FRIEND – A Dependable Semiautonomous Rehabilitation Robot

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Abstract

Within the AMaRob research project a complete reference platform for rehabilitation robots named FRIEND was built by an interdisciplinary team of researchers, therapists, engineers and designers. The robotic system was designed to primarily support people with quadriplegic disabilities in domestic and vocational fields. Based on new control concepts for service robotics, the user gains up to 90 minutes of independence acting autonomously with the robot system. FRIEND has therefore become a reference platform allowing further research on personal rehabilitation robots based on a dependable and comprehensive hardware and software.

1 Introduction

This paper describes the results of the AMaRob project (*Autonomous MAnipulator control for rehabilitation RO-Bots*). The goal of this project was research, development and introduction of new methods for manipulator control in robotic rehabilitation systems. A complete reference platform named FRIEND has been built by an interdisciplinary team of researchers, therapists, engineers and designers. This reference platform now allows further research on personal rehabilitation robots based on dependable and comprehensive hardware and software.

Figure 1: The rehabilitation robot FRIEND

FRIEND (Fig. 1) is designed to primarily support people with quadriplegic disabilities in domestic and professional fields. Based on novel developed control methods within the AMaRob project, the user is able to gain up to 90 minutes of independence acting autonomously with the robotic system. Three representative support scenarios were chosen to proof capacity and operation of the integrated control scheme. The first scenario includes *Activities of Daily Living* (ADL), like preparing a meal and providing support for eating and drinking. The second scenario regards assembly, sorting and quality control tasks in a rehabilitation workshop. Finally, the third scenario enables a disabled user to provide several service tasks at a service desk, e.g. in a library.

The rehabilitation system FRIEND itself is based on the integration of an electric wheelchair and a 7-DoF manipulator built from reconfigurable light-weight modules. The robot perceives his environment using different sensors, like a wrist mounted force/torque sensor, a prosthetic hand and a stereo camera system. In order to integrate various perspectives, an interdisciplinary consortium was established to define and design the robotic system. The core requirements for a care providing robot like FRIEND are execution of complete action schemes, dependable in different scenarios, adaptable to different tasks and users.

Especially the control of complete action sequences is required. The action sequences must support the different scenarios in a modular approach. Based on existing scenarios, further ones can be built to extend the systems capabilities and to adapt it to new tasks and to specific user requirements, depending on the disability of the user. Adaptation to the user is esp. important for the *Human-Machine Interface* (HMI) and the input devices, which can easily be integrated (e.g. chin joystick, speech input or a *Brain-Computer Interface* (BCI)). Another important requirement is the dependability of the complete rehabilitation system from the user's point of view, but also in the perspective of the therapists.

Reducing complexity is a key to achieve dependability and it is reached by sensor driven robot control as well as an intelligent environment. Fig. 2 shows elements of such an environment as it is used within the ADL scenario. In order to achieve an intelligent environment additional sensors and actors are used (e.g. door opener, scale, tray with position measurement etc.). The common feature of the additional sensors and actors is that they are used to implement important actions that can be carried out much easier by the robot. The implementation of the so-called *shared control mode* leads to a higher overall reliability of the complete system and improves the manipulation of objects in partially unknown environment. In shared control, the system is actively asking the user for support if for any reason autonomous actions cannot be generated. With this approach, FRIEND integrates the cognitive capabilities of its user into the control architecture, thus reducing the control complexity significantly.

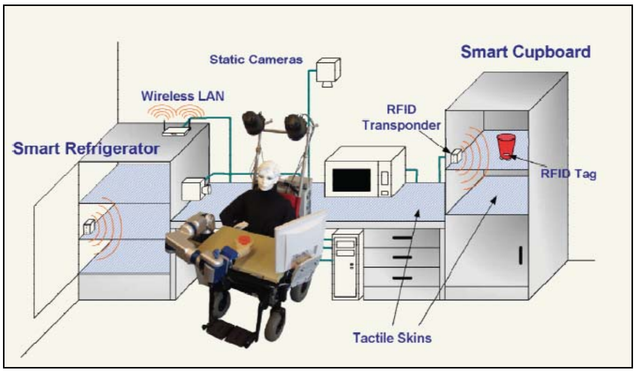

Figure 2: Intelligent Environment in the ADL-Scenario.

