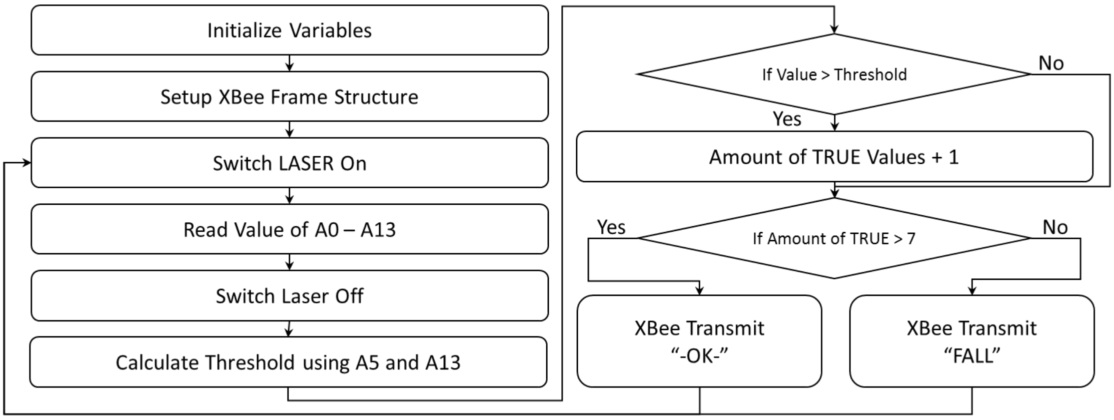


Figure 3.25: Flow diagram of the C++ algorithm on the Arduino Mega 2560.

As visible in Figure 3.25, the Arduino Mega 2560 is switching the laser off, when the photo resistor values are not checked. Furthermore, two photo resistors, which are interfaced on analog input A5 and A13, were used to setup dynamic thresholds, because of the environmental light conditions. In other words, the photo resistors receive a value already because of the environmental light condition, e.g. in the afternoon 900 and in the evening 300. The laser light hitting the photo resistors increase these numbers by 30 to 100. The different impact of the line laser to the different photo resistors is a result of the line laser, since the line laser has more light concentrated in the center of the line laser beam than at the edges.

However, this means as well that a fixed threshold in the program will not work sufficiently, since the light condition change over the day has a stronger impact than the laser. In order to avoid this effect, the bathroom of the test apartment was protected from direct sunlight. Unfortunately, even without direct sun light, the diffuse environmental daylight change was still strong enough to disturb the prototype. Therefore, two photo resistors on the edges were covered from the laser and used to predict the diffuse daylight in the environment in order to calculate a dynamic threshold. The average value of both photo resistors are used as the environmental light value EL. By using equation (9), the dynamic light threshold $\mathrm{LT_{Dynamic}}$ is calculated at each measurement using a constant value $\mathrm{LT_{Fix}}$:

$$\mathrm{LT_{Dynamic}} = \mathrm{LT_{Fix}} + \mathrm{EL} \qquad (9)$$

The value of $\mathrm{LT_{Fix}}$ was set to five in the algorithm, which is depicted in Figure 3.25. The other twelve photo resistors are used to compare their value against the threshold $\mathrm{LT_{Dynamic}}$. In case the incoming value is larger than the current dynamic light threshold $\mathrm{LT_{Dynamic}}$, the sensor counts as blocked. At the end of the algorithm, the amount of the positive blocked sensor is counted. If more than seven of twelve sensors were blocked at the same time, the fall detection recognized a fallen person. The amount seven of twelve was empirically defined for a person of 185 cm body height. The necessary amount of positive blocked sensors can differ in case of smaller inhabitants (e.g. 160 cm and smaller).

For transferring the information about a (not) fallen person, the XBee modules use a ZigBee protocol, which support two communication methods: The transparent mode and the Application Programming Interface (API) mode [180]. The transparent mode behaves like a serial interface and has to be treated similarly for transmission and receiving information. However, operating in the transparent mode yields sometimes some faulty transmitted packages. Fortunately, the API mode is much more robust, because here a specific frame structure is in use in order to transfer information (see Figure 3.26).

As seen in Figure 3.26, most of the parameters are accessible by the frame structure. This correlates to a higher flexibility, since the XBee modules must be programmed only once using the XCTU Configuration and Test Utility Software [182], where the appropriate software (for “coordinator”, “router” or “end device”) is uploaded to the XBee antenna and the network ID is given. The destination addresses of the XBee modules are normally permanently assigned when preparing the XBee antenna using the XCTU software. However, by adopting the address in the API frame (see Figure 3.26), a communication with any XBee module within the XBee network can be addressed.

The length of the frame has to be calculated in advance and depends on the amount of bytes, which are necessary for the data transmission. Therefore, two basic massages are defined in the fall detection, e.g. “FALL” for a detected fallen person, or “-OK-” in case no fallen person was detected. Both strings possess exactly four bytes, which allow the system to prepare the frame appropriately, whereas in Figure 3.26 six-bytes storage spaces are prepared.

1Byte	0x7E	Start Delimiter
2Byte	0x00 0x14	Length of the Frame
1Byte	0x10	Frame Type
1Byte	0x01	Frame ID
4Byte	0x00 0x13 0xA2 0x00	Destination Serial Number High
4Byte	0x40 0xB5 0x99 0x8D	Destination Serial Number Low
2Byte	0xFF 0xFE	16-Bit Address (if unknown)
1Byte	0x00	Broadcast Radius
1Byte	0x00	Options
6Byte	0x0D 0x46 0x41 0x4C 0x0C 0x0D	Message No. 1 for \rFALL\r
6Byte	0x0D 0x2D 0x4F 0x4B 0x2D 0x0D	Message No. 2 for \r-OK-\r
1Byte		Checksum, which Must be Calculated

Figure 3.26: Frame structure used in the algorithm of the Arduino Mega 2560, including the predefined bytes. The 6 byte message storages is presented twice, since one or both messages will be transmitted depending on the evaluation of the fall detection.

This is because the message string starts and ends with a carriage return, which requires four additional bytes of storage place. At the end of the frame, a checksum has to be calculated. For calculating the checksum, equation (10) is used [180]:

$$\text{Checksum} = 0\text{xFF} - \left[\left(\sum_{i=3}^{n-1} \text{Frame}(i)\ \&\ 0\text{xFF}\right)\right] \tag{10}$$

The reason why the sum is counted from the third byte i to the last byte $n-1$ is that the start delimiter, the two bytes for the length of the frame, as well as the last byte for the checksum itself (see Figure 3.26) are not considered for the calculation of the checksum. The checksum assures that the amount of faulty data transmission between the different XBee modules is reduced to zero, because if the checksum differs from the counter-calculated checksum of the receiving XBee antenna, the message will be ignored.

Since the checksum equation is directly implemented into the source code, it is possible to change the destination address of the XBee modules as well in the Arduino source code. At this stage, the fall detection functionality was proven by triggering a sound alert for the laboratory test (see chapter 4, section 4.1).

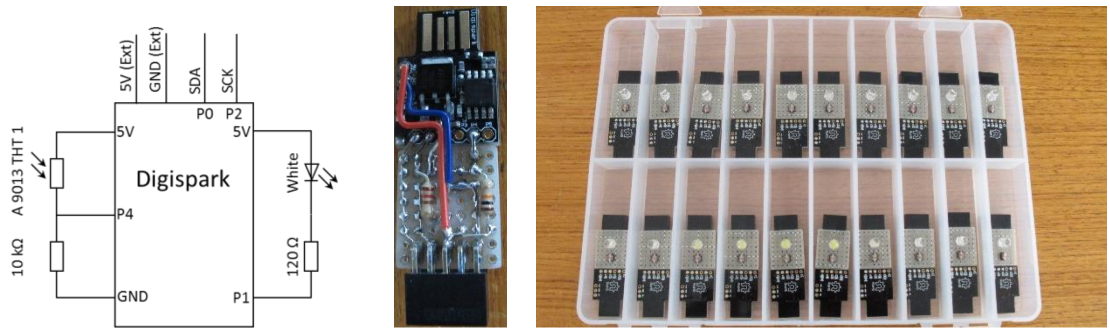
3.3.3 Functionality of the Improved Concept

Although the fall detection in subsection 3.3.1 and 3.3.2 introduced worked already reliable, it was necessary to increase the reliability and to reduce the installation efforts in order to address the requirements of section 2.4 sufficiently. Therefore, an improved concept was developed and realized, which is provided in this subsection.

In terms of the laboratory test results (see subsection 4.1.4), the proposed fall detection was further developed. On the design level, other profiles were chosen. It looks more like a baseboard compared to the first prototype. However, the main improvement focused on two main issues: The limited amount of sensors, which can be interfaced to the Arduino Mega 2560, and the impact of the environmental light.

As Figure 3.23 already showed, the photo resistors are interfaced via the analog inputs of the Arduino Mega 2560. The Arduino Mega 2560 board poses the largest amount of analog (and digital) inputs compared to other Arduino boards, whereas the prototype for the laboratory test (see subsection 3.3.1 and subsection 3.3.2) used nearly all analog inputs. Only two further analog interfaces are available for interfacing additional photo resistors. This issue can become especially critical for larger rooms, as the sensor density will decrease, because the same amount of sensors has to cover more surface area.

In order to solve this problem, a new interface for the photo resistors was implemented, using the I²C communication protocol. The I²C interface follows the master-slave principle, i.e. there is one microcontroller serving as master, and the others join the communication network as slaves. Therefore, each single photo resistor needs an individual microcontroller, which will communicate with the master microcontroller of the Arduino board. For this purpose, the developer board Digispark was used [183]. The Digispark provides an USB interface for programming, as well as five pins for direct interface to the ATtiny85 microcontroller. As shown in Figure 3.27, the Digispark serves mainly as I²C interface via the ATtiny85 microcontroller, between the master microcontroller and the photo resistor.

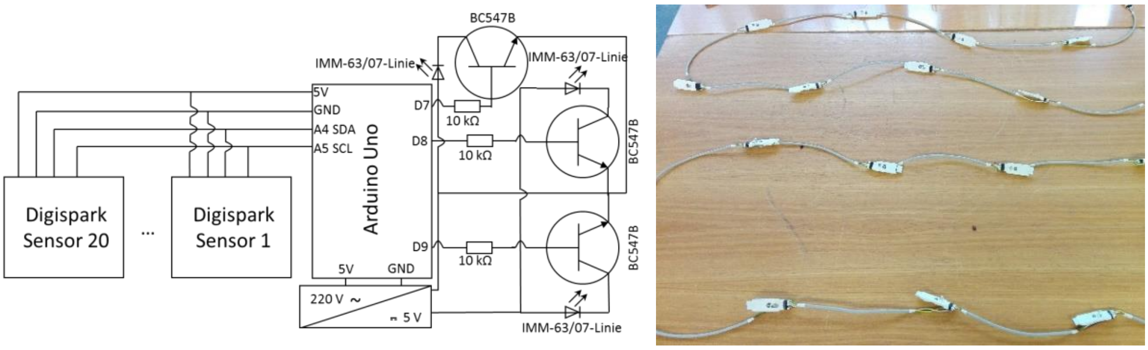


a) **b)** **c)**

Figure 3.27: The improved concept of the photo sensor. (a) The schematic connection to the Digispark. (b) The Digispark photo sensor on the backside. (c) The 20 photo sensors basing on the Digispark front side.

By this chance, an LED was added to the photo resistor as a new element. While preparing the fall detection for the laboratory test, great efforts were necessary in order to align the laser light properly to hit the photo resistors. In order to assure that the impact was large enough for the first version of the fall detection (see subsection 3.3.1), the results of the resistors were streamed on a serial monitor of the Arduino IDE. To ease this process, the LED was attached with the idea to stop shining in case the laser light is properly aligned. Thereby, photo sensors give an optical feedback, which helps to debug and calibrate this module.

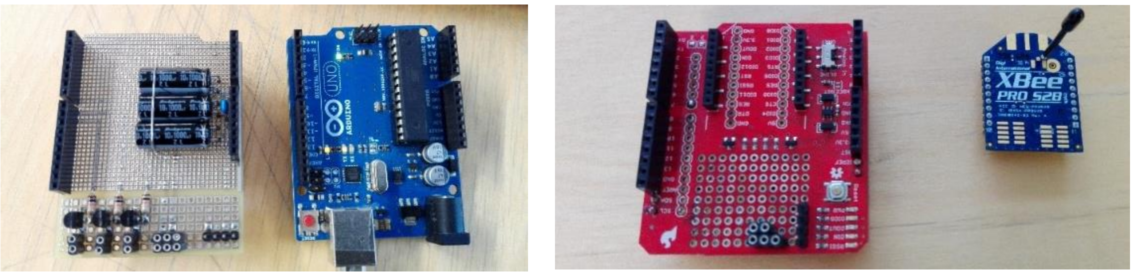
After preparing 20 such sensors according to the scheme depicted in Figure 3.27, all sensors were interfaced as shown in Figure 3.28.



a) **b)**

Figure 3.28: Interfacing of the improved fall detection. (a) The interfacing schematic of the fall detection. (b) The connection of the different Digisparks, which are now covered by an isolation and ready for implementing into a baseboard.

As visible in Figure 3.28, only four connection inputs are necessary for the 20 sensors. The amount of possible sensors is thereby only limited by the software internal identification address (ID), which is represented by a 10-bit number. When calculating the decimal number of a 10 bit binary number, where all bits are set as positive, the result would be: $11\ 1111\ 1111 = 1023$. Since the ID address 0 is also valid, this would mean that 1024 ID addresses can be distributed in the software code of the Digisparks, and sets the new maximal limit of interfaceable photo sensors. Due to this, the Arduino Mega 2560 was replaced with an Arduino Uno, which is smaller and more cost-efficient (see Figure 3.29).



a) **b)**

Figure 3.29: Components of the used Arduino Uno as the master microcontroller at the fall detection. (a) The Arduino Uno and the transistor interface for the three lasers. (b) The XBee antenna and the corresponding shield for interfacing the XBee module to the Arduino Uno.

Furthermore, a third laser was implemented in the second prototype. This was necessary because the improved prototype was implemented in the bathroom of a real apartment, which was longer in dimension (see Figure 3.30). Although the area of this bathroom was similar (nearly 6 m²), it was not possible to cover it by only two lasers because of the different room dimensions. Furthermore, the lasers are interfaced to the same power supply as the Arduino Mega 2560 in this prototype, which reduces the amount of necessary power sockets to one.

In the end it was not possible to place more than 19 photo sensors into the baseboard of the improved fall detection (see Figure 3.30), where the distance between two sensors was always ~ 25 cm. A special casing, which was designed using FreeCAD [184] and produced by a 3D-printer, hides the microcontroller e.g. under the sink (see Figure 3.30 (a)).

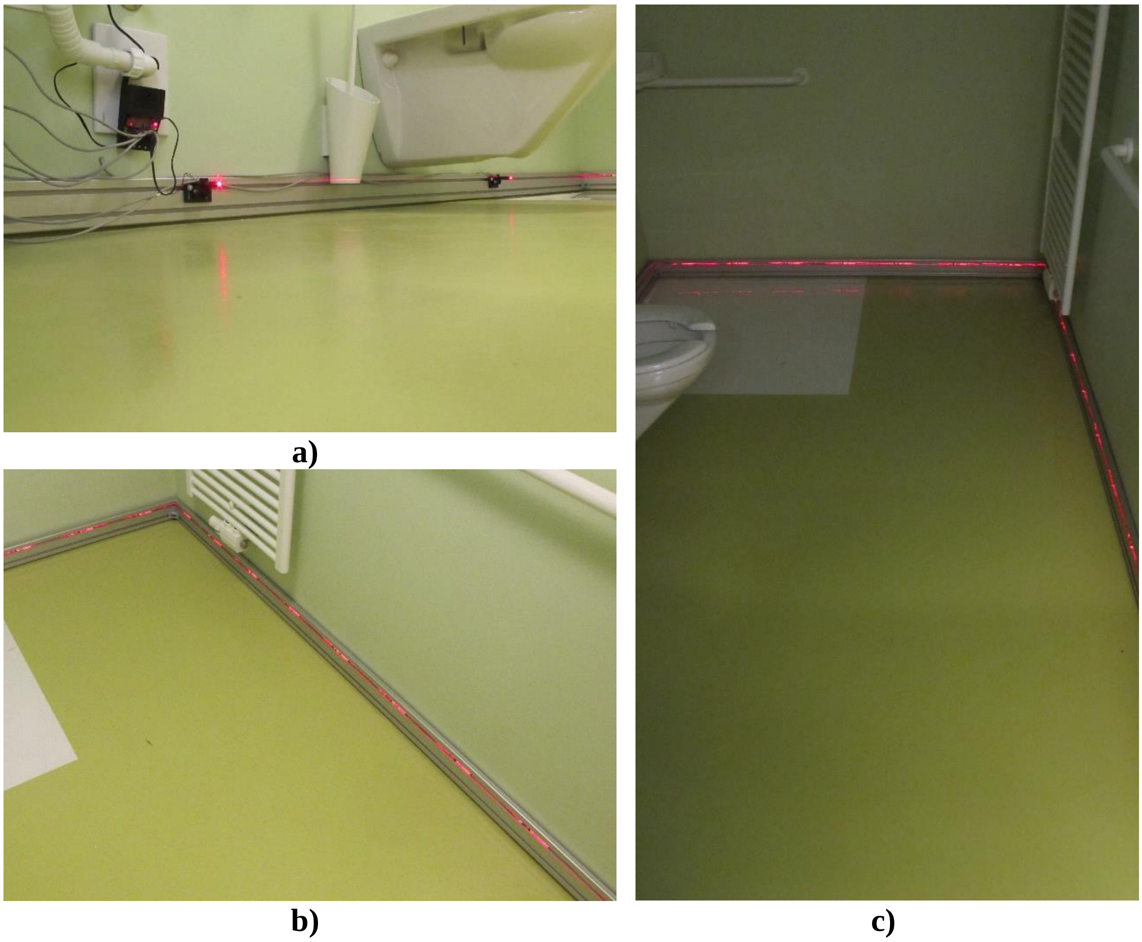


Figure 3.30: The improved fall detection implemented in a real apartment. (a) The Arduino Uno as master controller and two of three lasers attached to the baseboard. (b) The fall detection on the opposite side while the room light is switched on. (c) The fall detection from the entrance door of the bathroom, before the room light is switched on.

In order to solve the issue of the environmental daylight, a new functional concept was developed. The new concept foresees that the fall detection switches off the laser light, and then each single photo sensor measures the light impact, which affects the photo sensor within that second. For each single photo sensor, an individual dynamic threshold $LT_{Dynamic}$ will be calculated according to equation (9) (see page 56). After each single sensor received its individual threshold $LT_{Dynamic}$, the lasers are switched on. From this point on, the algorithm is the same as described in section 3.3.2, i.e. the measured light value is compared with the threshold and the sensor gives a feedback of being blocked or not etc.

However, in order to avoid changing the algorithm of each Digispark to modify one value, e.g. the value LT_{Fix}, each Digispark is just transferring the light values to the Arduino Uno board on request of the master controller. Thereby, it was possible to develop the algorithm depicted in Figure 3.31, which was uploaded to each single Digispark. For uploading the C++ source code on the Digispark, the Arduino IDE can be used after updating the standard Arduino IDE with the libraries of the Digisparks [185]. As visible in Figure 3.31, the Digispark is constantly measuring the light condition at each iteration. The master (i.e. the Arduino Uno) instructs the Digispark of the appropriate light sensor when to transmit the current value.

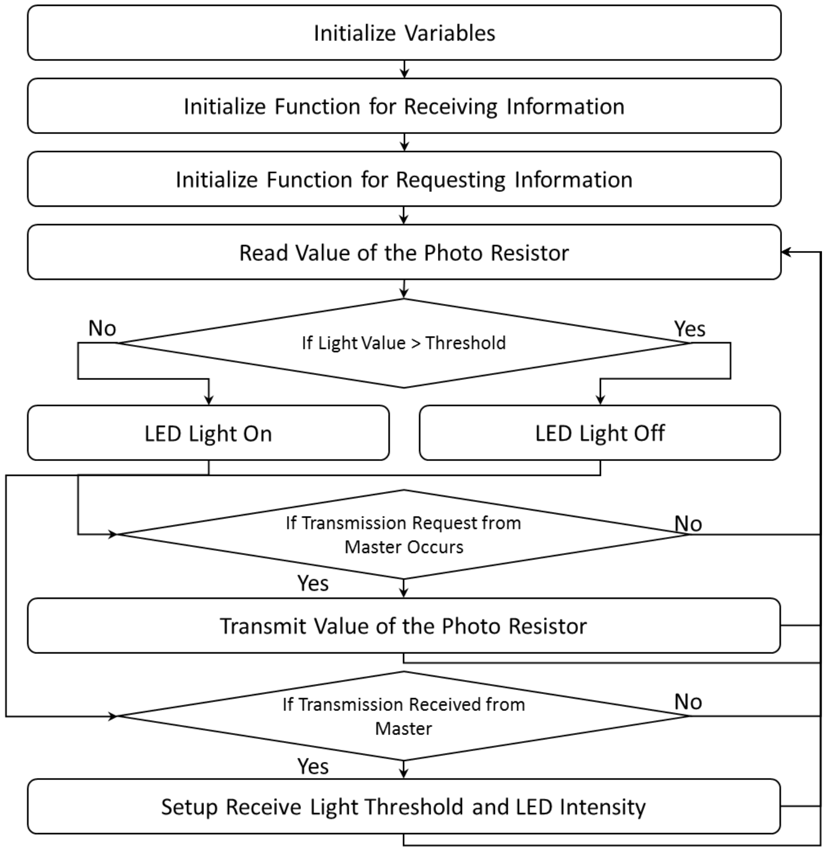


Figure 3.31: Algorithm of the photo sensor.

