A BCI Controlled Robotic Assistant for Quadriplegic People in Domestic and Professional Life

Sorin M. Grigorescu, Thorsten Lüth, Christos Fragkopoulos, Marco Cyriacks and Axel Gräser

***Abstract*—In this paper, a BCI control approach for the assistive robotic system FRIEND is presented. The objective of the robot is to assist elderly and persons with disabilities in their daily and professional life activities. FRIEND is presented here from an architectural point of view, that is, as an overall robotic device which includes many subareas of research, such as human-robot interaction, perception, object manipulation and path planning, robotic safety, etc. The integration of the hardware and software components is described relative to the interconnections between the various elements of FRIEND and the approach used for human-machine interaction. Since the robotic system is intended to be used especially by patients suffering from a high degree of disability (e.g. patients which are quadriplegic, have muscle diseases or serious paralysis due to strokes or many more other diseases with similar consequences for their independence), an alternative non-invasive *Brain-Computer Interface* (BCI) has been investigated. The FRIEND-BCI paradigm is explained within the overall structure of the robot. The capabilities of the robotic system are demonstrated in three support scenarios, one that deals with *Activities of Daily Living* (ADL) and two that are taking place in a rehabilitation workshop. The proposed robot was clinically evaluated through different tests that directly measure task execution time and hardware performance, as well as the acceptance of the robot by the end-users.**

***Index Terms*—Assistive robotics, Wheelchair-mounted manipulators, Brain-computer interfaces.**

I. Introduction

In recent years, especially in the last two decades, the worldwide healthcare community showed a high interest on rehabilitation robotic systems that can partially overtake tasks that usually are carried out by care-giving personnel [1]. The growing interest in this field of robotics is due to the fact that in a large number of healthcare areas there is a lack of trained personnel. Parallel to this, the number of elderly and persons with disabilities is increasing every year. In industrialized countries, like US, Europe, Japan or Canada, the number of estimated persons which suffer from a certain disability is approx. 75 mil, whereas the number of elderly is approx. 130 mil [2]. A certain percentage of persons from the mentioned statistics suffer from a form of severe disability which requires a 24h/day assistance from trained personnel. In Germany alone, the number of quadriplegic persons is estimated to be at around 6000, while new cases of *Amyotrophic Lateral Sclerosis* (ALS) are increasing every year by approx. 1400 [3]. These groups of persons with high disabilities currently need personal support for 24h/day and long for any technical system which could give them a temporal independence from personal assistance and may be used also for functional restoration.

Basically, although the field of rehabilitation robotics includes many aspects, such robotic systems are classified into two categories: *physical therapy and training robots* and *robotic aids for people with disabilities*. The goal of therapy robots is to help patients recover from different forms of accidents and maladies. On the other hand, assistive robots are there mainly to support persons with disabilities in *Activities of Daily Living* (ADL) and professional life. Assistive robots are further classified depending on the type of target users, namely fix manipulation aids, wheelchair-mounted manipulator systems, mobile autonomous and wheelchair navigation platforms, walking assistants and cognitive aids [1]. This classification represents an important aspect on the marketing strategies of such robots, since the goal would be not to obtain systems suitable only for a narrow range of tasks, but to build standardized robots that can be used in a broad range of application scenarios, thus ensuring also a lowering of manufacturing costs. The standardization is actually seriously taken into consideration by the service robotics community which currently lacks a standardized system to be used for research and development. Several institutes and companies took a step forward in this direction, such as Willow Garage in the US [4], which is responsible for building the PR2 robot, Fraunhofer Institute in Germany [5] with the Care-O-Bot platform, or the Institute of Automation (IAT) in Bremen with the FRIEND system described in this paper. Also, a problem in the rehabilitation robotics community, as well as in the service robotics one, is that mostly all teams working in this field start developing systems from scratch over and over again. Hence, no system becomes available for the end users. The goal of the FRIEND project described in this paper is to offer a basis for scientists in order to boost research in the growing field of rehabilitation robots.

The care-providing robot FRIEND (*Functional Robot with dexterous arm and user-frIENdly interface for Disabled people*), illustrated in Fig. 1 and commercially available since the beginning of 2010, is a semiautonomous robot designed to support disabled and elderly people in their daily life activities, like preparing and serving a meal, eating, drinking, or reintegration into professional life. FRIEND, which

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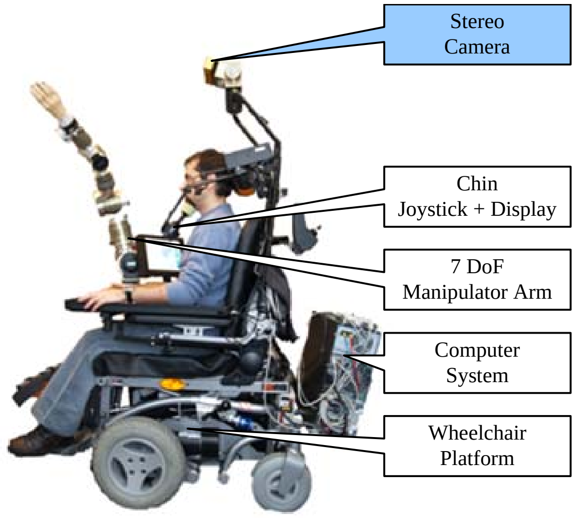


Fig. 1. The care-providing robotic system FRIEND.

fells into the category of wheelchair-mounted manipulator arm systems, enables a disabled user to perform a large set of tasks in daily and professional life self-determined and without any help from other people like therapists or nursing staff. Usually, patients with disabilities have to rely on care-giving personnel 24 h/day. The independence given to them through the FRIEND system presently aims to a minimum of 90 uninterrupted minutes, where certain tasks, commonly performed by trained persons, are transferred to the robot. The achieved independence is a proven benefit in the social life of the patients.

The FRIEND system is the result of more than a decade's work in the field of assistive robotics performed at the Institute of Automation from the University of Bremen in Germany. The robotic system presented in this paper is the 3rd generation of assistive robots designed at the institute, after FRIEND I [6], built in 1997, and FRIEND II [7], built in 2003. Throughout the paper, the 3rd FRIEND system will be mentioned only as FRIEND. A comparison between the three robots will be given in Section II.

In case of assistive robots such as FRIEND, one important part of their functionalities is related to the way in which the user interacts with the robot. The interaction is also dependent on the type of disability. For example, if the patient still has some motoric functions left, then, special input devices can be used to control the robotic system. Patients that are still able to move their head can interact with the robot via a chin joystick. In this paper we will concentrate on the usage of FRIEND by persons who are totally paralyzed below the neck and cannot move their head, shoulders and limbs. Therefore, an alternative input method is necessary to provide these persons the ability to control the robotic system. In recent years, a major progress in the field of *Brain-Computer Interfaces* (BCIs) has been encountered [8]. BCIs analyzes specific patterns in the user's brain activity and converts them into control commands for a variety of applications. The signal acquisition in BCIs can be classified into *invasive*, that acquire brain signals from sensors directly placed on (also referred to be *semi-invasive*) or in the brain, and *non-invasive*, which interpret brain activity patterns through an *electroencephalogram* (EEG). Due to the complexity of the human brain and its neuronal activity, the signal processing as well as the resultant BCI can be characterized as a slow form of communication; hence most BCIs have been used to control software applications. However, clinical studies show that the usage of BCI technology leads to a higher degree of autonomy and could improve the quality of life for people with severe motor disabilities [9]. The accuracy of BCI systems nowadays is stated to be very high for different approaches (around 90%) and therefore, based on the promising results with target users and independent of the low *Information Transfer Rate* (ITR), controlling robotic applications with the help of a BCI is a recently grown area in the BCI community. The expertise of the Institute of Automation in the field of BCI leaded to the integration of this alternative communication approach into FRIEND. An EEG based signal acquisition has been chosen as a way of interaction between the user and the robot.

The scope of this paper is to offer a *system level robotics article* which describes the hardware and software building blocks of FRIEND. The work presented here is the merging of a high number of research fields such as robotic system design, vision and perception, motion planning and control, software control architectures, human-machine interaction, BCI, safety, neurorehabilitation, psychology, etc. A detailed coverage of all the methods used in FRIEND would result in a large document. The authors therefore describe the concept of the current FRIEND system and its most important characteristics in comparison to other state-of-the-art assistive robots for persons with disabilities.

The rest of the paper is organized as follows. In Section II the state of the art in assistive robotics and BCI-robot interaction for the disabled will be given, followed by the description of the FRIEND concept in Section III. The initial support scenarios developed for FRIEND are explained in Section IV, whereas the approaches used for vision and motion planning are given in Section V. Section VI covers the safety mechanism implemented within the robot. Finally, a clinical evaluation of FRIEND is detailed in Section VII, before the conclusions from Section VIII.

II. Overview of the State of the Art

The history of rehabilitation robotics is strictly related to the basic field of robotics, although it did not obtain the same success as the one achieved by industrial robots. In this section an overview of the state-of-the-art in assistive robotic devices for persons with disabilities will be given, followed by a presentation of robots controlled through the BCI paradigm.

A. Assistive Robots

There are some commercial systems and research prototypes available which already demonstrate progress in the area of rehabilitation robots. However, the main focus of these systems is usually put on wheelchair navigation [10], thus only a few approaches concentrating on manipulation for the disabled. Known systems of the latter category are mainly limited by the range of applications, that is, they do not consider complete support scenarios for impaired users, but rather provide one or a few very specialized tasks, like for example the eating support device *Handy 1* [11] or other similar devices, such as the *Winsford Feeder* from RTD-Applied Resources Co., New Jersey, US, the *Neater Eater* from Buxton, UK or the meal assistance device *MySpoon* from Secom Co. Ltd., Tokyo, Japan. Other restrictions of existing systems are the lack of dexterity of manipulation capabilities, as e.g. RAPTOR possesses only a 4 *Degrees-of-Freedom* (DoF) robotic arm, or the MANUS system [12] with 6-DoF and no capability of autonomous operation.

Thus, there are merely a few relevant known robots for assisted living of persons with disabilities. In other words, there is no all-embracing robot system known which focuses on the special needs of disabled and/or elderly people in private as well as in professional life. Currently, *Handy 1* and MANUS are the mostly sold commercial products. They were developed for the use by disabled patients but have limited application due to their low degree of automation. *Handy 1*, developed within the *European Community* (EC) funded *Robotic Aid to Independent Living* (RAIL) project, only enables five specialized and similar tasks. It was primarily developed for food intake and was then extended to support drinking, shaving, make-up and painting. MANUS, developed by Exact Dynamics in the Netherlands, is mainly a light weight robot arm with no autonomous functionality and no support for complex autonomous task executions. Potential users are severely disabled people with limited, but still existing, hand function [13]. The Care-O-Bot system, developed by Fraunhofer IPA in Germany, represents a general purpose mobile manipulation platform [5]. Although several functionalities for assisting people in daily living are available, Care-O-Bot is not specifically designed for the needs of the persons with disabilities and elderly.

In the field of wheelchair-mounted manipulator systems, one core concept, also used in FRIEND, is the so-called *Semi-Autonomy*, or *Shared Responsibility*. This implies the involvement of the cognitive capabilities of the user in the functionalities of the robotic system (e.g. if an object of interest could not be detected by the vision system, the robot control architecture could ask the user either to identify the object and thus support the object recognition system, or even to manually drive the manipulator arm in order to bring it to a grasping position). Such methods, sometimes named "human-in-the-loop" in the work of H.A. Yanco [14], where also implied in robotic platforms such as the *KAIST Rehabilitation Engineering Service System* (KARES) [15], developed within the *Human Welfare Robotics Center* in Daejeon, South Korea. A similar concept was also used in France within the *Assistance by VIsion for Seizure of Objects* (AVISO) project [16].

The characteristics of the current FRIEND prototype are represented by major improvements in comparison to its predecessors, the robots FRIEND I [6] and FRIEND II [7]. All the three systems were designed and built at the IAT under different funded projects. Basically, all the robots consist of a manipulator arm mounted on an electrical wheelchair and various sensors needed to understand the surrounding environment for the purpose of autonomous manipulator path planning and object grasping. The first FRIEND was equipped with a MANUS arm, whereas the second with a 7-DoF AMTEC manipulator. Although the idea stayed the same, the 3rd generation of FRIEND represents a standard platform to be used as a general basis in developing rehabilitation scenarios for the disabled and elderly. In comparison to its previous versions, the last FRIEND was ergonomically designed by a consortium formed of designers, medical doctors and engineers. The components previously used were replaced with state-of-the-art robotic modules, such as the *Light Weight Arm* 3 (LWA3) from Schunk®, or the NEMO wheelchair from Meyra®. Parallel to the improved hardware, the robot control methods were also improved with components such as the newly introduced ROVIS (*RObust machine VIsion for Service robotics*) [17] system for robust image processing and a novel *Random Rapidly exploring Trees* (RRT) motion planner [18] to be used in connection to the visual data delivered by ROVIS. Also, the overall software structure of FRIEND was redesigned within a so-called *process model for development of semiautonomous service robots* [19].

B. Brain-Computer Interfaces in Rehabilitation Robotics

In this subsection we will focus on the control of robotic systems through BCI devices. Due to their ITR below 100 Bits/min., today's BCIs are not well suited for a low level control of a robot, e.g. to control all joints directly through a BCI. Such complicated tasks can be time consuming and therefore fatiguing and frustrating. In a shared control concept, a BCI based on *Steady-State Visual Evoked Potentials* (SSVEP) was used to send high-level commands to the rehabilitation robotic system FRIEND II [20]. A different approach (P300) uses the oddball paradigm [21] to generate one single command on a high-abstraction level. Starting from the idea of manipulating smart environments [22], a person can move a wheelchair to a predefined goal position [23]. In [24] it is demonstrated that a humanoid robot can be controlled in a pick-up and place scenario with high accuracy (95%) based on a P300 EEG interface. The BCI is used to select the desired object and location via visual feedback from the robot's cameras.