On the Arduino Uno side, the standard libraries for the I²C communication ("wire.h") was sufficient to establish the I²C network. Figure 3.32 shows the algorithm running on the master. The algorithm differs mainly at the beginning from the original as depicted in Figure 3.25 (see subsection 3.3.2). However, on the Digispark side it was not possible to use the library "wire.h", because of the hardware architecture of the ATtiny85. The provided Arduino IDE add-ons for the Digispark also only support the libraries for the master side. Therefore, the library "TinyWireS.h" [186] was additionally installed to the Digispark libraries, which enabled finally the system to establish the I²C communication.

In this algorithm, the lasers are switched off, in order to identify the individual threshold for each single Digispark one after another. When each single Digispark received its individual threshold $LT_{Dynamic}$, a light intensity value will be submitted by the Arduino Uno as well. This approach allows to modify LT_{Fix} of all Digisparks in the I²C network, as well enable to setup the light intensity of the LED of all Digisparks over the Arduino Uno.

Therefore, when the slave algorithm (see Figure 3.31) was uploaded to each Digispark, only the ID number differed each time, the rest of the algorithm is identical at each Digispark. For the prototype, which was installed in the bathroom (see Figure 3.30), LT_{Fix} was set to five at the Arduino Uno. Since the amount of the sensors increased, the amount of blocked sensors for a fall identification was modified to ten of 19.

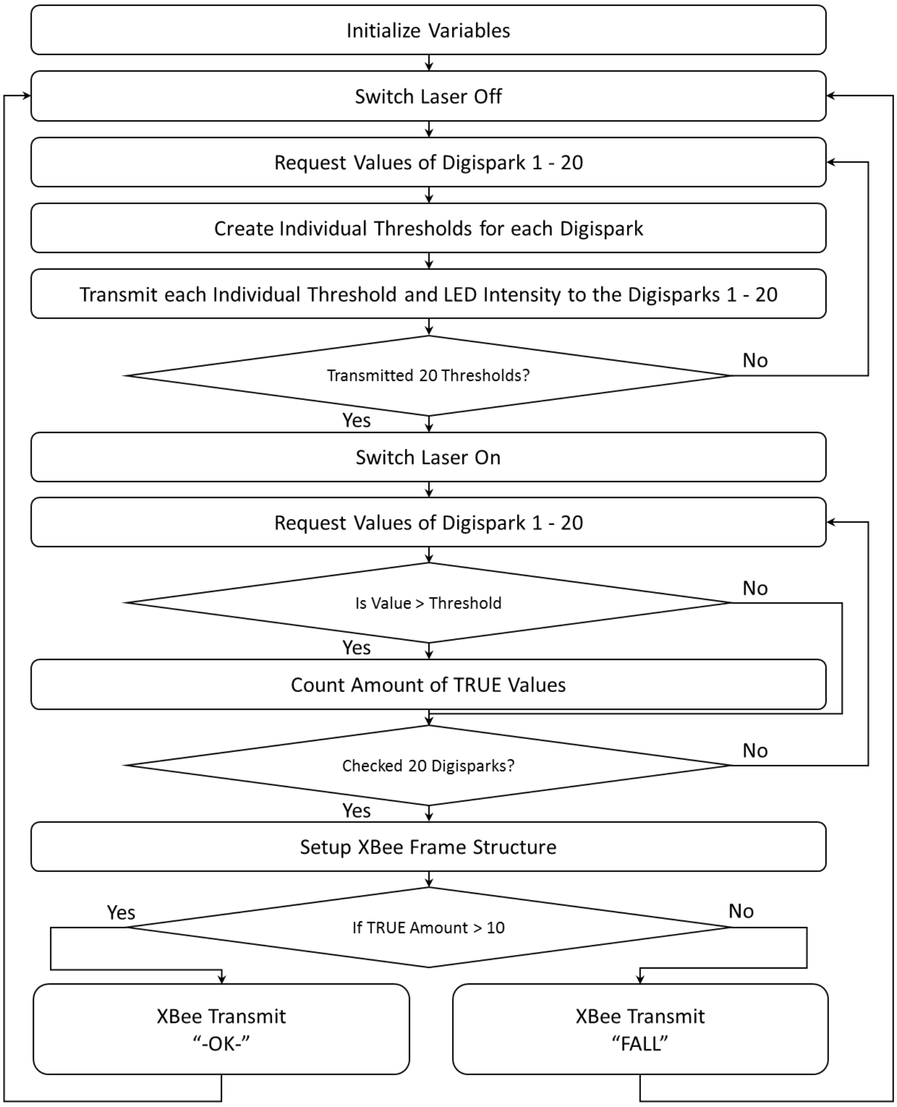
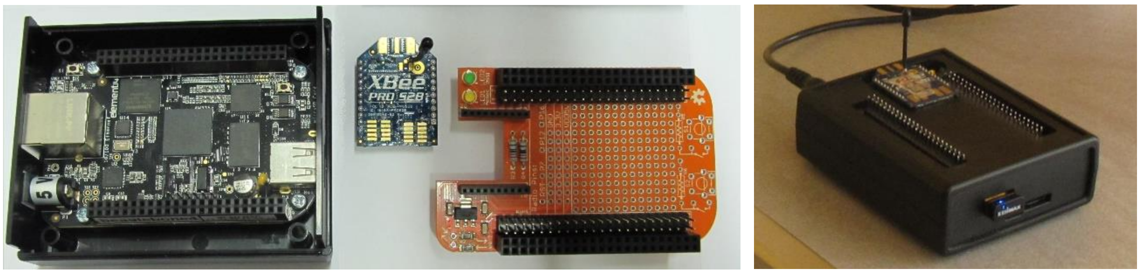


Figure 3.32: Algorithm on the Arduino Uno, which is the managing the master I²C protocol.

In addition to interface this prototype to the other systems e.g. over a local network, a gateway had to be developed. For this purpose a BBB was equipped with the coordinator XBee antenna via an appropriate XBee cape [187] (see Figure 3.33), where a Python script reads the incoming information from the fall detections and forwards the information accordingly via Wi-Fi.



a) b)

Figure 3.33: The fall detection gateway, which interfaces the XBee network with a Wi-Fi network. (a) The disassembled gateway, consisting of a BBB, an XBee Pro 2 antenna, and a BBB cape for interfacing the BBB with the XBee antenna. (b) The assembled gateway, including an attached USB Wi-Fi module.

To enable a BBB to communicate with an XBee antenna, the port “/dev/ttyO2” must be activated. In order to automate this process, a script was developed to execute the activation using system commands. This script was linked and registered at the boot loader of the BBB. Thereby it was possible to open the port “/dev/ttyO2” on boot. Similarly, the Python script was linked with the daemon loader, which is responsible for reading the incoming messages of the XBee network and to forward (on request of a server script) the information to a server, using the protocol of RabbitMQ (see subsection 4.2.1 for more details). Depending on the feedback of the fall detection, the state “TRUE” (for not fallen) or “FALSE” (for fallen) was transmitted to the RabbitMQ server.

3.4 The Ambient Health Monitoring System

In section 3.1, section 3.2 and section 3.3 the unobtrusive sensor integrations were described, which are important components of the “Ambient Health Monitoring System”. The prototypes described in section 3.1 and section 3.2 have a unique interface, where the user can read the results. However, due to the small size of the screens, these user interfaces are more for curious users who want to see the result immediately. The fall detection system described in section 3.3 has no user interface at all. What lacks in comparison to a real system in a system of just several AAL prototypes next to each other, is a unified user interface communicating with all proposed modules with the ability for the end-user to easily and intuitively access personal measurement results. Additionally, the measurement results should be stored at this user interface so that the data are accessible for the end-user independently from the measurement time.

Thanks to the modular approach, each of the described modules were successfully interfaced to an overall system in a real apartment for a user acceptance test, as well as to a personal user interface, which was developed after the field tests. In subsection 3.3.1, the overall system structure for the field test is described, which proves the modular approach of the prototypes. Since the user interface in the field test was developed by an external project partner, a unique user interface was realized later, in order to establish an independent “Ambient Health Monitoring System”. For this purpose, a concept of an interactive table was prototypically realized and described in subsection 3.4.2. The interface of the interactive table differs from the interface provided by the external project partners for the field test rendering the network of the field test was not operable anymore. Therefore, the finally developed network communication and interfaces for the interactive table are described in subsection 3.4.3. The necessary adaptions on the network level for interfacing the interactive table with the other modules of the system are described in subsection 3.4.4.

3.4.1 System Implementation in a Real Apartment

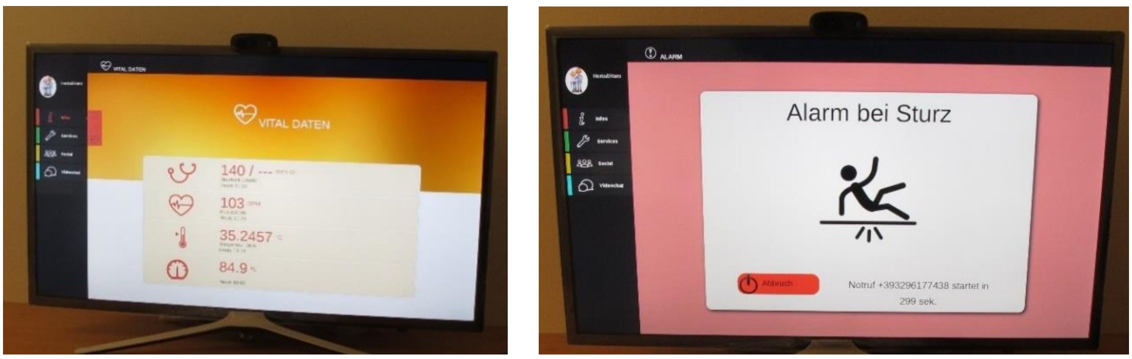
In addition to the development and functional test, the user acceptance is very important when developing new technologies. If a prototype is perfectly developed and functional, but rejected by the end user, then the entire development efforts are in vain. Therefore, the targeted end user opinion for the prototypes (the elderly) were considered very early (see section 4.1). The first real implementation outside the laboratory of the described prototypes of section 3.1, section 3.2 and section 3.3 was achieved when implementing the prototypes into a real apartment.

The apartment was a newly renovated apartment in the senior residence “Seniorenheim Peter Paul Schrott” in Deutschnofen, Italy [188]. Here it was possible within the Project “LISA Habitec” [189] to implement the unobtrusive fever detection, the cuff-free blood pressure monitor, and the novel fall detection module unobtrusively into the apartment next to other age related furniture and prototypes [190]. In Figure 3.34, the integrated prototypes (which were developed within this work) of the field test apartment are depicted.

a) **b)** **c)**

Figure 3.34: Final implemented prototypes in an apartment in Deutschnofen, Italy. (a) The unobtrusive implemented prototype for detecting fever (see section 3.1). (b) The cuff-free blood pressure monitor (see section 3.2). (c) The novel fall detection prototype (see section 3.3).

As seen in Figure 3.34, each prototype is unobtrusively implemented, i.e. the apartment looks like a “normal” apartment and avoids thereby stigmatization. The prototype of the fever detection (see Figure 3.34 (a)) and the fall detection (see Figure 3.34 (c)) do not have personal displays within the implementation of the apartment, since too many displays can lead to a poor user acceptance. Therefore, the project partner “GR Research GmbH” developed a smart TV in the project “LISA Habitec”, which includes several service functions for the elderly. To display the results of the sensors and to provide a silent alert for detected fallen persons are just one of many functions implemented in their smart TV (see Figure 3.35).



a) **b)**

Figure 3.35: The related GUIs of the smart TV developed by “GR Research GmbH”. (a) Display of the health related data. (b) Fall detection alert, which triggers an automated emergency call, if not interrupted by the remote controller of the smart TV.

The challenge here was to interface the prototypes with the foreign system of the smart TV from “GR Research GmbH”, since the depicted GUIs of Figure 3.35 are the unified main user interface for the field test. For this purpose, the entire system as depicted in Figure 3.36, moved to the apartment in Deutschnofen.

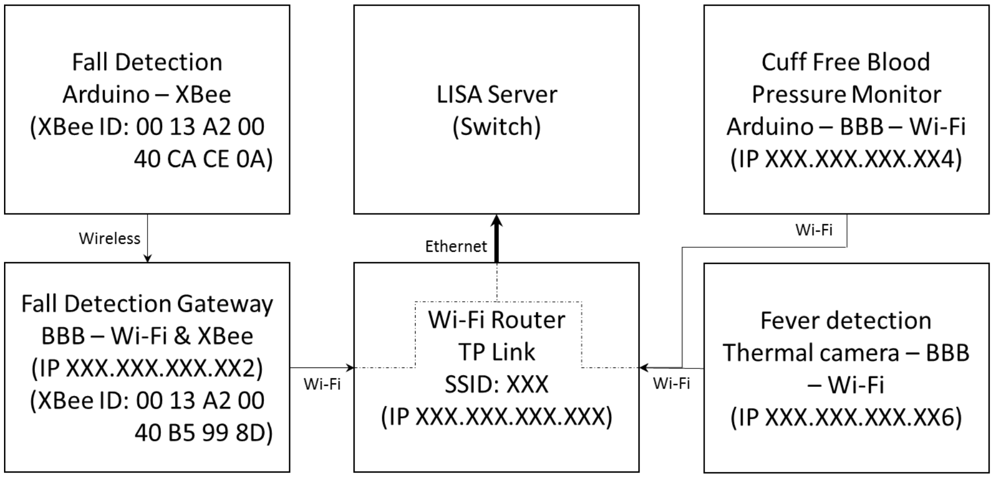


Figure 3.36: Communication scheme of the “Ambient Health Monitoring System” at the field test in Deutschnofen.

As depicted in Figure 3.36, the router forwards the data captured by the aforementioned modules to the LISA Server, which handles the data storage. The smart TV of the project “LISA Habitec” displays finally the stored data at the “LISA Server”. By moving the prototypes as well as the router, which interfaces the different modules with each other, a straightforward implementation in the senior residence “Seniorenheim Peter Paul Schrott” was possible.

The communication with the LISA Server was implemented using RabbitMQ [191]. In order to enable each single prototype to use the RabbitMQ protocol without modifying the source code too much, Python scripts were developed. Additionally, by this procedure the modularity was improved, since Python scripts are not necessary to compile, which allows quick adaption, e.g. on the IP address. At the appropriate position of the source code of each prototype, (i.e. when the prototypes successfully captured their value like the fever value) a system call of the Python script was implemented. Depending on what data has to be transmitted, the algorithm differs slightly at the beginning, as depicted in Figure 3.37.

The values of the blood pressure and temperature were passed as system parameters when starting the script. Larger data amounts (e.g. the ECG curve) were stored by the programs locally on the modules in a text file. Thereby the Python scripts loaded the samples in the text files into an array, which was transmitted using the RabbitMQ protocol. The fall detection gateway consisted of an RabbitMQ client, which reads the serial port (“/dev/ttyO2”) for the input of the fall detection, checks for the status and forwards true or false to the LISA server, depending on whether a person has fallen or not. The status NA should not occur unless the communication between the “XBee coordinator” and the “XBee end device” is corrupted.

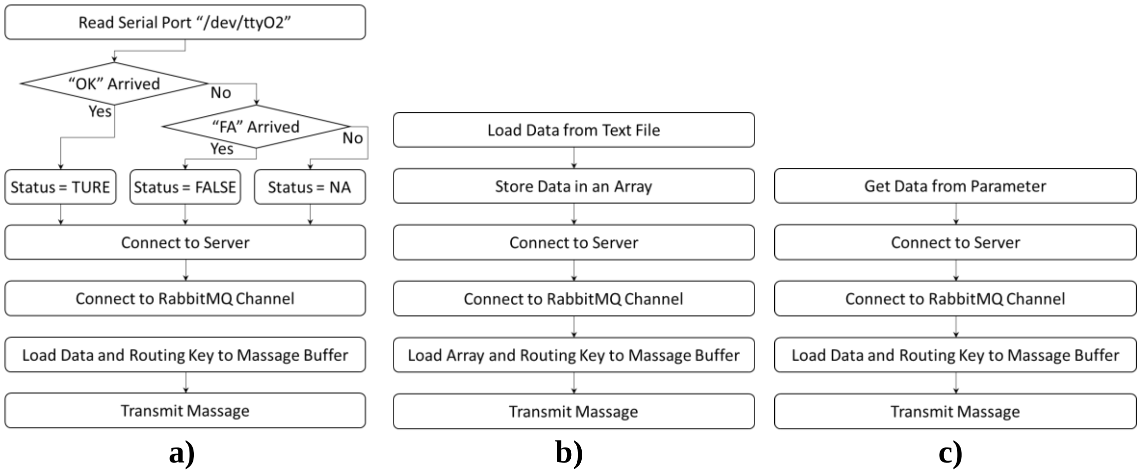


Figure 3.37: Algorithm of the RabbitMQ clients. (a) The algorithm of the fall detection gateway forwarding the information about a fallen person to the LISA Server. (b) The algorithm for forwarding large data amounts like an array with ECG data. (c) The algorithm for forwarding data passed by parameter, e.g. the fever value or the systolic blood pressure value.

3.4.2 Concept of the User Interface

Since the smart TV does not belong to this work, but was an essential part of the "Ambient Health Monitoring System", a unique solution had to be developed. Under consideration of the evaluation results of the field test (see section 4.2), a novel concept of a low-cost interactive table was developed. The idea of this concept was inspired by touchscreen monitors. The potential use of touchscreen monitors for elderly was investigated by several studies [93, 192, 193, 194], which confirmed the potential use of touchscreen applications for elderly. At the moment, touchscreens are mainly implemented in devices, which are less interesting for the elderly, because of the too high complexity and too small displays e.g. smartphones, tablets, and computer monitors (see subsection 2.3.4). Furthermore, neurodegenerative diseases like Alzheimer's disease or Parkinson's disease additionally aggravate the use of touchscreen applications [195]. In addition, the complexity of existing operating systems for the elderly is too sophisticated, especially for the elderly suffering from Alzheimer's disease.

Therefore, the concept of an interactive table is designed, according to the request in section 2.4, to display on a large surface with large text and buttons in order to support the user intuitively to stay mentally and physically active. The issue most interactive table solutions have is that they are mostly operating with a capacitive monitor, e.g. like the "Samsung SUR40 with Microsoft PixelSense" [128], which limits the size to ~ "1214 × 832 × 299". Furthermore, this interactive table's operating system is too complex for old-aged users. The proposed concept solution of this subsection aims to implement augmented reality, which projects an elderly-friendly GUI via a beamer on the surface of the table, and recognizes gestures at the same time using a depth camera (using the Kinect). By this approach, the fragile technology is out of reach by the elderly. Strikes, pitches and stabs are possible damages to a table plate, which can be cheaply replaced, as requested in section 2.4. Additionally, the proposed solution is less expensive compared to the "Microsoft Pixel Sense" solution, since the proposed solutions consist only of commercially cheap and available components like depth cameras, beamer and a computer.

There were two prototypes developed, which mount the beamer and Kinect differently as depicted in Figure 3.38. The prototype in Figure 3.38 (a) and Figure 3.38 (c) was the first prototype, since the development of the source code was in the foreground. The issue of this prototype was that the beamer and the Kinect are fix-mounted on the table plate. The second prototype is a more mobile version, since here the beamer and the Kinect are not fixed to the table plate. The structure visible in Figure 3.38 (b) and Figure 3.38 (d) assures that the relative position between the Kinect and the beamer is fixed.