On the other hand, for controlling robotic systems on a lower abstraction level, different strategies are implied. A finite state machine approach used to start and stop a wheelchair movement is discussed in [25]. As shown, a direct replace of joystick commands is difficult to handle via the BCI paradigm. In [26] the timing was investigated in a BCI-controlled pinball game. Four subjects were able to control the paddles in a reasonable way but, in addition, the accuracy was decreased due to false hits (the paddle was moved although the ball was not nearby). In case of mobile robotic applications such as autonomous wheelchairs, a "pseudo-joystick" control scheme seems to provide better results. A mobile platform can be moved to a nearby target that fits directional commands (e.g. "right", "left", "straight", "backwards") [27], [28]. Due to additional intelligence in the wheelchair (e.g. obstacle avoidance), these applications become semi-autonomous. A continuous kinematic control of a robot arm is only possible with invasive electrodes or electrode arrays [29]. Due to the very low ITR in non-invasive approaches, the low-level control of a robotic arm is practically reduced to the control of the robot's end-effector [30]. To summarize, relative to the mentioned state of the art, the FRIEND system, controlled via the BCI paradigm, is intended to provide a complete platform for implementing robotic tasks for the disabled and elderly people.

III. The FRIEND Concept

In this section, the overall user-oriented design of the FRIEND robot, from both the hardware and the software point of view, will be presented.

A. Hardware Design and Integration

The FRIEND system consists of a large number of components that are linked together for the purpose of reliable object grasping and manipulation. A view of FRIEND is shown in Fig. 1, where the main hardware elements are the standard wheelchair platform that provides a basis for ergonomic integration of robotic components, a 7-DoF LWA equipped with a gripper and sensors (force torque sensor and an anti-slipping mechanism) capable of handling objects up to 5 kg, a stereo camera system mounted on a 2-DoF *Pan-Tilt Head* (PTH) unit used for environment understanding, the *Human-Machine Interface* (HMI), an intelligent wheelchair tray for precise measurements of position, shape, size and weight of objects placed directly in front of the user, a *TFT-Display* used as a visual output device for the user and as an input device for care giving personnel through its touch panel, communication with appliances via remote (wireless) utilities (e.g. infrared, Bluetooth, RFID) and the computing system, represented by a standard PC computer with 8GB of RAM and two Intel® XEON QuadCores microprocessors, each working at a speed of 2.33GHz. The HMI is capable of handling different interfacing technologies, such as specific control inputs like chin and force joysticks used as input devices for users which have certain degree of movement of neck, arm or fingers (incomplete spinal cord injury), speech recognition and synthesizer system and a BCI used to derive input commands directly from the brainwaves of the user.

The interdependencies between the various components of FRIEND can be seen in Fig. 2, where the main coordinate transformations within the robotic system are illustrated. Within autonomous task execution, the goal of FRIEND is to detect 3D positions of objects of interest, $\{O\}$, in order to grasp and handle them. The *position and orientation* (pose) detection of $\{O\}$ is performed through the vision system with respect to the world coordinate system of the robot $\{W\}$, in this case considered as the robot's first, or base, joint. The relation between $\{W\}$ and the camera pose $\{C\}$ is obtained via the ${}^{C}_{W}T$ transformation, whereas the camera's orientation is controlled by modifying the pitch of the coordinate system $\{PTH_{Pan}\}$ and the yaw of $\{PTH_{Tilt}\}$.

Since the wheels and the manipulator arm are fixed to the electrical wheelchair and connected to the seat of the user through a suspension system, as depicted in Fig. 2, the

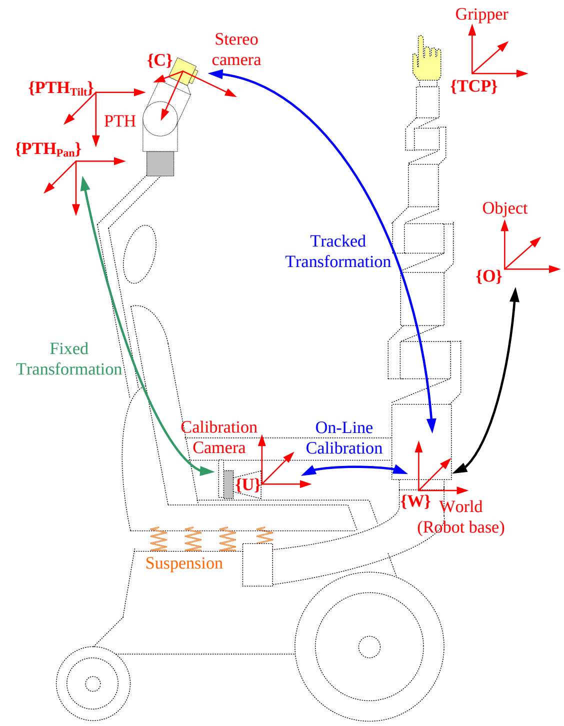


Fig. 2. Basic structure and coordinate transformations within FRIEND.

camera's pose varies considerably with respect to the world coordinate system $\{W\}$. This phenomenon occurs, for example, when the wheelchair, or the user in the seat, is moving. In order to cope with this problem the world coordinate system $\{W\}$ is tracked using the calibration camera $\{U\}$ mounted on the seat with respect to $\{PTH_{Pan}\}$. By on-line determining the pose of $\{U\}$, the final ${}^{C}_{W}T$ can be calculated as:

$$ {}^{C}_{W}T = {}^{C}_{PTH_{Tilt}}T \cdot {}^{PTH_{Tilt}}_{PTH_{Pan}}T \cdot {}^{PTH_{Pan}}_{U}T \cdot {}^{U}_{W}T. \quad (1) $$

Once the required coordinate transformations are known, the recognition of an object of interest $\{O\}$ can be performed, as will be explained in Section V. After recognition and 3D reconstruction, the object $\{O\}$ is further grasped and handled by the manipulator's gripper, which has the tool center point coordinates at $\{TCP\}$.

B. Overall Control Architecture

The control of a complex robot like FRIEND can only be achieved through an appropriate control framework. The used architecture, entitled MASSiVE (*MultiLayer Architecture for SemiAutonomous Service Robots with Verified Task Execution*), represents a distributed robotic control system which combines reactive behavior with classical artificial intelligence based task planning capabilities [7]. The MASSiVE is divided into four specific modules: HMI, *Reactive Layer*, *Sequencer* and *World Model*.