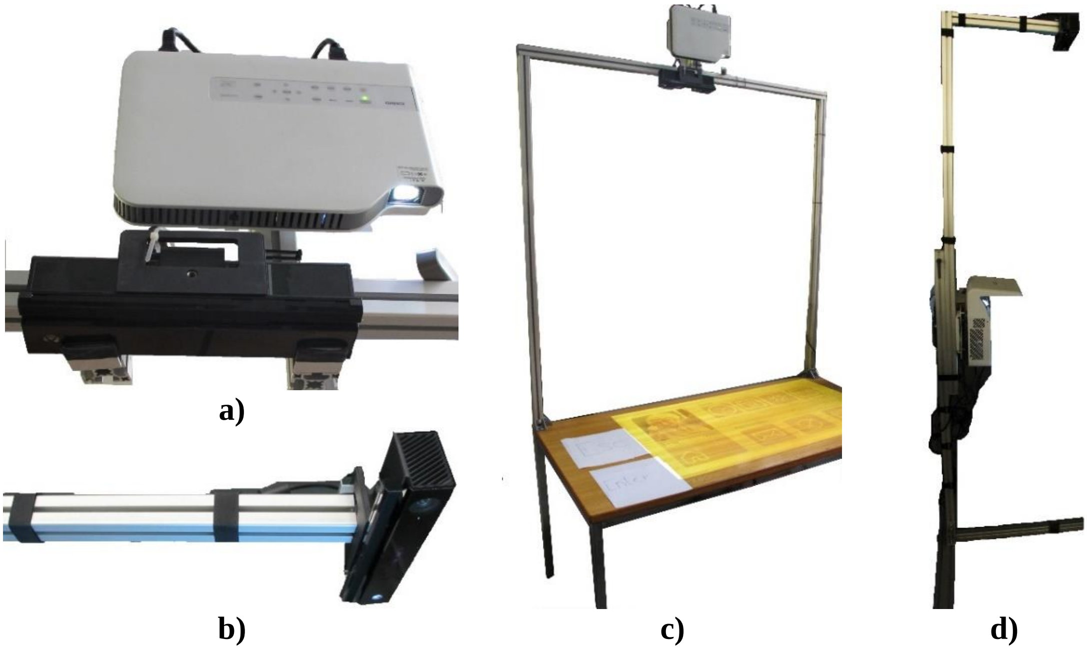


Figure 3.38: The used hardware configurations of the module of the interactive table. (a) The attached beamer and Kinect for the first prototype. (b) The attached Kinect for the second prototype without beamers, since an ultra-short distance beamer was used. (c) The first prototype of the interactive table, which is fix-mounted on a table. (d) The second prototype, which is operable on any table plate.

The software is the same on both prototypes, so the differences between the prototype of Figure 3.38 (c) and Figure 3.38 (d) consist only in the improved adaptability of the second prototype, which can use any table as a projection surface. The software is running on a computer, which is hidden in the background. On the second prototype (see Figure 3.38 (d)), a mini computer (“SHUTTLE DH170 I7 8G 250G SSD”) was used, which is hidden behind the beamer and also attached on the frame structure.

The graphical user interface (see Figure 3.39), developed by the Technical University of Eindhoven (TU/e) [196], provides several services to the user. In addition to time and weather information, the table is thought to host games, which stimulates the elderly mentally as well as physically via the large screen and the gesture recognition. For this purpose, a puzzle game was implemented (see Figure 3.39 (d)). The gaming aspect shall especially increase the user acceptance and enable additional services to the user, e.g. the “Health Data GUI”, which shows the results of the modules from section 3.1, section 3.2 and section 3.3 (for details regarding the “Health Data GUI” see subsection 3.4.3).

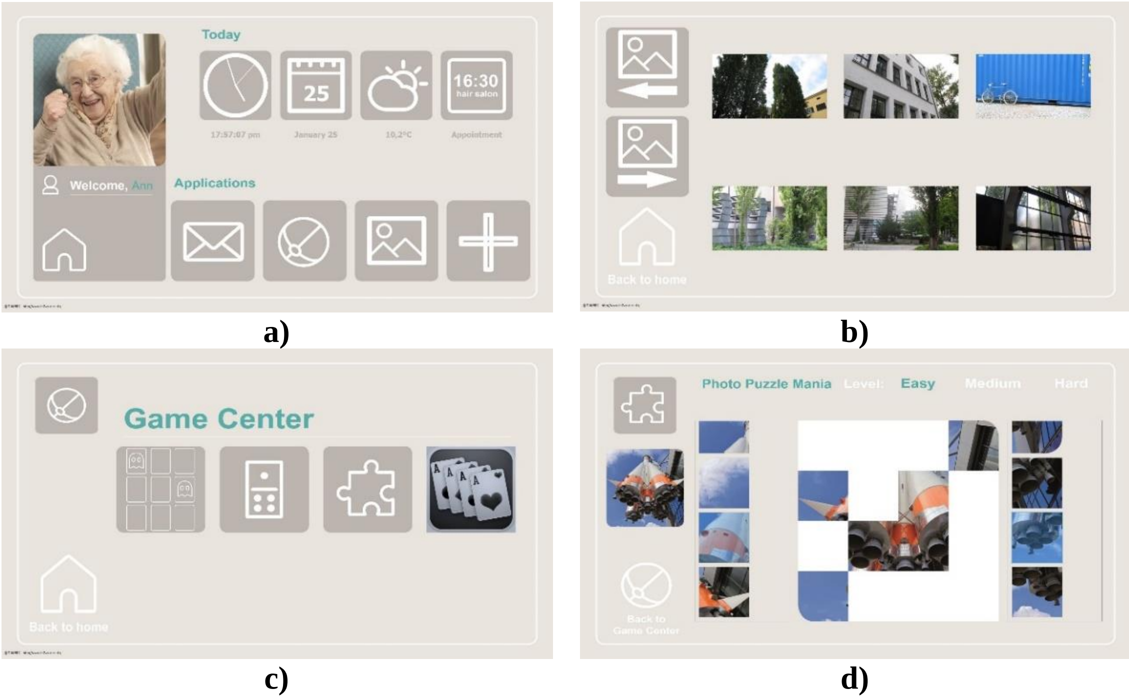


Figure 3.39: The GUI of the table, of which the design was developed in cooperation of TU/e [196], and realized within this work. (a) The first layer offering the user access to the different services. (b) The picture album of simple gesture instruction, in which the user can choose which image will be displayed e.g. full screen. (c) The game center with four exemplary installed games. (d) The puzzle game, which aims to keep the user physically and mentally active.

The Kinect 2 was used to recognize the user input for the touchscreen application, as requested in section 2.4, which overtakes the control of the mouse as well as some very specific keyboard events (e.g. ALT-F4 or ENTER). To implement this task, the depth image example application from the Kinect 2 SDK was used as foundation for the source code (see Figure 3.40 (a)). Here, the image was segmented into three colors (see Figure 3.40 (b)).

Figure 3.40: Kinect depth images. (a) The depth image from the original basic depth image example. (b) The modified version by the user interface algorithm, which cuts out all unnecessary information of the original image.

For the interpretation of the captured user input to control the mouse, the algorithm depicted in Figure 3.41 was used.

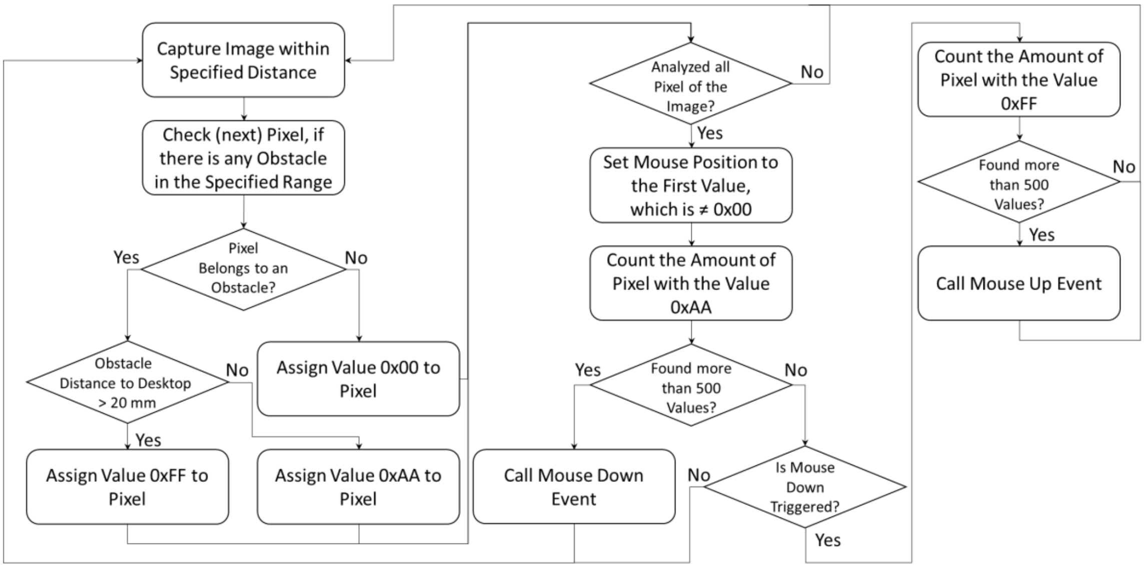


Figure 3.41: The algorithm, which controls the mouse via the Kinect. This algorithm is implemented in the basic depth source code example of the Kinect 2 SDK.

The color "black" is used for areas without important information for the gesture control, since the camera is only investigating the area above the table plate, where the projection is displayed. By setting the maximal and minimal distance, only objects or gestures between the table plate and the Kinect are recognized. Any object between the table plate and the camera is marked as "white", whereas objects, which are very close to the table plate (e.g. closer than 5 cm) are marked as "gray". The color "gray" is used to identify mouse click, mouse down, or mouse up events.

As shown in Figure 3.41, the mouse down and up events are recognized by the amount of changing pixels between gray and white, when the operator's hand moves closer to the tabletop. At the moment, up to 500 pixels of the recognized operator hand must change from white to gray for a mouse down event (i.e. the hand of the operator moves down to the tabletop, as depicted in Figure 3.40), or from gray to white for a mouse up event (i.e. the hand of the operator moves up from the tabletop). In order to align the Cartesian coordinate system of the mouse at position M_x and M_y with the hand position and the Cartesian coordinate system of the projected screen, equation (11) was used for this module depicted in Figure 3.38 (c):

$$\begin{aligned} M_x &= W_{max} - K_x \cdot A_x + W_{offset} \\ M_y &= K_y \cdot A_y + H_{offset} \end{aligned} \tag{11}$$

In equation (11), the variables K_x and K_y represent the coordinates of the hand position detected by the Kinect. These values have to be multiplied by the velocity values A_x for the X-Axes and A_y for the Y-Axes. These values align the movement speed of the mouse with the movement speed of the user hand. When these values are correct and the mouse is projected on the user hand, the mouse will maintain the same position on the user hand, even if the user moves the hand. For the proposed prototype, A_x was empirically identified and finally set to 6.25 and A_y to 6.4. These values differ depending on the relative position between the projector and the Kinect.

The mouse position at the coordinate $K_x = 0$ and $K_y = 0$ is at the top left position of the screen. However, when the acceleration values A_x and A_y are set up properly, the mouse position has an offset. To correct the offset, values W_{offset} at the X-Axis and H_{offset} at the Y-Axis are used. Furthermore, both values differ depending on the relative position between the Kinect and the projector. For the proposed prototype, W_{offset} was set to 1780 and H_{offset} was set to 1125. Both values were empirically identified. In order to correct the mirroring behavior of the camera, the movement orientation of the mouse has to be flipped by subtracting the entire equation on the X-Axes by the maximal width of the captured Kinect frame W_{max}.

As can be seen in Figure 3.38 (d), the Kinect camera's orientation is flipped by 180° over the X-Axis. The algorithm for interpreting the gesture as depicted in Figure 3.41 remains unchanged, however, due to the mirroring behavior of the Kinect, equation (11) has to be modified according to equation (12):

$$\begin{aligned} M_x &= K_x \cdot A_x + W_{offset} \\ M_y &= H_{max} - K_y \cdot A_y + H_{offset} \end{aligned} \tag{12}$$

In equation (12), the subtraction of the X-Axis equation from the value W_{max} is not necessary, since the Y-Axis is now affected by the mirroring behavior of the Kinect. Therefore, the entire equation for the Y-Axis has to be subtracted from the maximum height value H_{max} of the captured Kinect frame.

3.4.3 The Health Data GUI

In order to interface the prototype of the interactive table, e.g. from Figure 3.38 (c) with unobtrusive sensor modules from section 3.1, section 3.2, and section 3.3, an entire new communication was necessary to be developed. Furthermore, since now the smart TV as the user interface is missing, the interactive table described in subsection 3.4.2 has to replace the smart TV function of displaying the measurement results. For this purpose, a new "Health Data GUI" program was developed and implemented into the interactive table, which can display all measurements (see Figure 3.42).

The "Health Data GUI" of Figure 3.42 is activated by pressing the button with the white cross symbol on the main GUI (see Figure 3.39 (a), in subsection 3.4.2). The ECG curve and pulse curve are displayed above the detected systolic blood pressure and the temperature value of the last measurements. By translating the timestamp submitted with each data package, the individual measurement date is written under the systolic blood pressure and under the body temperature, respectively.

The proposed GUI always loads the text documents on startup, which contains the health data information. The text document information are stored by server applications, which receive the information via the Wi-Fi network. By touching the line charts, which plots the ECG or pulse, the user can zoom on the X-Axes, in order to plot only ten seconds of the last measurement. By pressing the button "Reload", the zoom at the ECG and pulse curve is reset, as well as the data updated in case new data were transferred in the meantime.

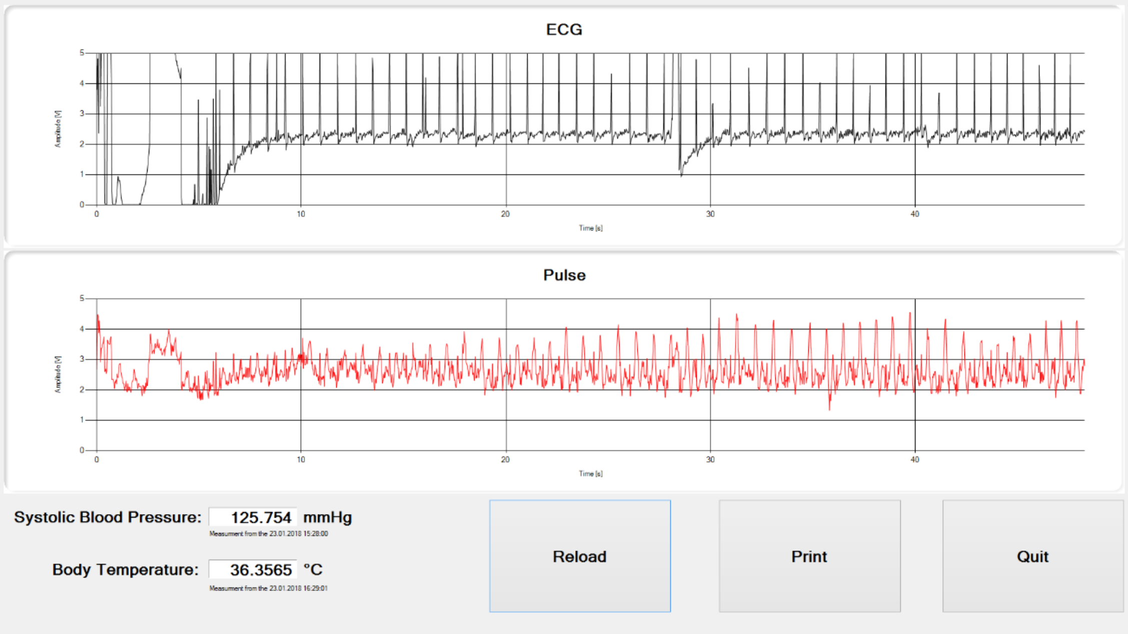
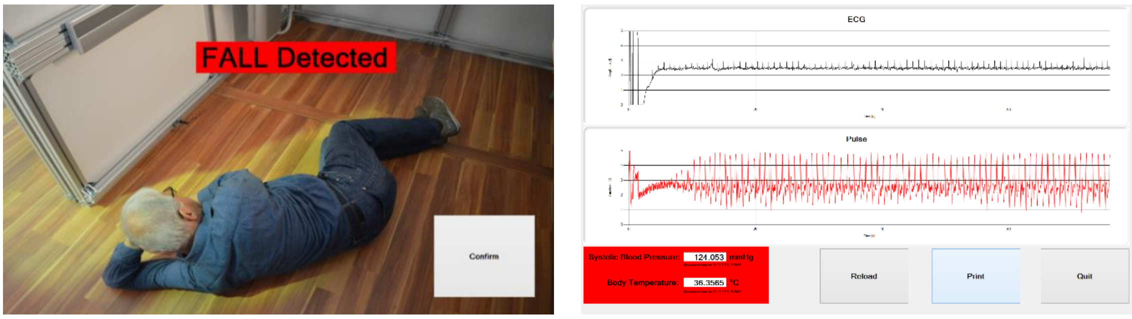


Figure 3.42: The “Health Data GUI”, displays the results of the unobtrusive sensors.

When the user press the button “Print”, a screenshot will be stored on the first USB device, which is plugged into the computer of the interactive table. In case there is no USB device connected to the computer, the screenshot is stored internally. Thereby, the end user is able to load these private data on a USB device and share the data, e.g. with a physician etc. In the future, the raw data as well could be stored on the USB device, in order to improve the data access for relatives and physicians.

In case a fall was detected by the module of section 3.3, a GUI will pop up to warn someone working on the interactive table that someone has fallen, e.g. in the bathroom (see Figure 3.43). Here, the fall detection is communicating via the XBee antennas. For this purpose, the XBee coordinator is directly interfaced via USB to the interactive table.



a) **b)**

Figure 3.43: The “Health Data GUI” when a fall was detected. (a) The fall detection alert. (b) The “Health Data GUI” after confirming the first fall detection.

When confirming the detected fall via the button at the corner, the user comes back to the “Health Data GUI”. A red box framing the blood pressure and fever value indicates that the fall event is still active. In case the fallen person stands up (i.e. the fall detection confirms that there is no fallen person detected anymore), the red frame will vanish. In case the GUI of Figure 3.43 (a) is still visible (i.e. the fall was not confirmed by the user of the interactive table) the fall detection will close the GUI depicted in Figure 3.43 (a) automatically and return back to the "Health Data GUI" depicted in Figure 3.43 (b), if the fall detection does not detect any fallen person.

The GUI of the fall detection as well as the health data was programed in that way, so that it stays always on top. Therefore, the "Quit" button is the only possibility for the user to close the program. Furthermore, keyboard commands like "ALT-F4" are ignored by this GUI. The objective of this program behavior is to force the user to check for a fallen person. Additionally, the GUI of the fall detection of Figure 3.43 (a) can be used in the future to implement an automated emergency call, which will trigger if a false alert is not confirmed within a given time (as proposed by the smart TV solution in subsection 3.4.1).

3.4.4 Final System Communication

When the smart TV of subsection 3.4.1 was replaced with the "Health Data GUI" of subsection 3.4.3 (which uses the interactive table of subsection 3.4.2 as medium), the system communication between all the modules had to be redeveloped. In this section, the final system communication is provided, which fuses all system modules finally to the "Ambient Health Monitoring System".

The overall communication process of the "Health Data GUI" is depicted in Figure 3.44. The computer, which operates the interactive table, serves as a server in this solution. However, it is also possible to decentralize the server and use a client application on the interactive table to download the data from an external server. Because of ethic and security reason, no access to any module via internet is planned and therefore the server was directly implemented in the interactive table at this development stage.

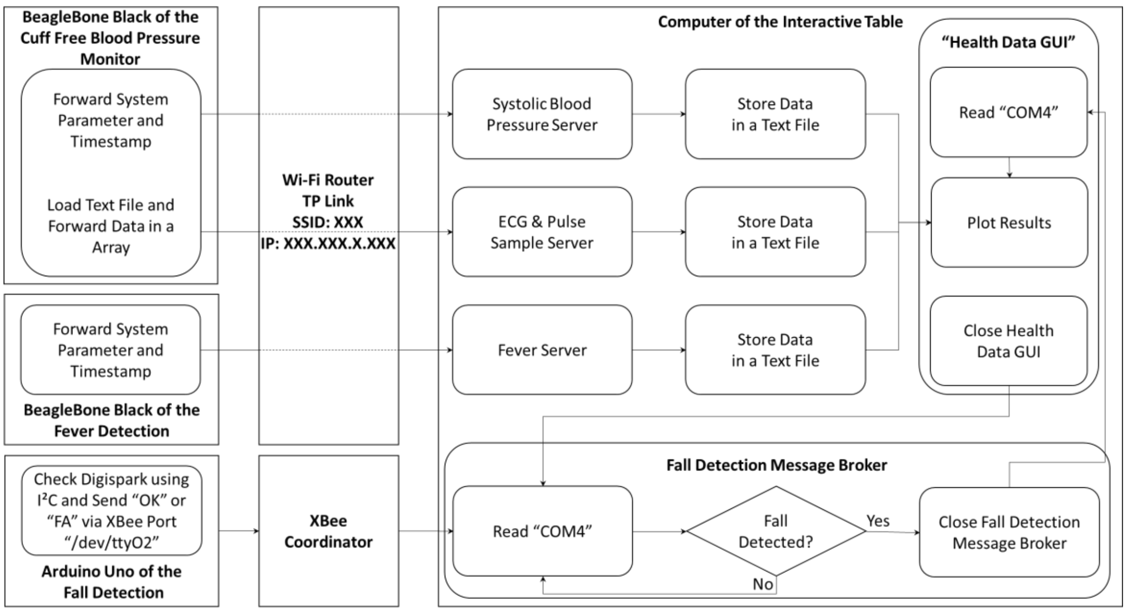


Figure 3.44: Schematic communication plan of the "Ambient Health Monitoring System" for displaying the results of the unobtrusive sensor prototypes on the "Health Data GUI".