The HMI operates at the user interaction level. User commands are acquired with the help of different input methods, such as BCI, and translated further into machine language for interpretation [7], [30]. The processing algorithms that convert

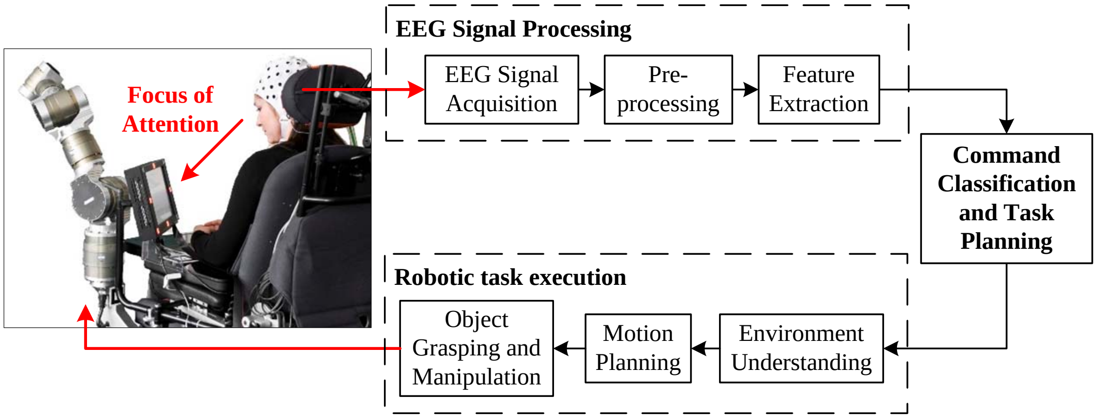


Fig. 3. The *User-BCI Loop* as a mean of interaction in FRIEND.

a user request into robot actions reside in the *Reactive Layer*. Here, the data collected from different *Sensors*, such as the *Machine Vision* module, is processed in order to "understand the environment". Further, the obtained information is used to convert the user's command into actions through the available *Manipulative Skills* and the 7-DoF manipulator. The sequence of operations needed to perform a specific task is generated by the *Sequencer* module.

C. The User-BCI Loop

For people suffering from a severe disability, the common interaction method used in FRIEND is the so-called User-BCI Loop, depicted in Fig. 3. The transition between the EEG signals and a robotic task is handled by the *Command Classification and Task Planning* module, which, based on the classified EEG pattern, generates the necessary task sequence needed to fulfill the requested robotic operation. Task knowledge information is further passed to the *Environment Understanding* and *Motion Planning* algorithms. The ideal solution of a BCI control would not need any external stimulus devices to elicit a classifiable brain activity, that is, the user controls the robotic manipulator just with his thoughts. In the BCI community, *Motor Imagery* [31] is established as such a type of communication. The patient imagines a hand, feet or tongue movement that can be detected in his brain activity and converted into a corresponding control command. Nevertheless, a stimulus based BCI paradigm allows the distinction between more different commands. Among all possible brain activity patterns, SSVEPs are reported to produce the highest ITR [32].

SSVEPs can be detected in the brain activity of the visual cortex. They are periodic components of the same frequency at a continuously flickering visual stimulus, as well as a number of harmonic frequencies that can be obtained when a person is focusing attention on that stimulus [33]. The strongest SSVEP response can be measured for stimulation frequencies around 15Hz [34]. The frequency separation of two frequencies can be lowered to $0.2Hz$ allowing a distinguishable SSVEP response [35].

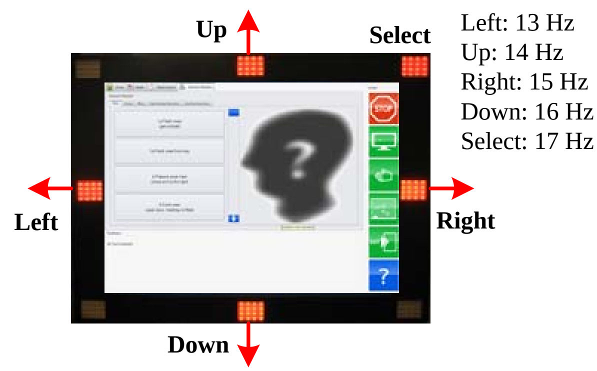


Fig. 4. The principle of FRIEND control through an SSVEP based BCI.

1) User Interface: In order to elicit SSVEPs in the user's brain activity, a visual stimulus is necessary. This stimulus might be flickering boxes on a display or light emitting diodes. In case of the FRIEND system, the visual stimulus consists of a frame placed around the TFT-Display of the system, as seen in Fig. 4. The LEDs are flickering with individual frequencies related to different control commands. In a cursor-based control, five LEDs are used (left, right, up, down, select). With the help of this visual stimulus, the user can control a cursor stepwise on the display and thus select different robotic tasks, surf the internet, or directly control the robot's end-effector $\{TCP\}$.

In order to reduce the number of BCI user interactions, an intelligent cursor movement was implemented. The main idea behind this concept is to automatically adapt the step width of the cursor, which gives its next position on the screen, depending on the current location and the selected BCI command. Namely, the step width is directly related to the layout of the HMI dialog, as illustrated in Fig. 4. As it will be shown in Section VII, the proposed HMI interface performed optimally with respect to its ITR, with an average value of $9.335s$.

2) Signal Processing: The acquired brain signal is spatial filtered with the *Minimum Energy Combination* [36] in order to magnify the SSVEP response and to decrease the nuisance signals coming from the environment, the electrodes or other brain processes. That kind of spatial filtering was validated in different applications beforehand [37]. In the resulting filtered signal, the SSVEP power is estimated for each frequency used as a stimulus of the extracted features similar to the squared *Discrete Fourier Transform* (DFT) [36]. These estimations for all frequencies N_f are then normalized into probabilities [37]:

$$p_i = \frac{\hat{P}_i}{\sum_{j=1}^{j=N_f} \hat{P}_j} \quad \text{with} \quad \sum_{i=1}^{i=N_f} p_i = 1 \tag{2}$$

where $\hat{P}_i$ is the *i*-th signal power estimation and $1 \leq i \leq N_f$. An unsupervised threshold based linear classifier is further used to classify the frequency on which the user is assumed to focus his attention. Based on practical investigations, the five stimuli classification threshold β is proposed to be set to $\beta = 0.35$.

D. Task Execution in Friend

Once the desired command has been chosen through a series of BCI commands, the *Sequencer* has to interpret and translate it to the appropriate sequence of actions that has to be called in order to fulfill the robotic task [7].

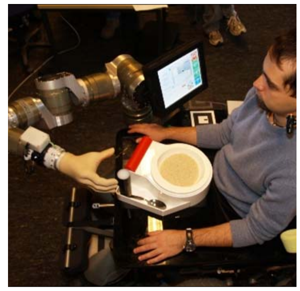
The execution of a task in FRIEND is divided into two methods: *Autonomous* and *Shared Control Execution*. In the situation of autonomous execution, all the called operations, such as object recognition or object manipulation, will be performed autonomously by the robot. If, for some reason, one of these operations fails (e.g. an object was not detected by the machine vision system), the control architecture switches to shared control mode and involves the cognitive capabilities of the user in the current robotic task. In this case, the user can support the system by giving certain information related to the environment, like an approximate position of an undetected object, thus aiding the vision module in locating the object. This "human-in-the-loop" concept [14] is also used in performing certain tuning operations, like the adjustment of the predefined position of a spoon in front of the user's mouth for feeding.