For realizing the communication depicted in Figure 3.44, the Python scripts of the individual modules of section 3.1, section 3.2, and section 3.3, which communicated via RabbitMQ to the RabbitMQ LISA Server, were replaced with newly developed Python client scripts, which connects to newly developed Python servers on the interactive table and forwards the information via a Wi-Fi router (see Figure 3.44). The clients are thereby linked as well via system commands with the C++ programs of the modules of section 3.1 and section 3.2. I.e. in the C++ source code, a system command is starting the Python clients and transfers the temperature and the systolic blood pressure as parameters to the client scripts. The ECG and pulse data are due to the large amount of stored data in a text file, which gets loaded as an array by the client script, before the data are transmitted to the interactive table server.

For displaying all the captured health data on the interactive table, individual server applications for each data type were developed using Python on Windows. I.e. there is a Python server script for capturing and storing the data of the temperature, the curves (ECG and pulse), and for the blood pressure (see Figure 3.44). The server of the ECG and pulse curve receives the entire sample in the format ECG amplitude, Pulse amplitude, and timestamp, which is stored in a double array before written on the hard drive in a text file. The blood pressure value as well as the temperature value are transferred as single values including the corresponding timestamp. The received values from the prototypes get stored in individual text files, which allows the "Health Data GUI" program of subsection 3.4.3 to load always the last transmitted results as depicted in Figure 3.44.

Because Windows does not originally support Python, it is necessary to install Python manually before Python scripts can be used on the interactive table. Therefore, in this module, Python 3.6.4 was manually installed [197].

Only the fall detection does not use a Python script as server application, or the Wi-Fi router as depicted in Figure 3.44. Instead, a direct communication between the fall detection and the interactive table via XBee antennas was established. For this purpose, a C# console application was developed, which serves as a message broker. The reason for using C# instead of Python was the easy access to the Windows serial ports, which is in Python only possible by installing additional libraries. The use of a message broker was necessary in order to read out the serial port continuously (here the port "COM4" was used). The XBee antenna communicates independently from the server while the message broker is reading out the serial port. In case a fall confirmation was transmitted, the message broker will close the serial port and start the "Health Data GUI" immediately (see Figure 3.44). The communication with the serial port "COM4" is thereby free for the "Health Data GUI". In case the user closes the "Health Data GUI", the program also closes the serial port and starts the C# message broker before the "Health Data GUI" shuts itself down.

Because of this, the message broker enables the possibility to listen to the "COM4" port permanently, even if the "Health Data GUI" is not active. The message broker will start the "Health Data GUI" when a fall alert is triggered as depicted in Figure 3.44. Since only one application can communicate with the same COM Port, where the XBee antenna is attached, the message broker closes itself as soon as the "Health Data GUI" starts. This approach allows two programs access to the same serial port.

In order to assure that all server applications, as well as the message broker application starts in the background on system boot, a batch file was developed, which starts all four programs when executed. A link of the batch file was placed at the auto start folder of Windows.

Thereby, the interactive table established a full “Health Monitoring System”, where three prototypical modules for unobtrusive fever detection, fall detection, and blood pressure detection transmit the health data to an intuitive unified user interface. The interactive table encourages use by simple user-oriented services e.g. games, and thus activates the user physically and mentally with the objective to train the user fitness and sanity as mentioned in chapter 1.

4 User-Tests and Discussion

In this chapter the laboratory test, the field test and the related results are described. Both tests investigated the user acceptance, whereas the contrast between the laboratory test and field test represents the achieved improvements of the modules due to the early consideration of the user opinion.

In order to assure the objectivity of the evaluation, the "Berlin Institute für Sozialforschung GmbH" (BIS) evaluated the prototypes [198]. The presented results interpreted from this work are based on the objective evaluation of the BIS, which is documented in the laboratory test report [199], as well as in the field test report [200]. In preparation for the tests, a scenario was prepared for each test. The questionnaires for the tests were developed in close cooperation by the BIS. During the tests, all prototypes have been maintained and observed regarding their functionality.

In these tests, several prototypes of the project LISA Habitec [189] were tested in four different rooms (bedroom, bathroom, kitchen, entrance room). The evaluation considered the modules of section 3.1, section 3.2 and section 3.3 as well as other products and prototypes from the consortia of LISA Habitec. However, in this chapter only the evaluation of the prototypes of section 3.1, section 3.2 and section 3.3 are provided. The module of section 3.4 was not considered in these tests, since this prototype was developed later. Some feedback of the software functions of the smart TV is also provided in subsection 4.3, because this feedback was considered while developing the prototype of the interactive table of section 3.4. This approach was possible, since the improvement suggestions of the smart TV affected mainly the GUI.

The difference between a laboratory test and a field test is the control. A laboratory test takes place under very controlled conditions, i.e. in a laboratory, unlike a field test. The execution and the results of the laboratory test are in section 4.1 provided. Unlike a laboratory test, a field test is executed in a more uncontrolled environment, i.e. in this case in an apartment of the retirement home "Seniorenheim Peter Paul Schrott" [188] in Deutschnofen. Since the opportunities to repair or fix a prototype are limited in a field test, the prototypes must have a more adult development stage. The execution and the results of the field test are in section 4.2 provided.

The laboratory test especially aims to consider the end user opinion in a very early development stage, whereas the field test is used more to evaluate the success of the development. The resulting comparison, which proves the successful development, is described in section 4.3.

4.1 Laboratory Test

The laboratory test was performed within the project LISA Habitec [189]. In the laboratory test, the proposed modules were initially tested by elderly users, in order to identify improvement potential.

The methodology of the laboratory test, which was setup in close cooperation with the BIS, is written in subsection 4.1.1. The results of the laboratory tests of the fever detection are written in subsection 4.1.2. The laboratory test results of the ECG implementation, which was the pre prototype of the cuff-free blood pressure monitor, are written in subsection 4.1.3. The laboratory test results of the first prototype of the fall detection (see subsection 3.1.1) are written in subsection 4.1.4.

4.1.1 Preparation and Methodology of the Laboratory Test

The BIS decided to combine quantitative and qualitative methods in order to identify open issues, propose improvement suggestions as well as to evaluate the prototypes according to best knowledge. For the quantitative investigation, questionnaires were used, which allow the researcher to compare the results of the prototypes against each other.

The questionnaires were designed by the BIS with respect to the developed modules, and were structured so that for each room in the apartment (bedroom, bathroom, kitchen, and entrance room) a unique questionnaire existed.

First, the BIS used a five-level Likert scale on the questionnaires [201], which ranged from important to unimportant. After the Likert scale, a “Smiley-Scale” (developed by the BIS [199, 200]) was used in order to identify the first impression of the user. The task of a “Smiley-Scale” is to mark spontaneously the smiley on the scale (which ranges from a very happy smiley to a very sad smiley), which corresponds to the personal impression of the participant. After the Smiley- and Likert scale, questionnaires regarding the potential apartment environment and their individual implemented functions were filled out by the testers. For the prototypes of section 3.1, and section 3.2, additional questions for the user interface or display, and potential intervention possibilities were considered. At the end of the questionnaires, the participants could write personal comments.

Additionally, the BIS used a general questionnaire, which aimed to capture the participant’s general impression of the test apartment. This questionnaire consisted of the “Smiley-Scale” (developed by the BIS [199, 200]) and a section where the testers has to mark the three most interesting functions.

In order to compensate for the human factor, i.e. the general technology acceptance of the user, a technology acceptance questionnaire of the BIS was prepared to record the technology acceptance of the participant. This questionnaire was also developed by the BIS. Furthermore, a questionnaire regarding the demographic change was also used at the laboratory test.

For the qualitative evaluation an interview guided by the BIS was used. In such an interview, the interviewee can openly discuss the impressions and thereby contribute new ideas for the future development of the modules.

For this laboratory test, nine elderly (five females, and four males) participated with an average age of 74 years. The youngest participant was 63 years old, and the oldest 92 years old. Seven of the test persons were already retired. Eight participants possess a graduation from high school, and five even an academic degree.

All participants signed at the beginning the consent form. In order to reduce the abstract situation (of the test apartment) for the testers, a scenario was written, which should give the individual an impression how such an apartment is operating in the future. The individual had the chance to read the scenario, which was additionally demonstrated on the prototypes before the participant repeated the demonstrated scenario tasks. Once a participant finished testing the implemented prototypes in a room, a questionnaire was filled out by the individual, before the test continued with the next prototype in the next room. At the fall detection, the elderly were allowed to test this module on their own, but most elderly preferred to see the demonstration and not to trigger an alert by pretending to fall. At the laboratory test, the fall detection used an acoustical signal, when a fall was detected.

Finally, the testers filled out the questionnaire regarding the technical acceptance and the demographic change, before the semi-structured interview took place. The test, which was structured according to Table 4.1, needed two hours for each interviewee.

Table 4.1: Schedule of the laboratory test for each test person.

Procedure	Duration in minutes
Test opening	
Welcoming and concerns form	5 minutes
Instruction and preliminary questions	5 minutes
Demonstration of the laboratory apartment	15 minutes
Sleeping room	
Testing	10 minutes
Questionnaire	5 minutes
Bathroom	
Testing	10 minutes
Questionnaire	5 minutes
Kitchen	
Testing	10 minutes
Questionnaire	5 minutes
Wardrobe	
Testing	10 minutes
Questionnaire	5 minutes
Test closing	
Semi-structured interview	15 minutes

The evaluation and acceptance of the technology by the testers were also analyzed by the BIS. According to the laboratory test report of the BIS [199], five participants have their own computer and a mobile phone, which they are using regularly. Three use their mobile phone more rarely and only two individuals use a tablet computer often or permanently. All participants agreed with the statement that technology is very useful, and eases the life and solves everyday problems.

Three participants see themselves as technology fans, whereas two do not understand technical devices very well. More than half of the participating body enjoy the different technological opportunities and two-thirds of them are already satisfied to know the basic operations of the technical devices (see Figure 4.1).

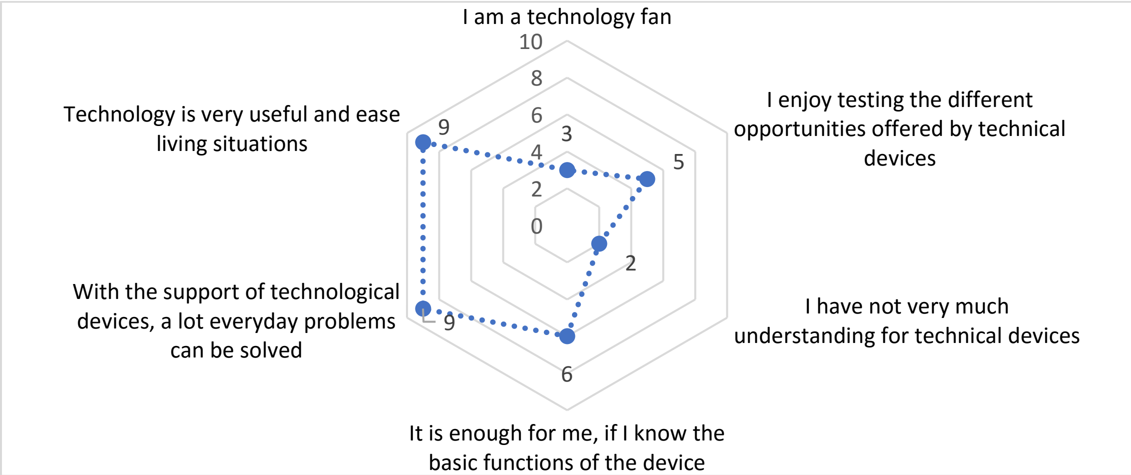


Figure 4.1: Technical acceptance of the test persons of the laboratory test. [199]

According to Engler & Schulze [199], the individuals are therefore very different. Some are very interested in technology and enjoy technological environments, whereas their counterparts just want to know the basics.

4.1.2 Laboratory Test Results of the Unobtrusive Fever Detection

The impression of the fever detection is widely scattered. The "Smiley-Scale" of the BIS showed that four participants have a positive impression of the fever detection of section 3.1, whereas three dislike the fever detection. Two individuals had a neutral first impression. Two-thirds of the test group see the fever detection as an easy-to-use and practical module. Three participants see the automated fever detection (see Figure 4.2) as valuable, whereas three people see this prototype as unimportant, and two are neutral to the value of this module [199].

a) **b)**

Figure 4.2: The unobtrusive implemented automated fever detection while the laboratory test. (a) A male tests the fever detection. (b) A female provides feedback while testing the fever detection.

Most testers see the retirement home or medical institutions as the only implementation area of the fever detection. Only one participant can imagine having the fever detection implemented in private households, or even in the participant's own household (see Figure 4.3).

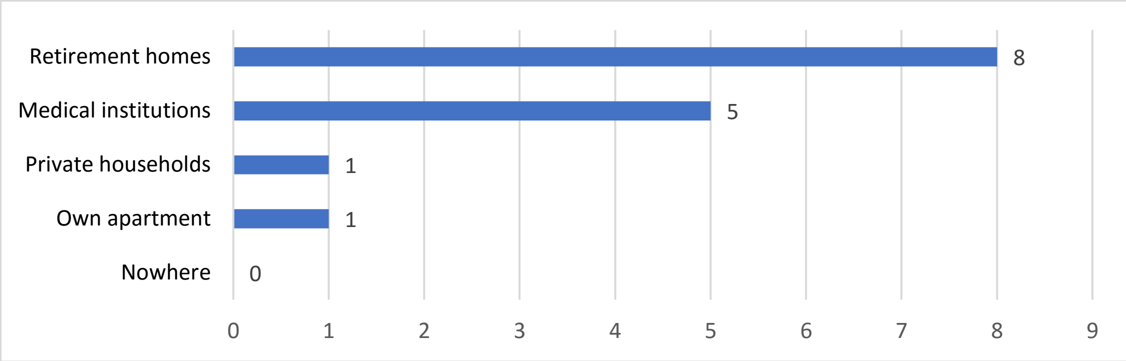


Figure 4.3: The amount of participants, who can imagine implementing the fever detection into the appropriate living areas. Here it was possible to select more than one option. [199]

Regarding how the fever detection should start, one-third wants to start the fever measurement automatically, and two-thirds prefer to trigger the measurement by standing at an appropriate position or pressing a button. Regarding the user interface for displaying the measurement results, most testers want to see the result immediately on a display in the bath environment (see Figure 4.4).

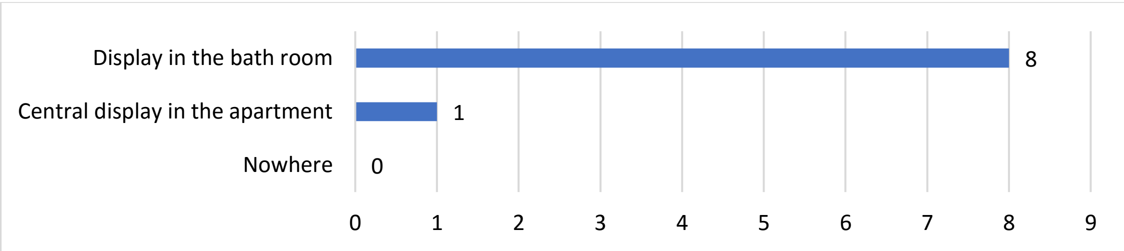


Figure 4.4: The amount of participants, who want to have the results of the fever detection displayed at the appropriate area. Here it was possible to select more than one option. [199]

Regarding the question, when the fever data should be displayed, four testers prefer to see the result after each measurement, and another group of four prefer to see the result only when any deviant values arise. Three individuals would prefer only on request to get the data displayed (see Figure 4.5).

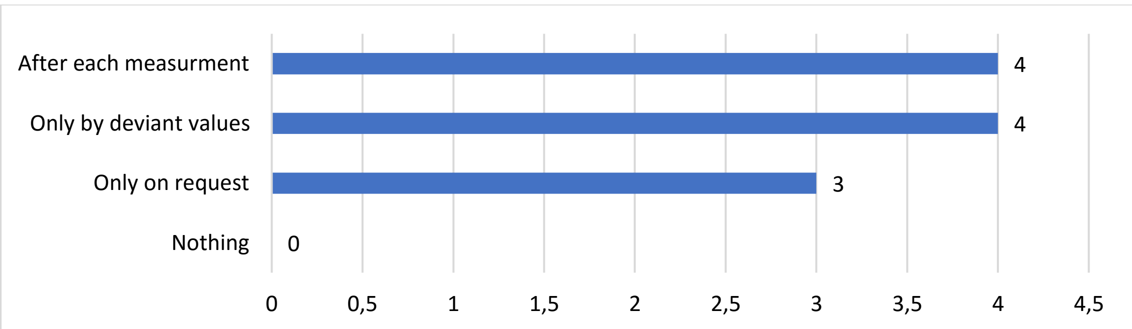


Figure 4.5: The amount of participants, who want to have the data of the fever detection displayed accordingly. Here it was possible to select more than one option. [199]

In case that temperature values are detected, which are abnormal (i.e. fever), most participants want someone to be contacted. Four testers prefer an optical alert and two an acoustical alert. Only one person prefers that there is no alert (see Figure 4.6).

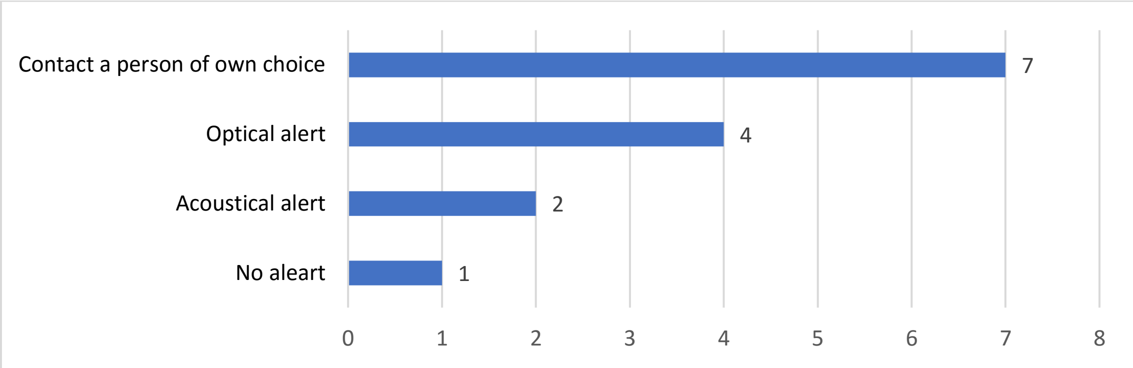


Figure 4.6: Amount of participants, who want to have the appropriate alert setting for the fever detection. Here it was possible to select more than one option. [199]

Additionally, the BIS investigated who should be contacted, in case abnormal values were detected. The participants unanimously want the care staff to be informed. In addition, relatives and neighbors were mentioned along with an ambulance (see Figure 4.7) as emergency contacts.

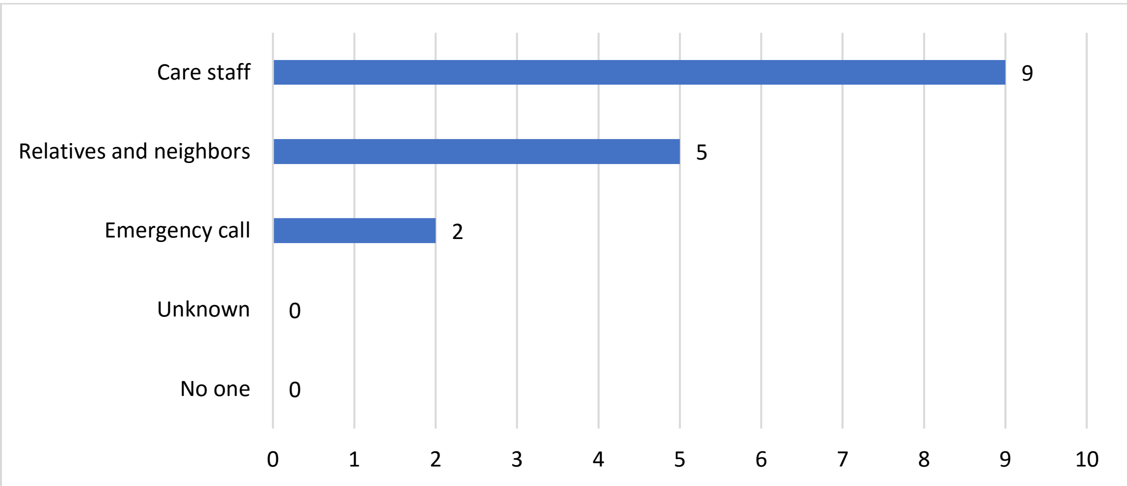


Figure 4.7: Amount of participants, who want to have the appropriate contacts called in case the fever detection identifies any abnormal value. Here it was possible to select more than one option. [199]

During the qualitative evaluation via a semi-structured interview, the interviewees mentioned concerns about the permanent fever measurement monitoring. According to Engler & Schulze [199], the participants would prefer a solution, where they can more actively control the measurement, e.g. by triggering the measurement manually. On the other hand, also some testers praised the idea to implement the automated fever detection into furniture. Since here the test persons are questioning the use of the automated fever detection, the affordability of this prototype is very important for the further success of this module.