IV. Robotic Support Scenarios

To prove the benefit of FRIEND and show the usefulness to prospective users, three basic support scenarios were implemented and tested at different levels. The scenarios have been defined within a consortium of medical therapists, engineers and designers. The goal of these scenarios is to set a basis for further development of service robotic tasks and to demonstrate the usability of the already available skills. Example snapshots of FRIEND operating within the proposed scenarios are illustrated in Fig. 5. The description of the three scenarios is further given, accompanied with explanatory use case diagrams.

A. Activities of Daily Living (ADL Scenario)

The ADL scenario, with its use case diagrams presented in Fig. 6(a,b), enables the user to prepare and serve meals or beverages. It represents the types of activities that a person performs in a domestic environment with typical household objects like refrigerators, bottles, glasses, meal-trays, etc.



(a)

(b)

Fig. 5. Typical service robotic scenes from the FRIEND environment. (a) Activities of daily living (e.g. feeding). (b) Working at a library desk.

The basic concept of the ADL scenario is the sequence of operations needed to "pour-in and serve a drink". As can be seen from Fig. 6(a), there are three actions that can be selected by the user. Firstly, the goal of the pour-in operation is to pour the drink from a recipient (e.g. a bottle) into a glass located onto the FRIEND's intelligent tray. The location of the recipient must be in the grasping range of the manipulator, such as within a refrigerator, on a nearby table, or on the system's tray. The poses of both the recipient and glass are obtained through the machine vision system. Once these are known, the manipulator can grasp the recipient and pours its content into the glass. The user can now drink the beverage by selecting the serve beverage action. This procedure uses the robotic arm to grasp the glass and bring it to the vicinity of the user's mouth. The beverage can now be drunk through a straw. Finally, the scenario ends when the user chooses the "place down glass" command.

The "serve a meal" scenario, with its components depicted in Fig. 6(b), is actually an extension of the preparing and serving a drink operations. In this case the complexity of the tasks is increased, since the number of involved objects and operations is higher. At the beginning of the scenario, the user selects the grasping of a cold meal from a container (e.g. refrigerator). Having in mind the current manipulation capabilities of LWA manipulators, the cold meal was stored in a specially designed meal-tray which can be grasped by the robotic arm. A snapshot of the meal-tray on the FRIEND's tray is shown in Fig. 5(a). As can be seen, the meal-tray and the additional spoon is equipped with handles that can be reliably grasped by the arm, thus ensuring a good robotic grip and an increased user safety. After its grasping, the meal is placed within a microwave oven for heating. Again, at every step, the poses of the meal-tray, as well as of the containers (e.g. refrigerator and microwave oven), are determined through the machine vision system. The doors of the containers are opened through an appliance communication device and closed by the robotic arm. Once the meal is heated, it is again grasped by the robot, placed in front of the user and the lid covering it is removed, as shown in Fig. 5(a). Using the spoon present on the tray, the meal is served via a repetitive action which brings the food to the mouth of the user. Finally, the scenario

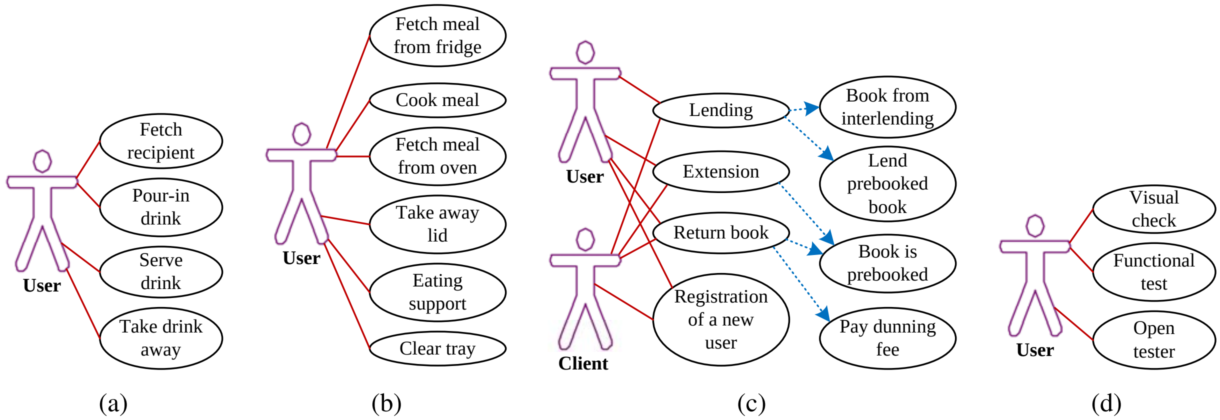


Fig. 6. Use case diagrams of the FRIEND support scenarios. (a) Prepare and serve a beverage. (b) Prepare and serve a meal. (c) Working at a library service desk. (d) Functional check of work pieces.

is ended by clearing the system's tray. Snapshots from the described operational sequence are presented in Fig. 7.

The spectrum of operations included in the ADL scenario covers a broad range of tasks that can be fulfilled by the users in a typical household environment. Thus, the basics set of components in the proposed demonstrator scenario can be used to implement other related tasks.

B. Working at a Library Service Desk

The second support scenario is a professional one, where the user is working at a library desk equipped with a laser scanner for reading IDs of books and customer IDs, as shown in Fig. 5(b). The task of the FRIEND's user is to handle outgoing and incoming books and other tasks at a library desk. A positive aspect of the library scenario is that the user has to interact with people, thus making his recovery and reintegration in professional life easier.

As can be seen from the use case in Fig. 6(c), the library scenario deals with many tasks required for interaction with the client, such as lending and lending extensions of books, manage their returns, or register a new library costumer. Although the number of operations seems relatively high, the basic required robotic tasks are book recognition and 3D reconstruction through the machine vision system and its manipulation using the robot arm. Currently, the library scenario is tested within a laboratory, tests which will be followed by their actual implementation in a real library environment.

C. Functional Check of Work Pieces

The third support scenario considers working in a maintenance workshop. Here, the user has to perform quality control tasks, like checking of electronic keypads for malfunctioning, as shown in the use case from Fig. 6(d).

In order to achieve the proposed tasks, two main operations have been implemented, namely, the *visual* and *functional check* of electronic keypads. Initially the keypads are placed within a container, or magazine, which has the pose determined via the FRIEND's vision system. In visual checking, a keypad is grasped by the robot and moved in front of the user. Further, functional checking is performed using a special device, or tester, in which the keypad must be inserted by the robot. The device proves that the interconnections within the electronic components are working. Once the checking is over, the keypad is released from the tester by the manipulator arm, grasped and placed in the keypads container.