4.1.3 Laboratory Test Results of the ECG Implementation

The first impression of the ECG implementation in a chair was also scattered. One tester had a bad first impression; four test persons had a neutral impression and another four a good impression.

The handling of the ECG application in the chair (depicted in Figure 4.8) was evaluated by six participants as "simple", and by seven as "practical". Three testers see the function as important, one as unimportant and two are neutral regarding the importance of this prototype.

a) **b)**

Figure 4.8: The pre prototype of the cuff-free blood pressure monitor during the laboratory test. (a) A male testing the ECG implementation. (b) A female testing the ECG implementation.

Four participants can imagine seeing this prototype in care home facilities or medical institutions. Only one can imagine seeing the prototype of section 3.2 in private homes, but two can imagine having the prototype in their own apartment. Only one tester cannot imagine any future installation in any area (see Figure 4.9).

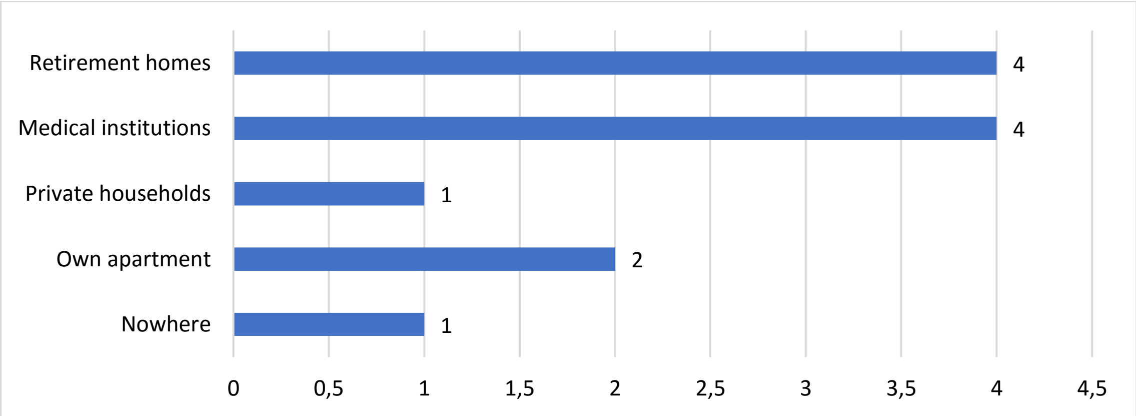


Figure 4.9: The amount of participants of the laboratory test, who can imagine implementing the ECG application into the appropriate areas. Here the participant could select more than one option. [199]

All testers want to start the ECG application manually. No participating member wants to be measured automatically, without triggering the measurement manually. Answering the question, how the measurement should be presented five people answered via a graphical figure, two would like to have only a number value as result, three prefer acoustical feedback and two would prefer that there is no feedback at all (see Figure 4.10).

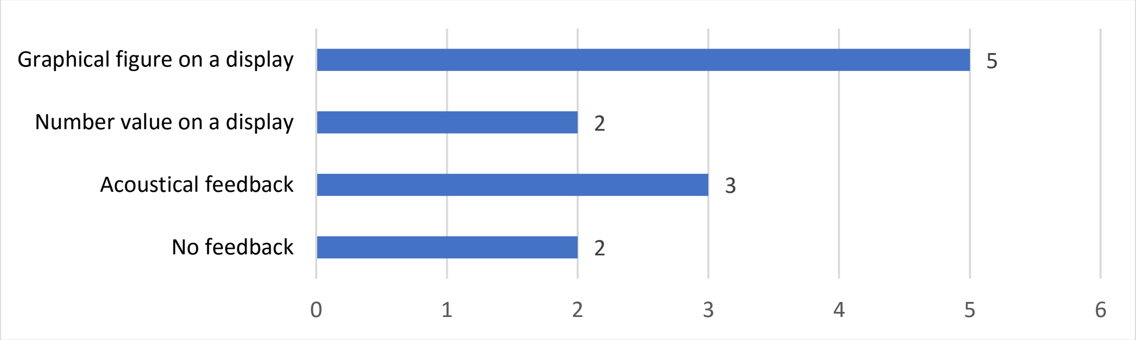


Figure 4.10: Preferred presentation of the captured data of the ECG implementation during the laboratory test. Here it was possible to select more than one option. [199]

On the question where the captured data should be displayed, one tester preferred the kitchen, four testers preferred a central display in the apartment, and one preferred nowhere. The other four participants are open to any further solution, as depicted in Figure 4.11.

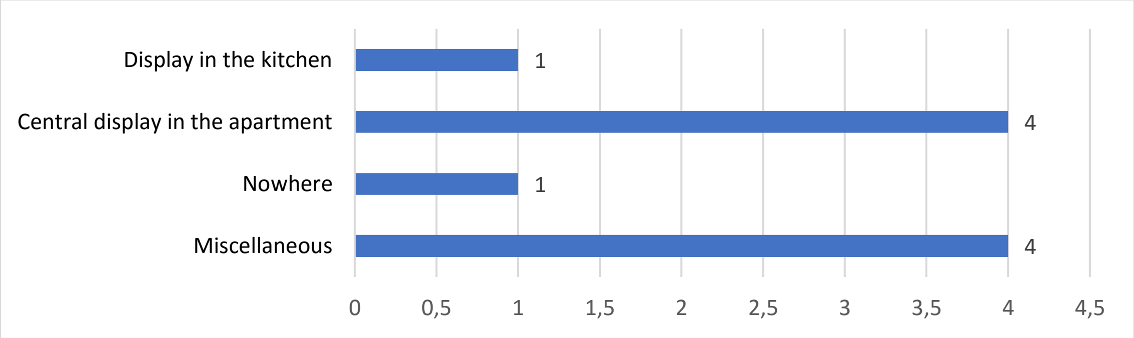


Figure 4.11: The amount of participants of the laboratory test, who want to have the results of the ECG pre prototype displayed in the appropriate area. Here a test person could select more than one option. [199]

Regarding the question, when the captured values should be displayed, one person answered that after each measurement the data should be displayed. Seven want to have only the result displayed when deviated values were captured. Five testers prefer to see the data only on request, and two do not want to have any display of the data (see Figure 4.12).

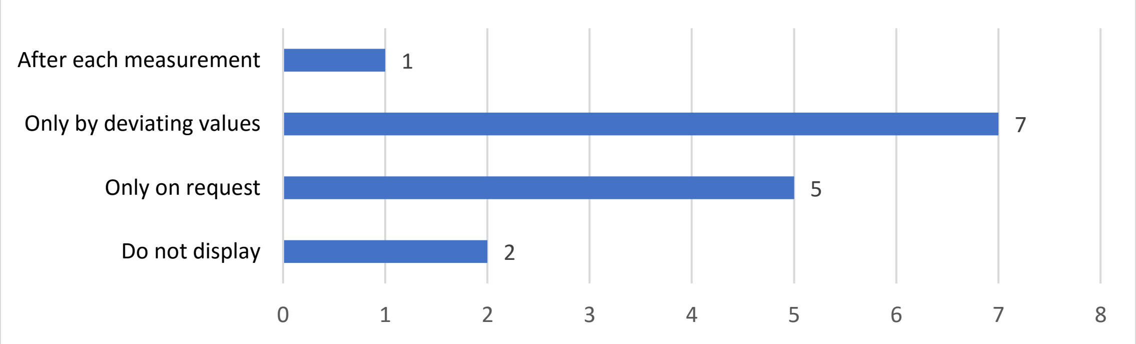


Figure 4.12: The amount of participants of the laboratory test, who want to have the data of the ECG implementation displayed accordingly. Here it was possible to select more than one option. [199]

Similar to subsection 4.1.2 of the fever detection, the testers mostly preferred a primarily selected person gets informed in case of deviating values. Four participants prefer an optical alert and one also an acoustical alert, as depicted in Figure 4.13.

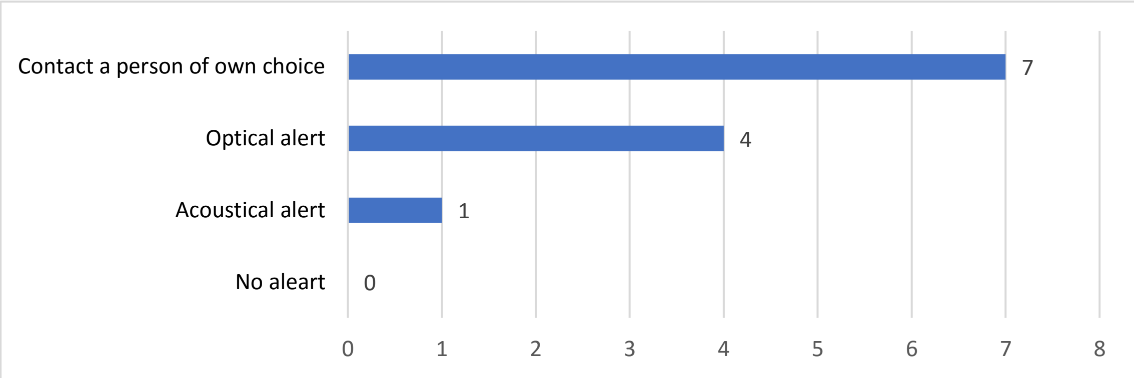


Figure 4.13: Amount of participants of the laboratory test, who want to have the appropriate alert setting for the ECG implementation. Here it was possible to select more than one option. [199]

Answering the question, who should be contacted in case deviating values were captured, the testers believe similarly as before in the fever detection in subsection 4.1.2. Most participants preferred that the care staff have to be informed first. Dissimilar to the fever detection, the testers favored the emergency call before alerting relatives and neighbors (see Figure 4.14).

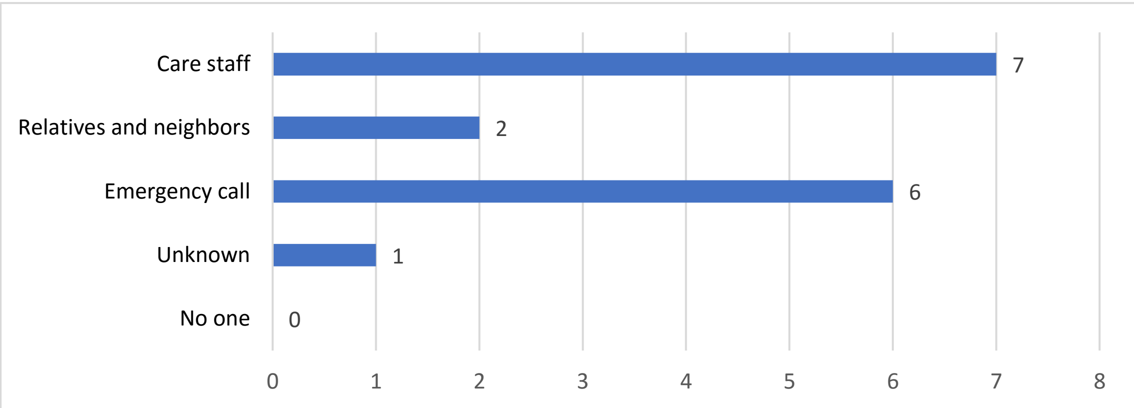


Figure 4.14: Amount of participants of the laboratory test, who want to have the appropriate contacts notified in case the ECG identifies any abnormal values. Here the test persons could select more than one option. [199]

During the semi-structured interview with the BIS for the qualitative evaluation, the interviewees praised, on the one hand, the implementation of the ECG application into furniture, but, on the other hand, mentioned concerns about the permanent monitoring. The participants prefer to trigger the measurement manually when they are interested in the measurement.

Furthermore, the testers criticized that for laypeople the interpretation of an ECG measurement is impossible. Therefore, the people would prefer a simpler feedback instead of a plot of the ECG data [199].

4.1.4 Laboratory Test Results of the Novel Fall Detection

The impression of the fall detection (see Figure 4.15) in subsection 3.3.1 is very positive. Only one tester (of nine) had a negative impression, while two had a good impression and the remaining six had even a very good impression on the “Smiley-Scale”.

Figure 4.15: The first prototype of the fall detection during the laboratory test. The elderly were allowed to test the fall detection at any time on their own.

Seven participants think that the handling of the fall detection is easy, and eight confirm that the fall detection is practical. Six participants evaluated the fall detection as valuable. Only one test person evaluated the fall detection as too complex.

Nearly all participants can imagine having the fall detection implemented in care facilities and medical institutions. Half of all testers can also imagine to have the fall detection implemented in private households or in their own household (see Figure 4.16).

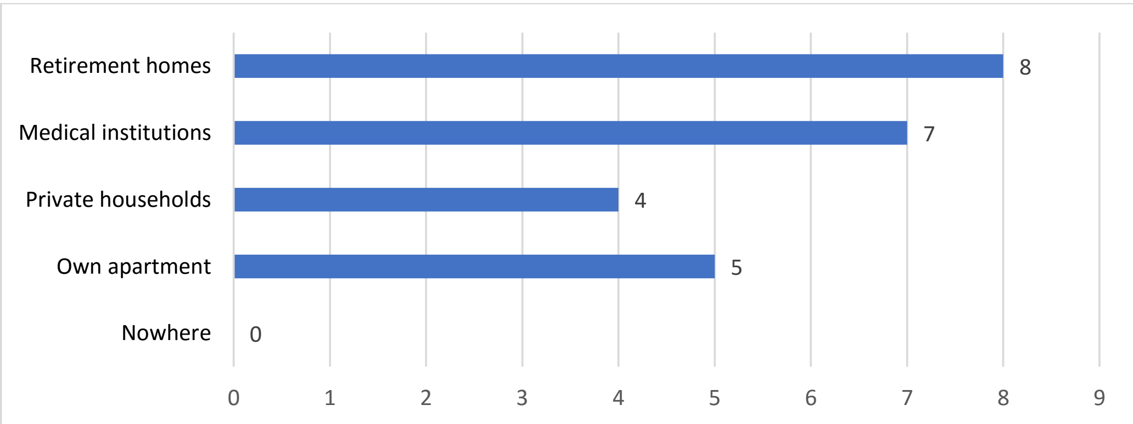


Figure 4.16: The amount of participants of the laboratory test, who can imagine implementing the fall detection into the appropriate areas. Here it was possible to select more than one option. [199]

Since from the beginning a silent alert was planned for the development of the fall detection, at this module no investigation regarding the user interface was performed. Instead, at this point, the participants were directly asked what should happen after a fall was registered.

Similar to responses in subsection 4.1.2 and subsection 4.1.3, the testers prefer to choose their own emergency contacts. Five people prefer also an acoustical alert, and only one person prefers an optical alert (see Figure 4.17).

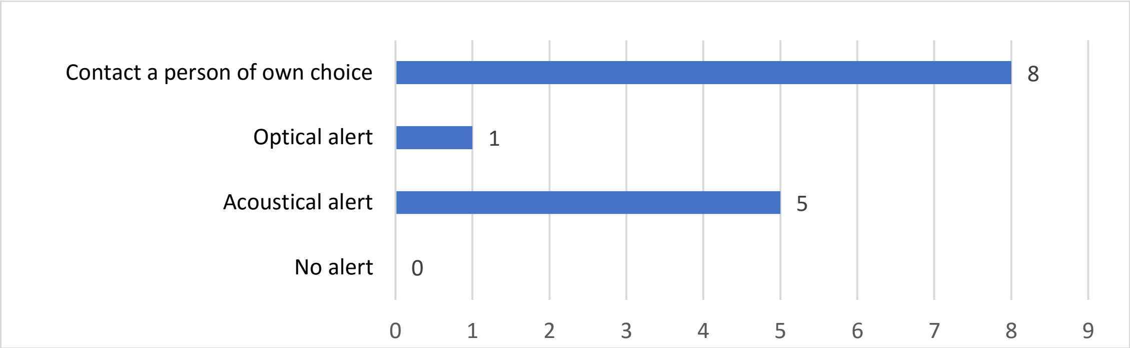


Figure 4.17: Amount of participants of the laboratory test, who want to have the appropriate alert setting for the fall detection. Here it was possible to select more than one option. [199]

Similar to the evaluation of the ECG, the participants prefer that first care staff is informed of a fall, followed by an emergency call to the ambulance, before alerting relatives and neighbors (see Figure 4.18).

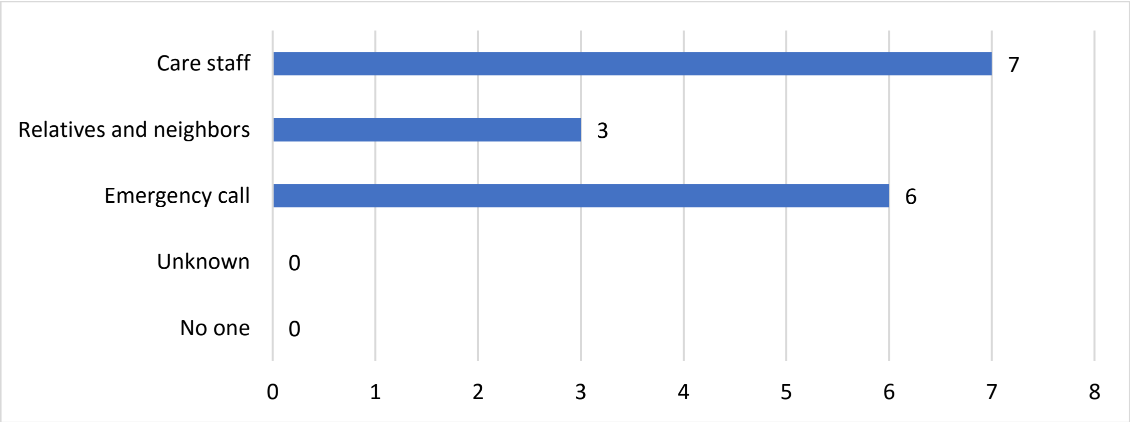


Figure 4.18: Amount of participants of the laboratory test, who want to have the appropriate contacts called in case the fall detection recognize a fall. Here it was possible to select more than one option. [199]

Furthermore, the participants were asked in the questionnaires how much time should pass after a detected fall before an alert trigger. The answer ranged between immediately and until seven and a half minutes. On average, the testers prefer that a fall alert would be triggered no later than four and a half minutes.

In the qualitative evaluation, which was executed by the semi-structured interview of the BIS with each participant, the fall detection was confirmed as the most supportive module of the laboratory test [199].

4.2 Field Test

The field test was executed within the project LISA Habitec [189] as well. In the field test, the modules of chapter 3 were initially implemented in a real apartment, as well as tested under these conditions by the elderly.

In this section the methodology of the field test is provided in subsection 4.2.1. The results of the field test for the fever detection are described in subsection 4.2.2. According to the evaluation results of the ECG implementation of subsection 4.1.3, the ECG was further developed to the cuff-free blood pressure monitor of section 3.2, since the blood pressure represents a value, which user can more easily understand. According to the usability requests of subsection 4.1.3, the interpretation of the systolic blood pressure is automated, but the measurement has to be triggered manually. The evaluation results of the cuff-free blood pressure monitor are written in subsection 4.2.3. The field test results of the improved fall detection, of which the concept is described in subsection 3.3.3, are written in subsection 4.2.4.

4.2.1 Preparation and Methodology of the Field Test

Like the laboratory test, the field test considered the quantitative evaluation with questionnaires, as well as qualitative evaluation by a semi-structured interview. The questionnaires for the field test, which were written by the BIS [198] depending on the prototypes, where categorized by the three rooms: the sleeping room, bathroom and entrance area. The kitchen was not further considered in the field test. This decision was project related, but had no impact on the development of the modules of section 3.1, section 3.2, and section 3.3. Additionally, a new element entered the field test, which was the smart TV of the project LISA Habitec. This smart TV was a primary main user interface, developed by the LISA Habitec consortia partner “GR Research GmbH”.