D. Components Modeling

Keeping in mind the complexity of the scenarios, the FRIEND system has to deal with a variety of objects, including bottles, glasses, meal-trays, books, tables and containers (e.g. refrigerators, microwave ovens, etc.). From the modeling point of view, the objects to be recognized and handled are classified into two categories: *Container Objects*, such as the fridge, microwave oven, library, or workshop desk, and *Objects to be Manipulated* such as bottles, glasses, meal-trays and books. The scenario-related task knowledge is provided by the *Sequencer* through *object classes*. Whenever the *Sequencer* activates a system operation, relevant information of object classes involved in the operation are made available in the *World Model*. This information is specified via object class characteristics encoded in an extensible ontology. A simplified section of this ontology is depicted in Fig. 8, where the objects involved in the ADL as well as in the library scenario are pointed out. In case of the fridge, which is a part of the ADL scenario, the characteristics *IsContainer*, *HasShelves* and *HasDoor* will be made available. For the tray with the meal, the knowledge about its components *Plate*, *Spoon* and *Lid* is supplied. All the objects that take part in the scenarios, as well as the whole FRIEND robot, are modeled within a so-called *Mapped Virtual Reality* (MVR) system. The data stored in the *World Model* is rendered within the MVR for the purpose of manipulator motion planning, as will be explained in the next section.

V. Methods for Robust Robotic Manipulation

The optimal functioning of the FRIEND system is strictly dependent on the available low level operations used in recognizing and reconstructing imaged objects and also on the way the motion of the robotic arm is planned. In this section, the approaches used in FRIEND for these issues are explained.

Fig. 7. Sequences of robotic operations within the "prepare and serve a meal" support scenario.

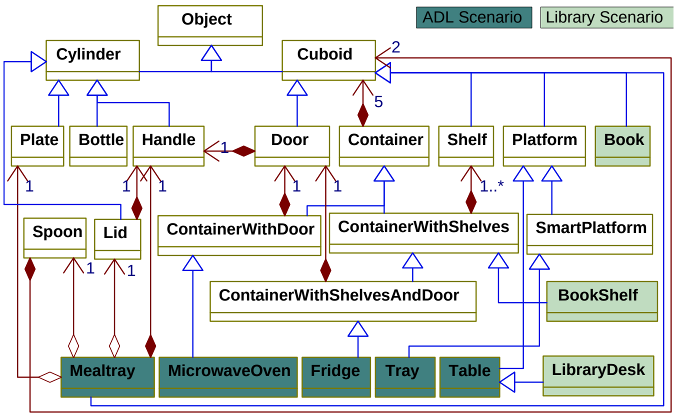


Fig. 8. Hierarchical ontology of objects that are involved in two rehabilitation robotic scenarios (ADL and library scenarios).

A. Robust Machine Vision for Service Robotics

In order to reliably grasp and handle an object $\{O\}$, its pose has to be precisely reconstructed within the MVR system, where the actual motion of the manipulator is planned. This reconstruction is achieved through the ROVIS machine vision architecture [17].

The ROVIS hardware is composed of a Bumblebee® global stereo camera attached to the 2-DoF PTH unit, mounted on a rack behind the user, as illustrated in Fig. 1. The precision and good 3D reconstruction results achieved via the stereo camera made it the most suited vision hardware component, in comparison to technologies such as *Laser* or *Time-of-Flight* (ToF) cameras.

The system is initialized through a camera calibration procedure. The first step in the *ROVIS Object Recognition and Reconstruction Chain* is the definition of the image *Region of Interest* (ROI) containing the objects to be recognized. The advantage of using an image ROI for further processing is that it minimizes the object search area in the 2D stereo image and reduces computation time. Depending on the number of detected objects, the user of FRIEND has to select the desired one through the BCI interface described in Section III. On the calculated image ROI, 2D feature-based object recognition is applied with the goal of extracting so-called *object feature points*. These points are inputs to the *3D reconstruction* module which calculates the object's pose. Finally, the 3D reconstructed objects are stored in the *World Model* and are used by the manipulative algorithms to plan manipulative tasks.

The success of object manipulation depends on the precision of 3D object reconstruction, which, on the other hand, relies on the precision of 2D feature extraction. In order to get a reliable 3D reconstruction result, the idea of inclusion of feedback control at image processing level has been adopted [17].

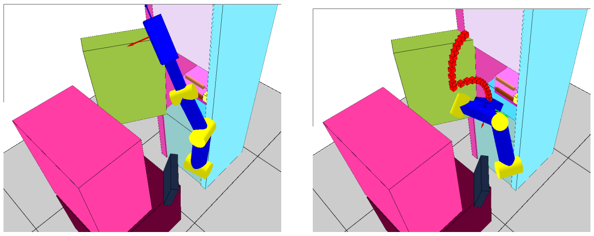
B. Collision-Free Motion Planning for Human Friendly Robot Interaction

Robust and fast motion planning algorithms are a demand in rehabilitation robots like FRIEND. Since FRIEND operates in clustered environments, the probability of collision during operation between the robot and the objects in the environment is high. These reasons motivate the implementation of a safe collision-free motion planner which can provide optimal $\{TCP\}$ trajectories based on visual information delivered by ROVIS [18].

1) Planning and Object Grasping: The proposed motion planner for FRIEND, entitled *Cell Based Bi-directional Rapidly Random exploring Trees* (CellBiRRT), functions in *Configuration Space* (CSpace) [18], since it is easier to control joints velocities then the velocities of the TCP. In principle, CellBiRRT works by dividing the Cartesian space into cells, each cell having a position (x, y, z) and orientation $(roll, pitch, yaw)$. For each iteration, the algorithm tries to expand towards the goal configuration Q_goal. The planner chooses the most appropriate cell and tries with small random variations to move in an area which is close to a generated cell. After a number of iterations, the planner delivers either success or failure if the time constraints are broken.

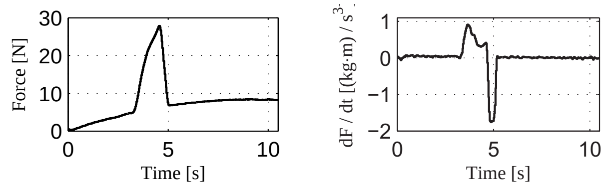
Within the MVR, the mapped visual data is divided into *the object to be manipulated* and *obstacles*. For CellBiRRT, each obstacle is a possible collision area. In order for the robot to grasp an object, it must first find a suitable grasping configuration for the manipulator arm, which strictly depends on the required pose of the TCP. Depending on the object to be manipulated, we have considered a hybrid system, were the grasping approaches are divided into *dynamic* and *static*. In the dynamic approach, an object can be grasped (e.g. bottle, glass, etc.) using a number of redundant configurations of the manipulator arm. The grasping configuration is thus dynamically calculated based on the shape of the object, resulting in a coordinate frame attached to the grasping point of the object. On the other hand, the static case deals with objects that can be manipulated through only one robotic configuration. An example of such an object is the meal-tray from the "prepare and serve a meal" scenario, which has to be manipulated in such a way that the meal is not spilled down. In this approach, a relative grasping frame is off-line calculated by manually moving the robot arm in the grasping pose, as:

$$ {}^{W}_{TCP}T = {}^{W}_{O}T \cdot {}^{O}_{TCP}T, \tag{3} $$



(a) (b)

Fig. 9. Trajectory result for a manipulative path planning experiment. (a) Starting pose. (b) Goal pose.