Each questionnaire started with a five stage Likert scale (ranging from important to unimportant), which aimed to estimate the importance of the prototypes for the user. As it was executed at the laboratory test (see section 4.1), a “Smiley-Scale” (developed by the BIS [199, 200]) was used to document the first impression of the testers, followed by the question, which living environments are potentially imaginable for the different prototypes. For the fever detection of section 3.1 and the cuff-free blood pressure monitor of section 3.2, questions regarding what should be done or who should be informed if deviating values were recorded were additionally asked in the questionnaires. At the end of each questionnaire, the participant had the opportunity to write comments. In addition, here the technical acceptance of the volunteer was documented by using an appropriate questionnaire designed by the BIS, in combination with a questionnaire aiming to record the demographic data of the participant (e.g. age, education, occupation etc.).

For the qualitative evaluation, a semi-structured interview by the BIS was used. In this interview, the interviewees are encouraged to speak openly and free. An interview guide is used just as memory and discussion support, and no answer possibilities were insinuated, thereby resulting in a less strict evaluation compared to the questionnaires. By adding or skipping different questions of the interview guide, the moderator has still the possibility to guide the discussion [200]. At this field test, 32 volunteers participated, whereas only individuals older than 69 were invited. The apartment at “Seniorenheim Peter Paul Schrott” [188] in Deutschnofen and the invitation, as well as the transport of the people to the field test was organized by the consortia partners of the project LISA Habitec [189]. The procedure of the field test followed the same structure as used in the laboratory test described in section 4.1.1.

In order to execute the field test with 32 testers in the given timeframe of three days, the group was invited for group evaluations (from two up to four people per group). Also at the field test the participants signed the consent form before the start of the field test. Again, a scenario considering the use of all prototypes was used for the demonstration. This scenario was based on the scenario of the laboratory test, but was adapted in order to cover all implemented functions of the test apartment. After the demonstration, the participants were encouraged to use the demonstrated functions room by room before they completed the questionnaires. At the end of the field test, each testing group was asked to answer some questions during the semi-structured interview (executed by the BIS), as well as to fill out the questionnaires regarding the technology acceptance. Here as well, the fall detection was mainly demonstrated and the elderly were allowed to trigger an alert on their own. However, according to the health condition of the tester, nobody wanted to trigger the alert by simulating a fall. The demonstration of the fall detection including the alert on the smart TV was sufficient for the elderly in order to answer questionnaires. This procedure, which is summarized in Table 4.2, required two hours per test group.

Table 4.2: Schedule of the field test for each test group.

Procedure	Duration in minutes
Test opening	
Welcoming and concerns form	5 minutes
Instruction and fist questions	5 minutes
Demonstration of the laboratory apartment	15 minutes
Sleeping room and health data measurement	
Testing	10 minutes
Questionnaire	5 minutes
Fall detection in the Bathroom	
Testing	10 minutes
Questionnaire	5 minutes
Kitchen and the LISA smart TV	
Testing	10 minutes
Questionnaire	5 minutes
Wardrobe	
Testing	10 minutes
Questionnaire	5 minutes
Test closing	
Semi-structured interview	15 minutes

According to Engler & Schulze [200], the variety within the testing group was ideal. There were participants interested in technology and that enjoy the use of technological devices, whereas some were mainly interested in only the basic functionality.

Nevertheless, nearly all group members agreed with the statement that technology is very usefully, can solve many daily problems, and eases living situations (see Figure 4.19).

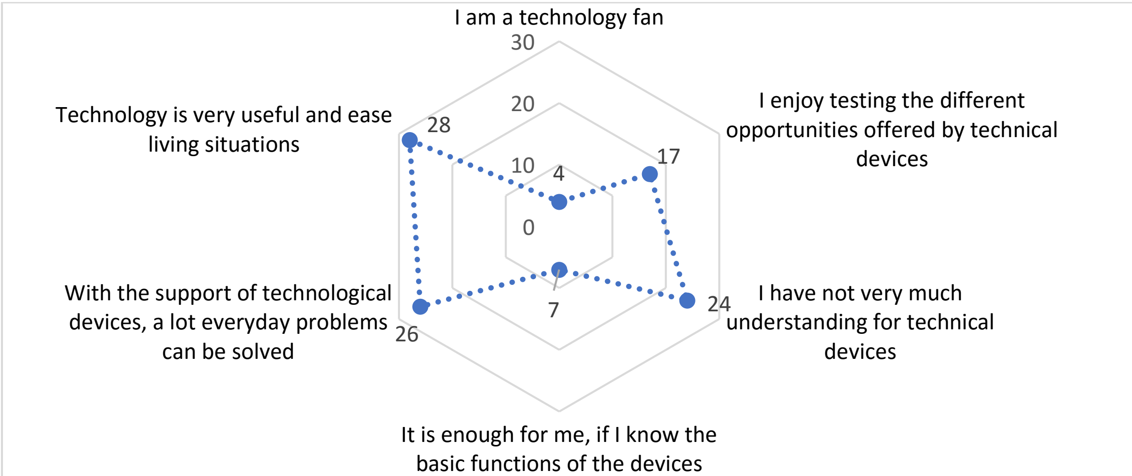


Figure 4.19: Technological acceptance of the participants of the field test. [200]

Two-thirds of the group are already satisfied to know the basic functions of a device, and half of all participants enjoy the possibilities offered by technological devices. Only seven participants have a minor understanding of technology, whereas only four confirmed to be a technology fan. [200]

4.2.2 Field Test Results of the Unobtrusive Fever Detection

The impression of the fever detection compared to the laboratory test did not change significantly. This is because the only changes are that the screen was hidden and the power supply issue was solved (see subsection 3.1.1). Despite these apparent modifications, the functionality was unchanged. In the field test, the fever detection impressed 15 participants positively, and four negatively. Eleven people had a neutral impression on the "Smiley scale".

The handling of the automated fever detection (see Figure 4.20) was evaluated by 15 testers as simple and by 14 as practical. Only three volunteers evaluated the fever detection as complicated and two as unpractical. Eleven participants see the fever detection as valuable, whereas seven think this prototype is unimportant. One tester evaluated this prototype in the field test as neutral in its value.

In the questionnaire, the participants were asked in which living environment they could imagine the automated fever detection. Here, 13 testers can imagine that the prototype will be used at care facilities, and seven think that medical institutes could benefit from this prototype. Eleven participants can imagine installing the automated fever detection into a private household, or in their own apartment. Only three people cannot imagine any future implementation into any living environment (see Figure 4.21).

Figure 4.20: The unobtrusive implemented automated fever detection during the field test.

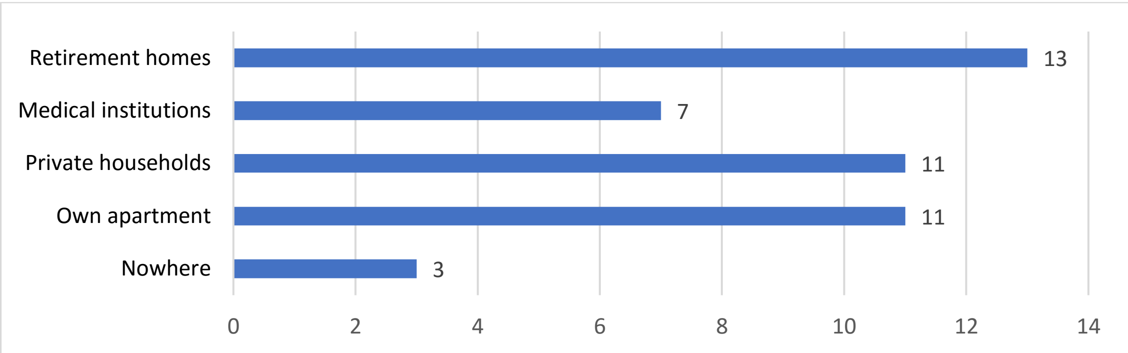


Figure 4.21: The amount of participants of the field test, who can imagine to implement the fever detection into the appropriate areas. Here it was possible to select more than one option. [200]

To compare the impact of evaluation feedback of the laboratory test with the field test, the testers' request during the laboratory test to have the fever values immediately displayed on a screen was ignored (see subsection 4.1.2). Therefore, the directly attached display was hidden in the field test. The measurement result was displayed only on a central user interface, i.e. the smart TV. Here the testers were asked, how the values should be displayed: As a single value of the last measurement, or as a progression curve over time. Most participants (i.e. 17) prefer to have just the last measurement displayed, whereas eight prefer to have a progression curve plotted.

In case deviant values are registered by the fever detection, 17 people preferred that a person of choice is contacted, and 14 favored the emergency call of the ambulance. Additionally, five testers would like to have an optical alert and nine also an acoustical alert (see Figure 4.22).

In the field test, as well as at the semi-structured interview, it was observed that for the fever detection the participants prefer an additional interface (beside the smart TV), where the individuals can immediately see the measurement results. [200]

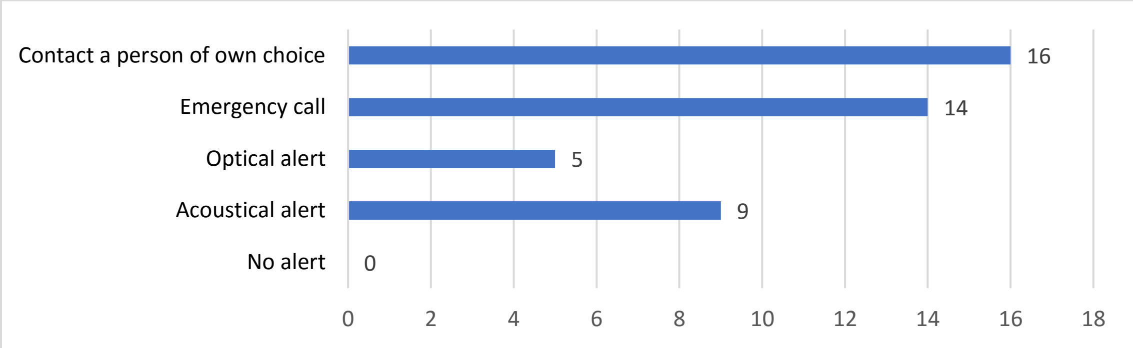
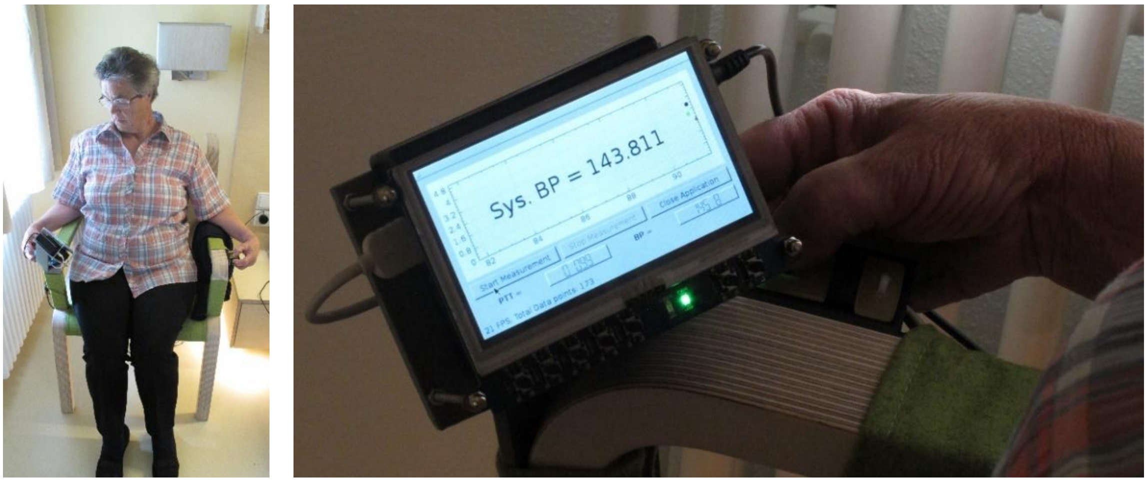


Figure 4.22: Amount of participants of the field test, who want to have the appropriate alert setting for the fever detection. Here it was possible to select more than one option. [200]

4.2.3 Field Test of the Results Cuff Free Blood Pressure Monitor

The cuff-free blood pressure monitor of section 3.2 made a good first impression in general on the participants in the field test (see Figure 4.23). Only six testers had a bad impression according to the “Smiley-Scale” and eight a neutral, whereas 17 evaluated a good or very good impression.



a) **b)**

Figure 4.23: The cuff-free blood pressure monitor during testing in the field test. (a) A participant measures the systolic blood pressure. (b) A measurement result of a participant.

Regarding the complexity of this module, ten testers evaluated the complexity as simple, and only six as too complex. Five testers evaluated the complexity as adequate (i.e. not too complex but also not so simple). Additionally, 13 participants see the cuff-free blood pressure monitor as practical, and eight as unpractical, whereas one tester remained neutral regarding the practicability. Most participants (i.e. twelve) evaluated the prototype in the field test as valuable, and only four as unimportant. Only four stayed neutral for the evaluation of the value.

In contrast to the laboratory test, the question, how the measurements should be triggered, was not answered unambiguously. In order to start the blood pressure measurement, the user had to trigger the measurement on the touchscreen before grasping the measurement handles (see Figure 3.16 at subsection 3.2.3). This was developed because of the feedback of the laboratory test (see subsection 4.1.3). However, now 13 participants confirmed that an automated measurement, which is not triggered by the user is also an acceptable option, and only ten participants preferred the state of the art (seven could not answer this question).

For the implementation area, 16 testers can imagine seeing the cuff-free blood pressure monitor of section 3.2 in care facilities. Twelve volunteers can also imagine seeing the cuff-free blood pressure monitor in private homes, and even 13 in their own apartment. Only two people cannot imagine having the cuff-free blood pressure monitor implemented in any environment (see Figure 4.24).

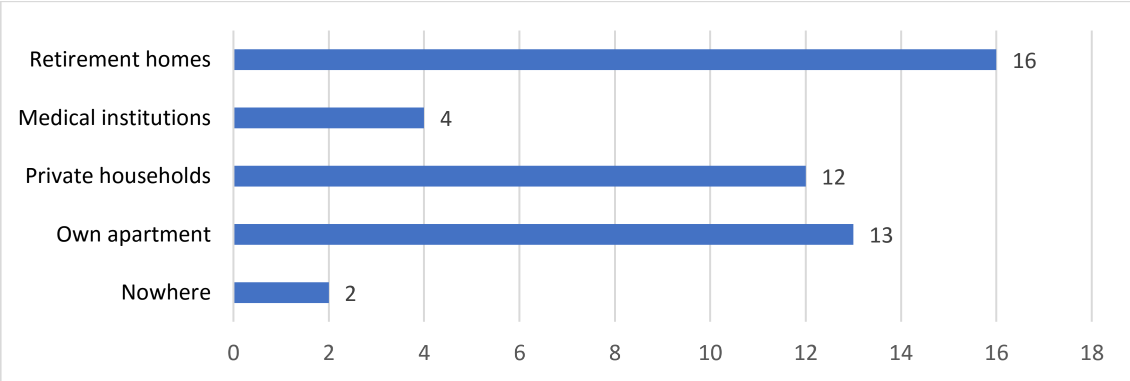


Figure 4.24: The amount of participants of the field test, who can imagine implementing the fever detection into the appropriate areas. Here it was possible to select more than one option. [200]

Similar to the fever detection field test results of subsection 4.2.2, displaying the last value was sufficient for most (i.e. 16) testers, whereas twelve people prefer the progression curve over time for the systolic blood pressure value.

Regarding the question what should happen in case deviating values are registered by the prototype of section 3.2, 17 participants answered that the care staff should be informed (or the ambulance), and 16 believe a person of choice should be contacted. This is similar to the fever detection responses. Additionally, some users would like to have an acoustical alert (six people) and an optical alert (four people) (see Figure 4.25).

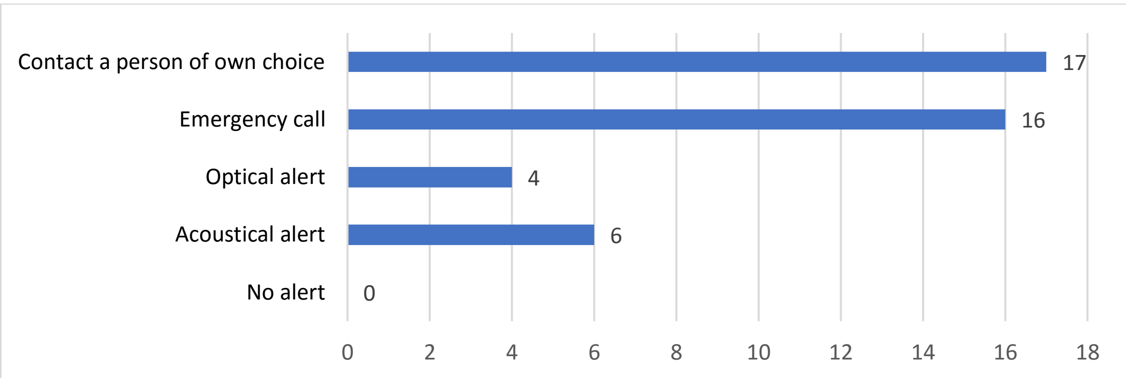


Figure 4.25: Amount of participants, who want to have the appropriate alert setting for the cuff-free blood pressure monitor. Here it was possible to select more than one option. [200]

During the semi-structured interview, the interviewee expressed that the cuff-free blood pressure monitor in the chair is an interesting and easy possibility to monitor the blood pressure, stating especially the inconvenience of the alternative blood pressure measurement with the cuff [200].

4.2.4 Field Test Results of the Novel Fall Detection

The fall detection (see Figure 3.30 in subsection 3.3.3) also made a ”very positive” impression for 15 testers in the field test, and for eleven people it made a “positive” impression. Only two participants had a bad impression and one remained neutral in impression. Also the complexity was mostly evaluated positively, since 17 testers think the fall detection is easy to handle. Only three people evaluated the fall detection as complex and only one remained neutral. However, no user evaluated the fall detection of section 3.3 as impracticable. Only one user remained neutral. All other testers evaluated the fall detection as practical. The value of this module was similarly evaluated; no participant thinks that the fall detection is unimportant, and only one remained neutral while all others evaluated the fall detection as valuable.

Regarding the question, in which living environments is the fall detection of the field test imaginable for the user, 22 answered at care facilities, nine at medical institutions, 13 at single households, and even 19 at their own apartment (see Figure 4.26).

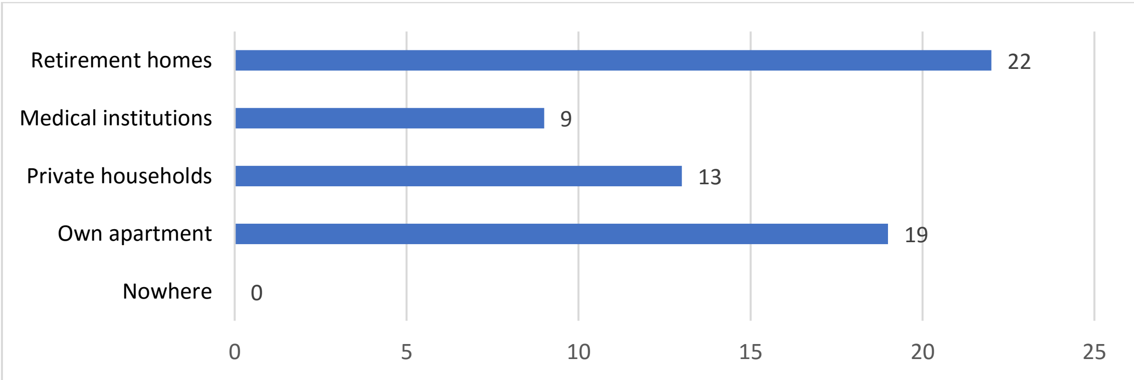


Figure 4.26: The amount of participants of the field test, who can imagine implementing the fall detection into the appropriate areas. Here it was possible to select more than one option. [200]

Additionally, the testers were asked in which apartment room he or she would like to have an additional fall detection, in addition to the bathroom. Only four confirmed that the bathroom is enough, while three would like to have the fall detection additionally in the bedroom and two participants would prefer to have the fall detection in the kitchen. The remaining 21 people answered that they would like to have the fall detection installed in all rooms (see Figure 4.27).

As already mentioned in subsection 3.4.1, the fall detection of the field test was communicating via RabbitMQ to the LISA Server. Thereby, the smart TV was able to trigger an alert, which calls automatically a person of choice, if the alert is not aborted in a given time, i.e. confirmed as false alert from the user (for the field test the time was set to one minute). These settings are results of the laboratory test of subsection 4.1.4. In order to investigate if the realization is appropriate, the volunteers were asked how they like the response of the fall detection.

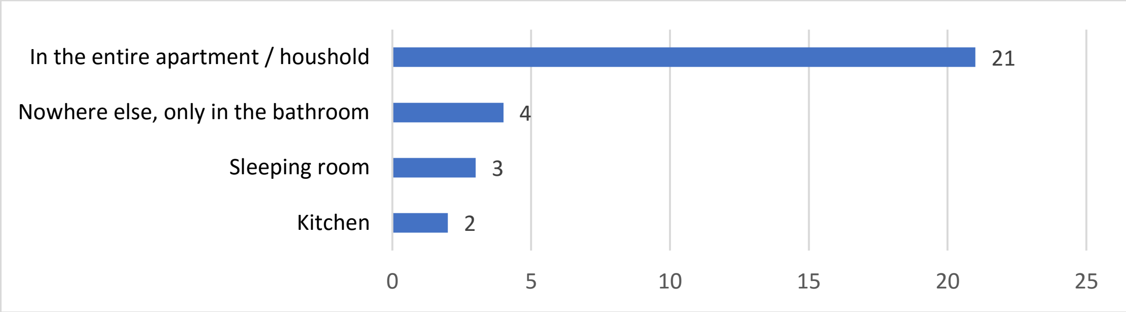


Figure 4.27: The amount of participants of the field test, who would like to have the fall detection implemented in the appropriate rooms of an apartment or household. [200]

The majority with 13 testers answered that the fall detection reaction is perfect as presented in the field test. Nine volunteers would prefer to call immediately a person of choice and five would prefer an acoustical alert. Three participants proposed different periods for the interruption of the alert (see Figure 4.28).

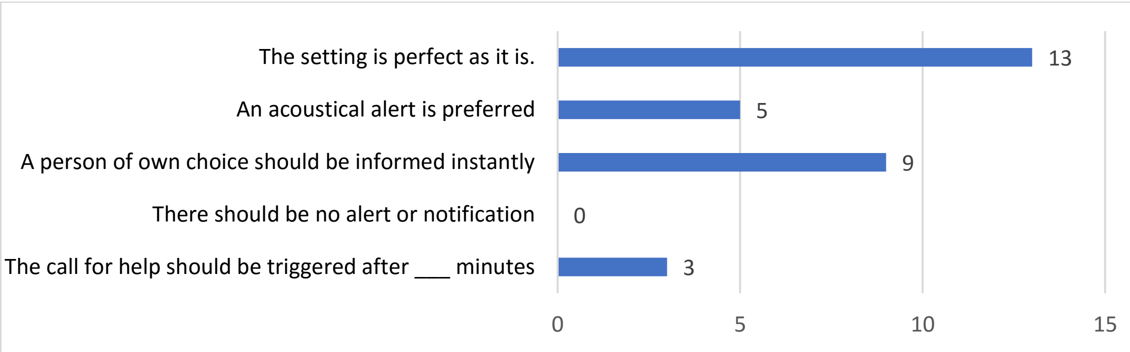


Figure 4.28: The amount of participants of the field test, who would like to have a specific fall detection behavior. [200]

Furthermore, the group members were asked, who should be notified about a fall. The care staff is once more the leading response with 16 votes, followed by relatives and neighbors, which has 13. Twelve participants would prefer to call the ambulance as well in case a fall was detected (see Figure 4.29).

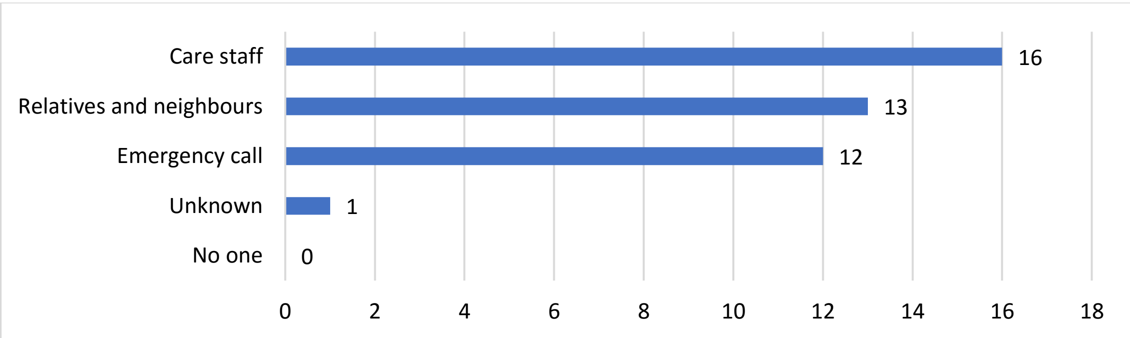


Figure 4.29: Amount of participants of the field test, who want to have the appropriate contacts called in case the fall detection recognizes a fall. Here it was possible to select more than one option. [200]

The semi-structured interview, which was guided by the BIS, confirmed the importance of the fall detection. The elderly especially, who live in a single household, see the fall detection as very important, which explains why most participants preferred to have the fall detection installed in the entire apartment, instead of only in the bathroom. The function of the smart TV, which recognizes a fall and triggers the appropriate alert (see subsection 3.4.1), was especially appreciated by the group, even in the case the smart TV was switched off [200].

4.3 Discussion of the User Acceptance Progress

The evaluation of the prototypes of section 3.1, section 3.2 and section 3.3 in the laboratory test gives a first indication about the developmental success as well as the progress in improving the prototypes after the laboratory test. In the laboratory test, most participants evaluated the fall detection (technical details see subsection 3.3.1 and subsection 3.3.2) as important, whereas half of the participants evaluated the fever detection (technical details see section 3.1) and the pre prototype of the cuff-free blood pressure monitor (technical details see section 3.2) as important (see Figure 4.30).

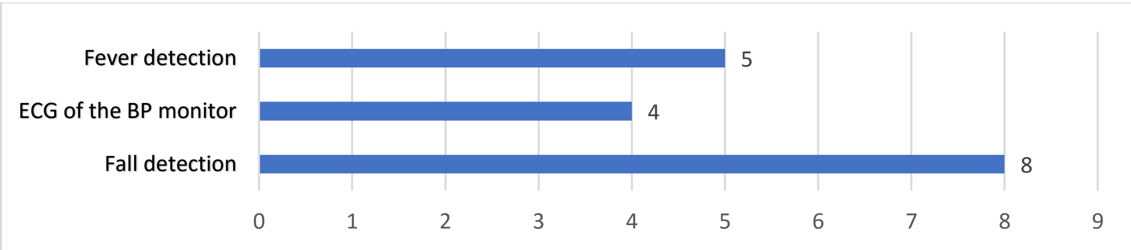


Figure 4.30: Amount of participants of the laboratory test, which evaluated each prototype as important [199].

Since the smart TV of the project LISA Habitec offered additional services, besides displaying the results of the proposed modules of the fever detection, the cuff-free blood pressure monitor and the novel fall detection, a questionnaire allowed comparison of the importance of these functions with one another. The result of this questionnaire is depicted in Figure 4.31.

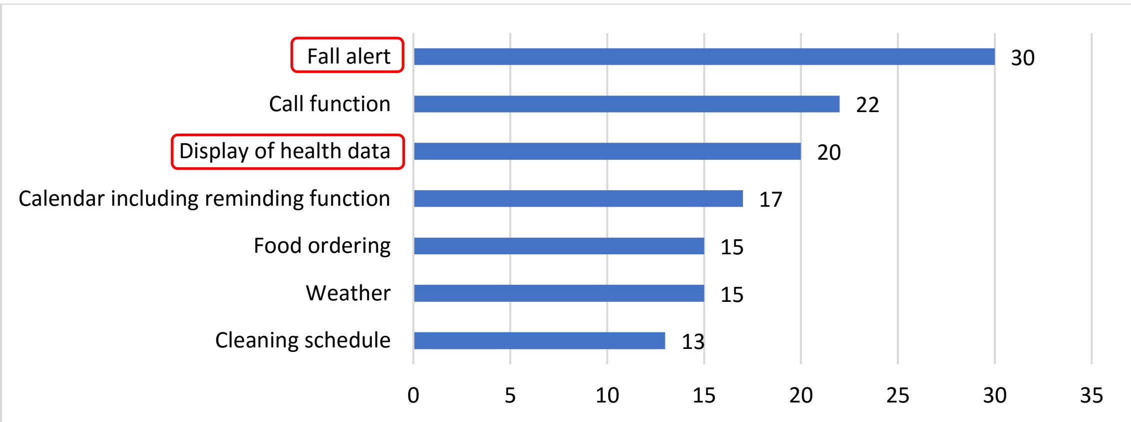


Figure 4.31: The amount of participants of the field test, who evaluated the different functions of the smart TV of the project LISA Habitec as important. Here it was possible to select more than one option. [200]

As seen in Figure 4.31, the fall detection and the health data display are among the top three functions, which were evaluated as important for the elderly.

In order to compare the developmental success of the health tracking system, the testers in the field test were allowed to also measure their blood pressure with a commercial devices at the wrist. Furthermore, a body scale was also available in the field test (see Figure 4.32).

a) **b)**

Figure 4.32: The used commercial available devices for comparing the user acceptance with existing health monitoring device and the proposed modules. (a) The used blood pressure monitor. (b) The used body scale.

The value ranking of the participants of all four health data devices (i.e. the unobtrusive fever detection, cuff free blood pressure monitor, body scale and commercial blood pressure monitor) are depicted in Figure 4.33.

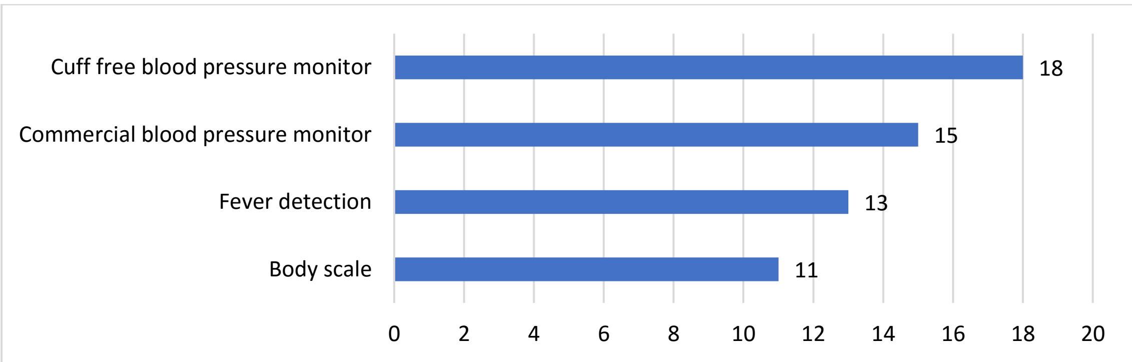


Figure 4.33: The amount of participants of the field test, who evaluated the different health monitoring devices as important.

The novel cuff-free blood pressure monitor, which operates without a cuff, is preferred over the commercially available solution (see Figure 4.33). Regarding the automated fever detection, the volunteers stated in the laboratory test and in the field test that they are not convinced about the importance of this device. But still, the automated fever detection module seems to have a higher importance than a body scale, which is nowadays a device found in nearly every household.

The user acceptance can also be documented mostly as improved after the field test, by comparing the relative amounts of the feedback (see Table 4.3).

Table 4.3: Relative comparison of the amount of participants, who evaluated the prototypes as important by percentage.

Prototype	Laboratory test results	Field test results
Fever detection	55.5 %	40.625 %
Cuff-free Blood Pressure Monitor	44.4 %	56,25 %
Fall detection	88.8 %	93.75 %

The cuff-free blood pressure monitor and the fall detection was relatively more often evaluated as valuable, because of the implemented improvements according to the laboratory test results. Only the fever detection was relatively seen a bit weaker. This was most likely caused by ignoring the user feedback regarding the direct implemented display, where the user rejected the suggestion to display the result only at a central user interface (see subsection 4.1.2). Since the fever measurement in the field test was only visible on the smart TV, the user acceptance dropped (see subsection 4.2.2). Therefore, in the final implementation described in section 3.4, the fever detection has still its own display and forwards the data to the main user interface.

Although the smart TV solutions was mostly greatly appreciated by the testers, some complained during the field test that even a (smart) TV is too complex for their private household. Therefore, the interactive table was developed, which possesses an intuitive touchscreen function. The obtained health data are transferred to the interactive table server (see subsection 3.4.3), and are displayed according to the users feedback of the field test. Therefore, all data are plotted on the interactive table, e.g. the ECG curve, the pulse curve, as well as the last value of the systolic blood pressure and of body temperature.

The functionality of the dominant fall alert system was as well implemented into the interactive table, since the “Health Data GUI” always starts, when a fallen person is detected. In addition, the interactive table proves that the modular approach of the “Ambient Health Monitoring System” (as requested in section 2.4) is given, so that the developed modules can join other networks and user interface with minor efforts.

The feature to call a third person was the only function not implemented yet, because of outstanding future tests, where appropriate contacts have to be available. Therefore, the automated alerts, in case deviating body temperature, ECG or blood pressure values are recognized, are still outstanding and will be included in future research (see section 5.2).

5 Conclusion and Outlook

In this work an "Ambient Health Monitoring System" was developed and tested successfully. Chapter 1 introduced the need of such system in the near future is increasing, due to the demographic change. The work developed in this solution address the health issue of aged like fever, cardiovascular diseases and hypertension, osteoporosis and the related risk to fall, as well as currently available solutions on the market and ongoing research approach, and were introduced in chapter 2. Thereby the current technological limitations were highlighted, which were addressed by the developed system in chapter 3. In chapter 3 and chapter 4, the implementation of the "Ambient Health Monitoring System", and the performed tests are described.

Although the development and the test were successful, additional implementations and improvements of the modules are planned, as the proposed system is only a first proof of concept, which can be seen as a foundation for developing more unobtrusive and accurate modules in the future. In section 5.1, the additional implementations and improvement approaches are described, which are planned, and in some cases already underway. Furthermore, a summary of the achievements of this work is provided in section 5.2. In section 5.3, an outlook about the potential impact of AAL application in the far future is given.

5.1 Next Development Approaches of the Ambient Health Monitoring System

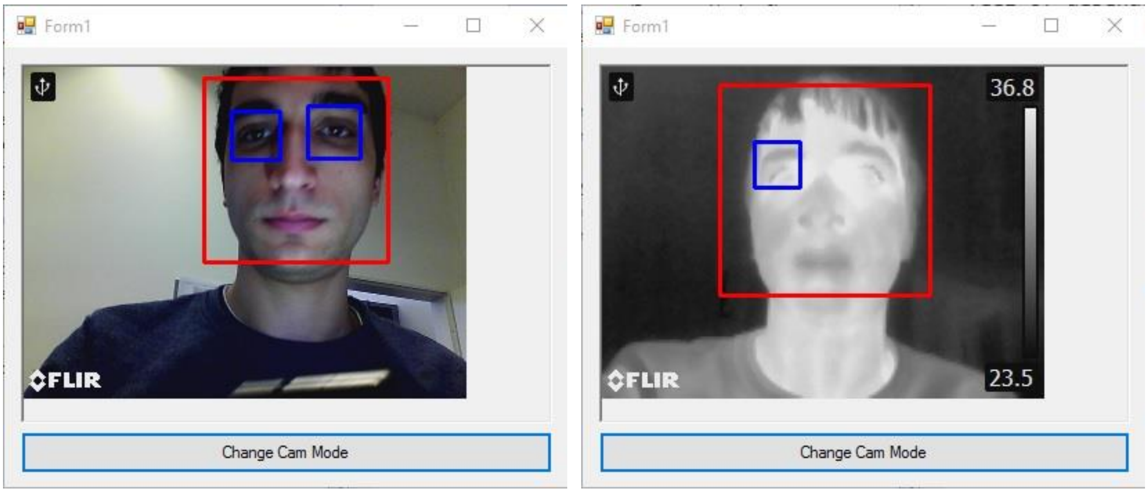
In this section, the further technical developments of the proposed modules are presented. Therefore, for each module the current progress is provided, which already is in terms of their current functionality, accuracy or reliability under development. In subsection 5.1.1, an alternative approach is described to unobtrusively monitor the body temperature, including first implementation attempts. In subsection 5.1.2, a development concept is described, which aims to transfer the cuff-free blood pressure monitor from the chair into a bed. The improvement implementations of the fall detection, which aim to increase the low-cost aspect and easiness of installation, are described in subsection 5.1.3. In section 5.1.4, a concept is provided for analyzing the gesture input of the user while controlling the interactive table, including a primary proof of the concept, which shows how the gesture tracking and health related data are captured.

5.1.1 Future Work of the Unobtrusive Fever Detection

In section 3.1, the concept of an automated fever detector is presented. This module is able to measure the body temperature on the forehead, and an approach to increase the reliability is to measure on the eyes [102]. However, image recognition of human eyes is not functional in thermal images. This is due to the weak contrast human eyes have in thermal images (see subsection 3.1.2). However, the used thermal camera FLIR E6 has an integrated RGB camera. In case a program switches the image stream between the RGB camera and the thermal camera, the location of the human eyes could be tracked in the RGB camera.

The coordinates have to be transferred to the thermal camera, where then the temperature tracking is performed. For this purpose, a software was developed (see Figure 5.1), which enables the investigation of this approach and further development toward a full functional module.

Since it is necessary to measure only on one eye, the first identified eye will be used for the fever detection. Unfortunately, this implementation approach leads to some additional issues. Since the necessary software development kit is only compatible with Windows, it is not possible to use a single board computer, as those only work with Linux operating systems. A Windows minicomputer, which is more expensive and larger compared to a single board computer, would be the best approach to still have a computer, which is small enough for an unobtrusive implementation.



a) **b)**

Figure 5.1: Face-eye detection test software of the FLIR E6 via the SDK. (a) The recognized face and eyes. (b) The transferred eye position into the face detection in the thermal image.

Additionally, as can be seen in Figure 5.1, the RGB camera and the thermal camera have a different resolution and a minor offset in the X and Y coordinate to each other, which has to be compensated within the program. For this purpose, the face recognition is used. Because the face proportion does not change during the measurement, the eye coordinates of the RGB image can be used in relation to the recognized face. I.e. this approach still executes the face recognition in the thermal image. As soon as the face is recognized, the eye position is located relative to the coordinates of the RGB camera (see Figure 5.1 (b)). Therefore, the user is not forced to stand still during the measurement, since the program is still able to update the position of the detected eye via the face recognition. At this point the same statistical approach to filter potentially wrong measurements caused by too fast movements is planned to implement in this prototype, as described in subsection 3.1.2.

After a successful measurement, the thermal camera will display and transfer the final result, as proposed in section 3.1, and finally switch back to the RGB mode to await the next measurement attempt.

5.1.2 Future Work of the Cuff Free Blood Pressure Monitor

The concept of the cuff-free blood pressure monitoring was successfully implemented into a chair. According to the field test and laboratory test (see chapter 4), the implementation had to be insofar obvious that the user can trigger the measurement. An automated measurement, one that the user is unaware when executing, was rejected by the test persons regarding the implementation into a chair while the laboratory and field test (see chapter 4). Therefore, it is planned to implement this solution into a bed, which would allow monitoring the blood pressure changes while sleeping. However, to investigate this approach in the bed, a new development is necessary.

The used capacitive electrodes are very sensitive to noise and artefacts. Therefore, the capacitive electrodes have to be newly designed, and soft electrodes have to be used (see Figure 5.2).

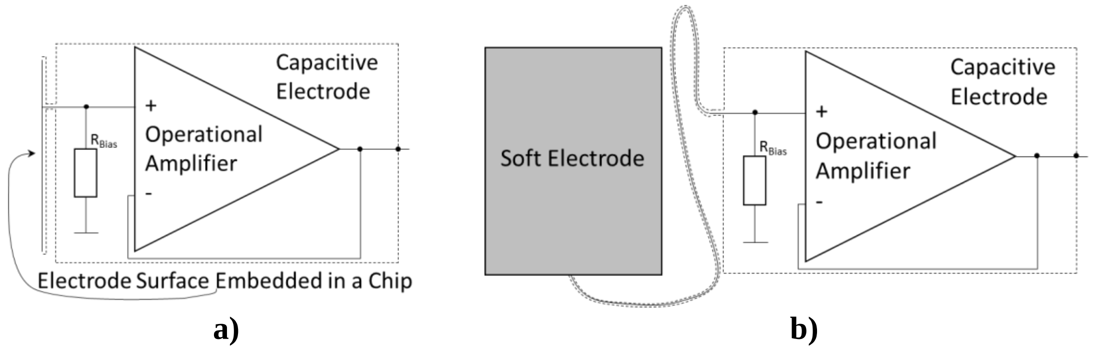


Figure 5.2: Schematic concept of the future capacitive electrodes in direct comparison to the currently used capacitive electrodes. (a) The capacitive electrode, where operation amplifier and electrode surface are on the same chip (see Figure 3.15). (b) The novel concept, where the electrode surface is dispatched from the circuit in order to realize a soft electrode.