(a) (b)

Fig. 10. Measured force during manipulator-surface contact (a) and its derivative (b).

where, ${}^{W}_{TCP}T$ is the relative frame. By varying the ${}^{W}_{O}T$ transformation, the optimal relative grasping frame can be calculated. Once the frame is acquired, it is stored in the system's World Model for later on-line usage.

During on-line operation, for each inverse kinematics configuration, a different collision-free grasping frame is obtained. The optimal pose of the robot arm is the optimal kinematic choice from a set of collision free configurations previously calculated using Eq. 3 and an inverse kinematics model. This kinematic choice is obtained by optimizing the following cost function:

$$J = A \cdot d_c + (1 - A) \cdot d_{min}, \tag{4}$$

where, $A \in [0, 1]$ is a weighting factor, d_c is the configuration space distance metric between two kinematic configurations and d_min the minimum allowed distance from the manipulator to the obstacles. In our implementation we have chosen $d_min = 10mm$. Depending on the choice of A, the calculated optimal solution can be closer to the initial starting pose of the manipulator, or one with an average maximum distance from the arm to the obstacles.

The grasping motion of the manipulator arm is also divided into a *coarse* and a *fine* approach motion. The coarse approach is based solely on the visual data available in the MVR and is aimed at moving the arm closer to the object grasping pose. Once this pose has been reached, the planner switches to a fine approach mode where additional sensory information from the gripper's 6-DoF *Force Torque* (FT) sensor is used for grasping the object of interest. Mainly, the objective of the FT sensor is to detect if the gripper has made contact with the object.

The motion trajectories of the manipulator are planned in the MVR system, which provides results related to the distances between the rendered objects. In order to overcome inaccuracies introduced by different rendering errors, the manipulator is moving around the obstacles with a minimum tolerance distance of $10mm$. An example of a planned trajectory is illustrated in Fig. 9.

2) Handling Grasped Objects: Also, another ability required by a motion planner is its capability to handle grasped objects. For example, a glass should be kept upright in order not to spill the drink. To achieve this, the proposed planner checks not only possible collisions, but also if the arm is inside manipulative limits.

This constraint is guaranteed by the motion planner itself. Being an RRT planner, the main benefit of CellBiRRT is that it can cope with constraints like position and orientation of the TCP. From the off-line calculated relative frame, the planner knows if a certain object (e.g. glass, meal-tray, etc.) must be handled in a special way. In this case, the manipulator's trajectories are generated within the considered pose constrains. For handling such objects, we have considered in our implementation an orientation tolerance of $10°$.

VI. Safety Issues in FRIEND

One important feature of rehabilitation robots is their safety with respect to the user [38]. The safety issue is approached in FRIEND from the hardware, as well as from the software points of view. Currently there are no safety standards for service and rehabilitation robotics. The lack of such standardization is also due to the fact that there are a relatively low number of commercially available robotic platforms on the market, most of them still being research projects.

The main purpose of the safety mechanisms in FRIEND is to avoid harming the patient with the robotic arm. Firstly, this is achieved by monitoring the communication of the arm's joints with the motion planning component described in Section V. Following automation safety standards, the communication is supervised by a so-called *Watchdog Unit* [38] which verifies the consistence of the information packages transferred between the arm and the control unit. If in any case this information is not consistent with the ideal communication, then the power supply of the robot arm is cut off, thus stopping its motion.

A second hardware safety measure is given by the FT sensor mounted on the end-effector of the manipulator arm. The sensor gives a quantitative value of the contact forces between the gripper $\{TCP\}$ and the touched surface. The measured data plays a crucial role in the safety mechanism, since the manipulator arm is moving very close to the user, especially in the "prepare and serve a meal scenario", where the user has to be feed via a spoon grasped by the manipulator. If the derivative of the measured contact force increases above a predefined threshold value, then the path planning method will redraw the arm from its current motion. An example of surface contact through the manipulator's $\{TCP\}$ is given in Fig. 10. The force's derivative ensures force detection independent of the movement of the arm, since it measures changes in the force encountered between the gripper and the environment. In Fig. 10(b), it can be seen how the force's derivative changes at time $t = 4s$ when the arm encounters an obstacle. Although this trajectory switching robotic motion method in not implemented in the traditional impedance control approach, it

TABLE I
STATISTICAL RESULTS OF TASK EXECUTION TIME IN FRIEND.

	Healthy subjects				**Subjects with disabilities**			
Test person	1	2	3	4	5	6	7	8
Machine vision [s]	2.06	1.81	2.28	2.19	2.41	2.58	3.29	1.94
Motion planning [s]	2.47	2.42	2.74	3.18	4.89	2.83	3.13	2.30
Total execution time [s]	4.53	4.23	5.02	5.37	7.30	5.41	6.42	4.24

provides an efficient safety measure in case the manipulator encounters a human person during its trajectory.

The increased sensitivity of the FT sensor made it possible to implement the safety measure based only on the derivative of the contact force, hence neglecting its absolute value. One possible disadvantage of neglecting the force's absolute value is the decreased variation of its derivative for very slow motions of the manipulator arm. However, during operation, the velocities of the arm are always high enough to ensure a good response of the force's derivative in case an object or a person is in the trajectory of the gripper. The advantage of using a derivative based surface contact measurement is that the robot can manipulate relatively heavy objects without treating them as obstacles. Namely, when an object is grasped, although the force needed to lift the object is high, its derivative remains below the predefined threshold.

A so-called software safety measure in FRIEND is the simulation of the user's space during motion planning in MVR. The area in MVR where the user is located behaves like obstacles. With this methodology the robot arm cannot violate the perimeter of the user during its motion.

An additional robotic safety mechanism is added at software architecture level, that is, within the MASSiVE framework presented in Section III. After the sequence of operations needed to fulfill a specific robotic task has been constructed, a verification of this sequence is performed through its transformation into an equivalent *Petri Net* [19]. The obtained *Petri Net* representation is verified for run-time execution errors using the formalism of *Petri Nets*, thus ensuring a suitable generation of primitive robotic operations. In future, additional safety measures that ensure safety also in case of one failing part of the system will be taken into account.

VII. Clinical Evaluation

One of the most complex problems when developing rehabilitation robots, or assistive robots in particularly, is their clinical evaluation. Traditionally, as pointed out in [39], engineers evaluate the performance of robotic systems by measuring different metrics, like "time to task completion" or "the number of successful / unsuccessful grasps". This approach, although is suitable for testing the hardware and software equipment, fails to include the users experiences with the system and its degree of acceptance. Also, the suggested performance measures found in literature are specifically designed for a particular type of system, hence making their general use difficult. In [39] a number of guidelines, together with a survey and two case studies, on how to develop performance evaluation methods for assistive robots are given. One main fact pointed out by the paper is the assessment of the user's

TABLE II
PROBLEMS DURING TASK EXECUTION IN FRIEND.

Robotic task name	**No. of errors (out of 45 trials)**
Task selection	4
Object recognition	7
Object grasping	2

Quality of Life (QoL) improvement through the robotic system and also the inclusion of medical doctors in the evaluation procedure. Often the performance of an assistive robot is described via semantic differential scales which quantify the satisfaction degree of the user (e.g. *0 = unsatisfied* to *5 = very satisfied*).

Clinical tests with the FRIEND robot took place at the *Neurologic Rehabilitation Center Friedehorst* (NRZ), Bremen, Germany. NRZ is one of Germany's leading neurological rehabilitation centers for children and young adults, providing therapies for patients with traumatic injuries, stroke, intracerebral bleedings and inflammatory diseases of the peripheral nervous system, epilepsy or congenital malformations. To improve continuous caretaking from early rehabilitation to reintegration into school and vocational careers, the concept of FRIEND was adopted by NRZ therapists and successfully introduced in their everyday work. In Fig. 11, sample steps from the ADL "preparing and serving a meal" scenario, during evaluation in NRZ, can be seen. The tests were divided into two parts: *robotic evaluation* and *user acceptance*. Within the robotic evaluation tests, the speed and precision of different stages of processing have been quantified. The evaluated stages are:

1) Precision of 3D object reconstruction in variable illumination conditions;
2) Success of object grasping;
3) Total execution time of a task.

Based on the above performance measures, statistical results of robotic task execution within the "prepare and serve a meal" can be seen in Table I, whereas in Table II the number of encountered problems during testing are available. For testing the FRIEND system, a number of eight subjects have been involved, half of them having a form of physical disability, while the other half being healthy. The comparison between healthy and disabled persons was made in order to show that FRIEND provides similar optimal results for both groups. As can be seen from Table I, the differences in execution time are small.

Performance evaluation results of the machine vision system operating in variable illumination conditions can be found in [17]. Detail results on the reliability of the developed motion

Fig. 11. Sequences of robotic operations within the “prepare and serve a meal” support scenario during testing at the NRZ rehabilitation center.

TABLE III
SPEED OF THE BCI.

	Healthy subjects			
Test person	1	2	3	4
Left (13Hz) [s]	6.62	4.72	7.26	6.89
Up (14Hz) [s]	8.39	5.58	7.63	13.94
Right (15Hz) [s]	5.60	5.42	12.26	20.30
Down (16Hz) [s]	9.14	8.55	6.73	15.91
Select (17Hz) [s]	12.91	8.52	8.71	11.73
Average [s]	8.53	6.56	8.52	13.73

TABLE IV
ANSWERS TO QUESTIONNAIRE FROM PERSONS WITH DISABILITIES THAT TRIED THE FRIEND SYSTEM.

	Subjects with disabilities			
Test person	1	2	3	4
Question 1	2	1	2	2
Question 2	2	2	1	2
Question 3	1	0	0	0
Question 4	0	0	0	0
Question 5	3	2	2	3

planner and the BCI interaction paradigm are to be found in [18] and [37], respectively.

The speed of the BCI device and the human-machine interface response has to be evaluated in a separate session when the subject gets random tasks to focus attention to specific stimuli of the LED-frame (see Fig. 4). These measurements took place in a laboratory environment with healthy users. The focus of the BCI communication in the system lies on accuracy and not on speed. Therefore, the threshold for the classification of the probability values of the frequencies is set to $\beta = 0.45$. In addition, an idle period of $1s$ after each classification is introduced. During that idle period, no classification will take place in order to prevent a classification of the same command twice. The results of the additional BCI measurements are presented in Table III.

An additional session regarding the speed of the BCI for disabled subjects was not performed. However, similar evaluation sessions within a spelling task using five stimuli revealed that there is no significant difference in the BCI performance between healthy and disabled subjects [40]. Therefore, the speed of the BCI and the human-machine interaction in case of disabled subjects can be assumed to be in the same range as for healthy subjects in this specific task.

The second evaluation stage, of user acceptance, included a series of semantic descriptions provided by the test person through the following questionnaire:

1) When using it, did FRIEND improved your QoL?
2) Would the functionalities of FRIEND help you in your daily life?
3) Do you think that FRIEND will replace care-giving personnel?
4) Do you think that FRIEND is better than a care-giving person?
5) Is the robot user-friendly?

The user questions presented above have a scale ranging from 0 to 3, as (*0 = no*, *1 = in a small degree*, *2 = in many ways*, *3 = yes, a lot*). In Table IV, the answers of the test subjects with disabilities to the given questionnaire can be seen. It is important to notice that although the QoL of the subjects seems to have been improved, they all agree that at the current stage, a robotic system will probably not replace care giving personnel. Nevertheless, such a robot brings lots of functionalities and a certain degree of independence in the private and professional live of persons with disabilities.

From the statistical results presented in this section it can be concluded that FRIEND is a potential system that can be used for assisting elderly and persons with disabilities. Nevertheless, there is still a long way to convince potential users. Also, further testing is planned in order to better understand the capabilities of FRIEND and also the needs of the patients.

VIII. DISCUSSION AND OUTLOOK

In this paper, the FRIEND robotic system, together with a BCI based human-machine interface has been presented. The goal of FRIEND is to support and give a certain autonomy to elderly and persons with disabilities that have to rely on care-giving personnel 24h/day. The achieved independence is a proven benefit to the social life of the patients. In order to demonstrate the capabilities of FRIEND, three rehabilitation support scenarios have been developed. The research results obtain in the project and within the development of the support scenarios are valid not only within the FRIEND system, but can be transferable to many other areas of robotics. Commercially, FRIEND is now available as a completely integrated system or in a component fashion comprising functional subsets of FRIEND (e.g. a stereo vision system on a PTH, the wheelchair system NEMO and the reconfigurable LWA3). The system is targeting for use in rehabilitation research areas. Beside this, FRIEND is promoted as a dependable and durable test bed for supervised tests with disabled patients in the field of rehabilitation robotics. The same strategy has also been promoted in the US by Willow Garage and their PR2 robot [4] with the goal to achieve a standardized platform which can be used by researchers to continuously develop the field of robotics. Further on, in order to develop a market for such assistive robots, it is necessary to not only convince the prospective users and therapists, but also financial insurance companies and social welfare offices.

As future developments in FRIEND, the integration of learning mechanism within the control architecture is considered. This concept will take into account the past actions selected by the patient and will be used to automatically adapt the robot to better suit the needs of the user. Also, as mentioned in the previous section, further testing of the proposed robotic platform is planned in different rehabilitation institutes. To overcome the significant difference in subject's individual ability to use a BCI presented here and in similar papers [28], further developments consider a so-called *BCI-Wizard* to automatically determine the best frequencies and parameters for each subject.

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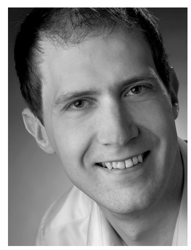

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