Since the distance between the noninverting operation amplifier and the electrode surface will be larger than the standard solution (see Figure 5.2 (b)), the impact of the noise is expected to become worse by this approach. In literature, most research groups try to solve the problem of the noise sensitivity by the Driven-Ground-Leg electrodes and guarding [160, 161]. However, analog filtering enables a faster real-time signal capturing. For this purpose, the schematic designed electrodes, appropriate filter, as well as ECG amplifier was developed [202, 203], which already filters the captured signals and allows a comfortable implementation into a bed. Additionally, the time necessary to suppress the oscillations and artefacts will be improved, due to its analog implementation. Therefore, this approach will enable a fast tracking of the capacitive ECG in the bed.

In addition, the pulse sensor has to be replaced by a different method, since the optical sensor needs direct contact to a finger or earlobe. According to Mase et al. [204], it is possible to measure the pulse curve via microwave reflectometry. Here, first prototypes exist, which measure the heart rate variability at the thigh via an in-the-chair implemented microwave sensor. Alternatively it is also possible to measure on the human back in order to detect the stress of a car driver, via the pulse curve [205]. The microwave reflectometry allows the device to capture the pulse curve even through cloth, which will enable an unobtrusive implementation and full automation of the proposal of section 3.2 into the bed environment.

By fusing the capacitive electrodes for the bed with the microwave reflectometry (e.g. the NJR4265RF2C1 [206]) and using the concept of section 3.2, an unobtrusive automated blood pressure mattress is in development, which will be able to monitor the blood pressure fluctuation e.g. while sleeping.

5.1.3 Future Work of the Novel Fall Detection

Although the fall detection prototype of subsection 3.3.3 is better compared to its first development iteration (see subsection 3.3.1), the lasers are still the weak point of the fall detection, because of the difficult calibration of the laser light angle. Additionally, the lasers in the current design are also the most expensive components in this module. Here, the new conceptual idea would be to replace the laser with infrared LEDs, which emit diffuse infrared light.

Thereby, the daylight impact would decrease as well, since the module would work on infrared basis. Additionally, the light sources would fit in the profiles of the baseboard, i.e. no extra laser holders are necessary. The concept (depicted in Figure 5.3) assumes that each Digispark (see subsection 3.3.3) will be equipped with an infrared sensor and infrared LED. When the sensors are placed consecutively in front of each other (see Figure 5.3), the infrared barrier should be sufficiently established.

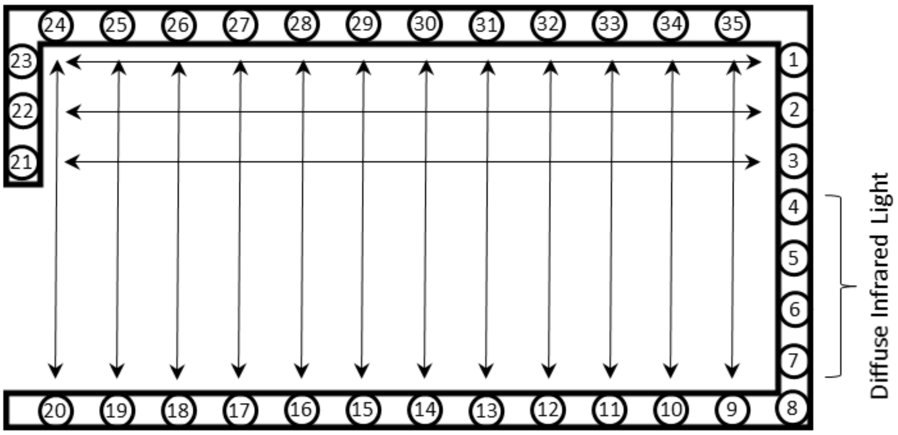


Figure 5.3: Schematic of the next development stage of the novel fall detection. The infrared sensor/transmitter number four to seven are thought to work on diffuse infrared light. All other sensors use their infrared sensor to provide sufficient infrared emission to the opposite infrared sensor.

Furthermore, infrared LEDs are much cheaper compared to infrared lasers, which will support the low-cost goal of the proposed system. The diffuse emission behavior of LEDs also avoid the issue of the light calibration. However, at the moment, it is unknown how accurate this system can detect a fall, compared to the solution of section 3.3, where a 100 % accuracy over weeks was investigated as long as no one accidentally alters the laser light orientation.

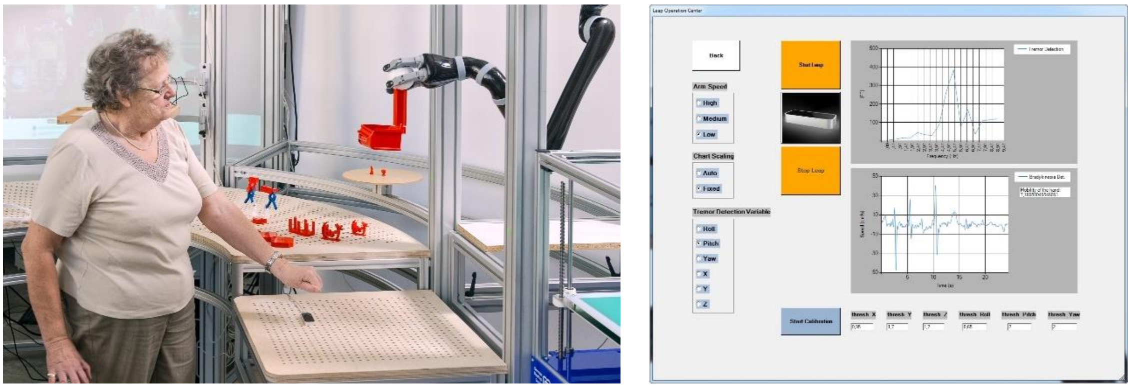
Further research is imperative to determine what should happen after a fall is detected. Most current concepts focus on alerting someone else. However, via modern technology, e.g. mobile robots, automated help could be realized.

For this approach, it was already possible to develop a small server application using a BBB, which enables a mobile platform to communicate with the fall detection from subsection 3.3.3. I.e. if the fall detection triggers an alert, a mobile platform drives to the room, where the alert was triggered. At the moment, investigations take place regarding the kind of support services the robot has to offer in order to help a fallen person, as well as how to identify a threatening situation, where the robot has to alert e.g. the ambulance.

5.1.4 Future Work of the Human-Machine-Interface

The use of gestures in order to control an operating system is just one potential scenario application for depth images. Another approach is the user movement analysis. The Kinect, which might be used for the gesture recognition of the interactive table of the "Ambient Health Monitoring System" (see subsection 3.4.2), was used by several research groups to investigate gait pattern and related diseases [207, 208]. Since the interactive table tries to activate the user mentally and physically e.g. by games (see subsection 3.4.2), and allows the user to see all recorded data of the proposed system, it is most likely that the interactive table will be used regularly. Therefore, the approach to investigate the movement pattern can be realized as well for the hand, while someone is controlling the interactive table.

A similar approach was already realized, where a hand-tracking sensor (the Leap Motion sensor) was interfaced with a robotic arm (see Figure 5.4) [92].



a) **b)**

Figure 5.4: The Leap Motion sensor as controller for a robotic arm. (a) An elderly person steering the robotic arm via gestures by using the Leap Motion sensor. (b) A GUI plotting the measured frequency domain in order to show tremors and movement speed captured by the Leap Motion sensor.

While the user was controlling the robotic arm via hand gestures, a program in the background was analyzing the movement frequency and movement speed [209]. Both values are important parameters to identify tremor and bradykinesia, which belong to the cardinal symptoms of the Parkinson's disease [210]. The algorithmic approach of Güttler et al. [209], implemented into the interactive table, will enable this module to support the early detection of neurological diseases like Parkinson.

The unknown factor within this idea is the question of the accuracy. The Leap Motion sensor operates in part by two infrared LEDs, by which a reflection of the hand is captured by three infrared sensors. Thereby, the Leap Motion sensor accuracy is in the sub-millimeter range and supports a high sample rate [211]. The Kinect resolution (see Figure 3.40 on page 68), decreases with increasing distance to the target object. On the contrary, the Leap Motion sensor has a very limited recognition area compared to the Kinect solution.

In addition to the gesture analysis implementation, the accuracy of the hand tracking is expected to improve, which enables the system to lower the necessary recognition distance of the Kinect and thus the system sensitivity of the interactive table.

5.2 Conclusion of the Proposed AAL System

The demographic change will worsen the health care situation in the future, which will result in an overtaxing of care facilities and hospitals. Additionally, the percentage of working people will further reduce, which will lead to more job vacancies, especially within demanding mental and physical occupations, e.g. care staff. Even today, care home facilities have problems hiring enough care staff.

Relatives (i.e. the children of the seniors) will be very busy with their own occupational carrier, encouraging the greater need of systems like the proposed "Ambient Heath Monitoring System" in the future. The objective of the proposed solution is to relieve care staff, care facilities and medical institutions. For this purpose, sensors for health data monitoring, information and communication technologies have been successfully implemented into furniture and the home environment, under consideration of the requirements in Table 2.2, of section 2.4.

By this approach, health data can be monitored simply, unobtrusively and quickly (as requested in section 2.4), while the inhabitant of the apartment continues with daily activities. The fever detection is used to monitor the current health condition, whereas the fall detection aims to be a cost-efficient and easy-to-install module, which increases the security and interference time in case of a home accident. The reliability of the proposed fall detection was investigated for weeks, which proved the permanent operation ability and the reliability of the fall detection (as requested in section 2.4). Both concepts (the fever detection and the fall detection) are fully automated. The cuff-free blood pressure monitor is not fully automated, because of the feedback provided by participants in the laboratory test (see section 4.1.3). During the field tests, this statement was confirmed from independent testers (see section 4.2.3). Therefore, the implementation must be still unobtrusive, in order to avoid stigmatization, but the user needs to trigger the measurement. While measuring the ECG curve, the pulse curve is recorded as well. Based on the PTT, the systolic blood pressure is automatically predicted, which enabled an alternative blood pressure measurement, which is cuff-free and noninvasive (as requested in section 2.4). All these implementations communicate with a user interface, which operates on the principle of augmented reality.

Any existing table can become an interactive table, which encourages the user to use e.g. its game applications. Therefore, the prototype is robust against strikes, pitches, stabs on the table plate, and simultaneously enables the user an intuitive gesture controller. The tabletop offers a large surface, so that large buttons and characters can be displayed, as requested in section 2.4. The interactive table aims to activate the user mentally and physically at the same time and provide the “Health Data GUI” program, which displays the measurement results (see section 3.4).

The proposed solution collects health relevant data, e.g. body temperature, fall detection, ECG curve, pulse curve and the systolic blood pressure, which are important values for making a medical diagnosis. From the technical point of view, the technical realization of a remote access via the internet to the proposed “Ambient Health Monitoring System” is no problem, but unfortunately data security issues prevented this development step. However, companies like Patientus [212], which offer ordination hours with physicians via the internet, would be enabled to increase the quality of their service when using the proposed “Ambient Health Monitoring System” including a tele-medical data transfer application. Since there is currently no established internet connection to the proposed “Ambient Health Monitoring System”, it was not possible to implement the automated alerts as already mentioned in section 4.3.

Since it is most likely that the user has to buy (or rent) future AAL solutions, the low-cost aspect was considered during the development of all proposed solutions (as requested in section 2.4). Additionally, the unobtrusive implementation aims to support the furniture or the home environment to look unchanged, while the home is updated with medical sensors. This approach is essential in order to achieve an appropriate user acceptance. The user acceptance of the proposed application (see Figure 5.5) was evaluated in the laboratory and field test with more than 50 %. Comparing to other medical products on the market, e.g. a body scale, all prototypes were even more accepted by the participants (see Table 4.3 at section 4.3), which proves the success of the developed system.

Furthermore, the proposed systems will help to produce future health data bases, which will support the preventive medicine in the future. There are chronic diseases, which could be cured, if the affected would be able to change the life style in old age, e.g. diabetes type II. Systems like the proposed “Ambient Health Monitoring System” will enable the user to spot pathologic changes early and will help to support the change from the bad life style in an earlier life phase, where the chance of curing and prevention is greater.

The documentation of medical data in the home environment, along with in care facilities and hospitals, can be automated in the future by such approaches in order to relieve the care staff the burden to constantly measure. Additionally, such a systems enables physicians to avoid redundant ordination hours, since the system can be further developed in so far that it gives advice, when someone should go to a physician and when it is better to stay at home for curing.

Further improved implementations exists already, e.g. the automated fever detection is currently under development for improved accuracy (see subsection 5.1.1). The cuff-free blood pressure monitor is under development for full automated implementation in the bed (see subsection 5.1.2). The fall detection is at the moment under investigation to determine how a fallen person can be supported to help themselves before an emergency call is triggered, e.g. by a robotic mobile platform (see subsection 5.1.3).

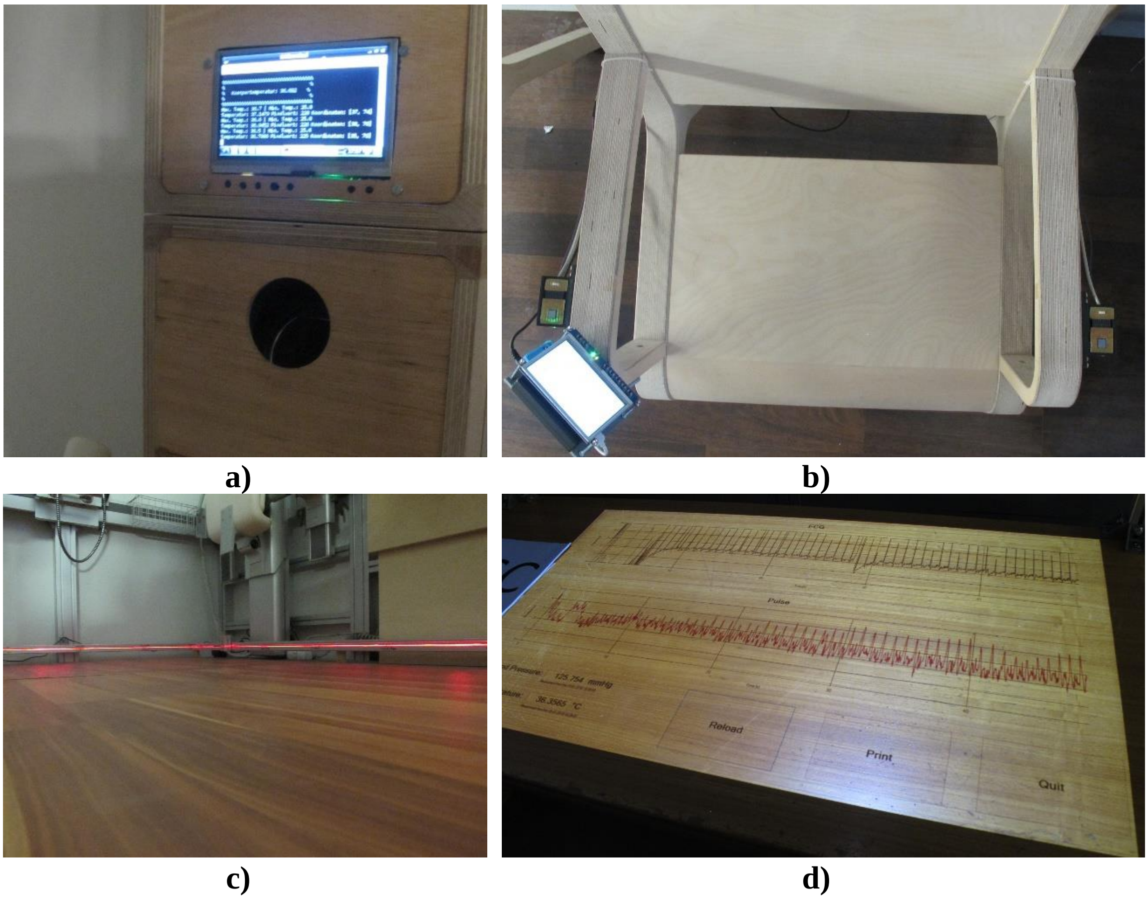


Figure 5.5: Final integrated prototypes in the test apartment after the field test, under consideration of the results state in Table 4.3. (a) The unobtrusive fever detection. (b) The cuff-free blood pressure monitor implemented in a chair. (c) The fall detection implemented in a baseboard. (d) The main user interface displaying the measurement results.

The user interface currently supports the mental and physical activation of elderly by means of augmented reality. There is also a plan to implement a gesture analyzation, which is operating unobtrusively in the background (see subsection 5.1.4).

5.3 Future AAL Research Potential

The car industry was one of the first sectors that started the implementation of such technology into the (car) environment. Today cars can track the fatigue of a driver and soon maybe the stress level as well [213]. Compared to the research of the car industry, the research area of Ambient/Active Assisted Living is still quite young. However, in the next 20 to 40 years, this research area will mature and AAL solutions will enter the public market, care facilities and apartments of the elderly. Young people will also benefit by such AAL solutions as proposed in this work, since the preventive medicine will thereby increase in efficiency.

For tele-medical applications in the future, many research efforts will be investigated regarding topics like data security, data anonymity, and data protection against hackers. Depending on the outcomes of this future research area, the interface to hospitals in the future is maybe possible. In combination with the wearable sensor technology, a seamless 24-hour health monitoring can be realized in the future.

With the combination of smart homes and security technology, AAL will contribute towards a highly advanced home security level in the future, which will trigger the request of such approaches for the working environment. According to Goh et al. [214], it is already important to pay more attention to safety and health issues on construction site. Unfortunately, according to Gyi et al. [215], the communication between the different departments, which are responsible for health and security matters, is quite limited. Therefore, a possible solution is to implement such technology into appropriate devices on construction sites, e.g. cranes, excavators etc. [216], which will increase the security for the operator, as well as all people within the environment (i.e. coworkers and pedestrians etc.).

The potential applications of health data recognition sensors, as used in the "Ambient Health Monitoring System", is unpredictably large for the future. In this work an initial small approach was done by developing a system, which is able to measure the pulse curve, ECG, body temperature, and systolic blood pressure as unobtrusively as possible. Additionally, a fall detection system increases the security of the inhabitant. Furthermore, an interactive table enables the user to have the intuitive control over the entire system, and both physically and mentally activates the user for training purposes, while remaining unobtrusive within the living environment. There are plans to improve the accuracy and reliability of the proposed modules. In the future, additional functionalities such as breath detection, movement analysis, and oxygen saturation measurements will be added to the already existing proposed "Ambient Health Monitoring System".

Appendix

List of Abbreviations

AAL	**Active/Ambient Assisted Living** is a young research area, which tries to develop technologies for the elderly, in order to increase the safety, independency and comfort of seniors.
API	In this work, **Application Programming Interface** are addressing the XBee transmission mode, which ensure the successful data transmission using the ZigBee protocol.
Apps	**Apps** is short for application, which is a synonym for program. Mostly programs on smartphones and IPhone are called apps.
BBB	The **BeagleBone Black** is a single board computer, which has an onboard memory.
BCI	**Brain Computer Interface** is a device, which tries to interpret the EEG recorded electrical activity of the brain, in order to control different applications. The objective of BCIs is to control devices via thoughts.
CT	**Computer Tomography**, is a device which operates based on x-ray in order to plot the inner organs and bone structure of a person. Opposite to a normal x-ray device, a CT is able to depict the entire human body even three dimensional.
C++	A program language based on C. **C++** is compatible with most microcontroller and operating systems.
C#	A programming language based on C and C++. **C#** enables the fast development of desktop programs and application on Windows computers. The disadvantage is the incompatibility with other operating systems.
ECG	**Electrocardiogram** shows the electric activity of the heart and is used in medicine to diagnose potential heart issues.
EEG	**Electroencephalography** measures the electric activity of the human brain. This device is very often used for identifying neurodegenerative diseases, as well as in sleep research.
GUI	The **Graphical User Interface** is mostly the interface between device/system and the user. The **Graphical User Interface** uses graphical designed forms in order to exchange information with the user.

ICT	The **Information and Communication Technology** is addressing all devices, collecting and exchanging data with each other.
PTT	The **Pulse Transit Time** value describes the necessary time a pulse wave travels from the heart to the measurement point. This value change of the PTT behaves linearly to the blood pressure change.
PWV	The **Pulse Wave Velocity** addresses the speed of a blood wave, which is sent out from the left ventricle of the heart. The value change of the PWV behaves linearly to the blood pressure change.
Python	**Python** is a script language, which enables researchers and software developers to design source code and programs. Unlike programming languages, it is not necessary to compile the source code. Therefore, the program **Python** has to be installed, which directly executes the source code.
SDK	**Software Development Kits** are a collection of libraries of specific hardware, which enable developers and researchers to design their own program for the appropriate device. The hardware manufacturer are mostly the SDK provider.
STD	The **Standard deviation** is a value which describes how large the deviation of a measurement series is, which was used to calculate the average value.
Wi-Fi	**Wi-Fi** addresses mostly the wireless connection between computers via a Wi-Fi router.

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