Software reliability, maintainability and upgradeability for future applications are achieved through the implementation of a distributed multilayer control architecture for service robotics, entitled MASSiVE (*Multilayer Architecture for Semi-autonomous Service robots with Verrified task Execution*) [21]. Fig. 3 and 4 show the multilayer structure of the basis software system of FRIEND. The main processing layers are Sequencer, which plans sequences of tasks, the HMI and the reactive layer. In the reactive layer sensors data is processed, as well as the path planning of the manipulator arm. All those components are linked together via the Sequencer, which acts as a system manager [3]. The Sequencer plays the role of a discrete event controller that plans and controls action sequences by means of predefined task knowledge.

The processing layers in MASSiVE provide also offline services for abstract task specification, as well as transformation of elementary process structures into Petri Nets (PN) for task sequence verification. The online layer executes asynchronous skills and provides means for data acquisition and data transfer to hardware components (sensors and actuators). PN are used for formal task verification and finally guarantee the reachability of the target. With the help of PN, verification resource conflicts, logical modeling mistakes, erroneous data flow and dead-locks of the task planning routines are avoided.

Recognition and 3D reconstruction of objects in the FRIEND scenarios has been solved by the novel machine vision system ROVIS (*RObust machine VIsion for Service robotics*) [2] illustrated in Fig. 5. ROVIS uses feedback control at image processing levels for coping with external influences like variable illumination conditions and cluttered scenes [11]. The reliable execution of a manipulation task requires robot motion planning and sensor based trajectory control. These topics are covered by a real time motion planning algorithm in configuration and Cartesian space [1]. Improving clearance for robot motion follows two basic strategies – moving the end-effector by avoiding obstacles and moving the elbow by observing a redundancy circle. The wrist mounted force torque sensor enables the system to autonomously detect unexpected collisions and further, on-line, correct the motion trajectory.

The reference platform FRIEND includes the above described hardware and software components and is configurable to further research and development projects in a modular way. Reusable modules, like the dexterous robot arm with manipulator control and path planning, as well as the stereo-vision system, mounted on a *Pan-Tilt Head* (PTH), can be used independently.

2 State of the art

There are some commercial systems and research prototypes available which already demonstrate some progress in the area of rehabilitation robots [24]. However main focus of these systems is usually put on wheelchair navigation [25], only a few approaches concentrate on manipulation. Known systems of the latter category are mainly limited by the range of applications. 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 [26][27] or other similar devices, e.g. Winsford Feeder (RTD-Applied Resources Corp. , New Jersey, US), Neater Eater (Buxton, UK, [28]) or MySpoon (Secom Co. Ltd., Tokyo, JP). Other restrictions of existing systems are the lack of dexterity of manipulation capabilities, as e.g. RAPTOR [29] possesses only a 4-DoF robotic arm, or the MANUS [30] robot arm with 6-DoF and no capability of autonomous operation.

Thus, there are merely a few relevant known commercial robots for assisted living of disabled people. No commercial all-embracing robot system is known which focuses on the special needs of disabled and/or elderly people in private as well as in professional life. None of the systems is in competition to the developments in FRIEND. Handy 1 and MANUS are the most advanced 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 Commission* (EC) funded 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 [31]. 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 hand function [32]. The Care-O-Bot system, developed by Fraunhofer IPA, represents a general purpose mobile manipulation platform [33]. Although several functionalities for assisting people in daily living are available, the robot is not designed for the needs of the disabled and elderly.

To summarize, none of the known systems and system approaches are to be compared with FRIEND which provides a complete platform for implementing robotic tasks for the disabled. A problem in the rehabilitation robotics community 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. With the availability of FRIEND this situation will change.

3 Project goals

The care-providing robotic system FRIEND, commercially available since the beginning of 2010, is a semi-autonomous robot designed to support disabled and elderly people in their daily life activities, like preparing and serving a meal, eating, drinking, or reintegration in to professional life. FRIEND enables the disabled user (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) 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.

Disabled people have to rely 24 h/day on care-giving personnel. The independence given through the FRIEND system presently aims at least 90 uninterrupted minutes of independence, where certain tasks commonly performed by supporting persons are transferred to the robot. The achieved independence is a proven benefit in the social life of the patients.

The goals of FRIEND have been demonstrated in different scenarios where a large number of consecutive action sequences are performed. Those sequences, necessary to fulfil the demands of the robot system's user are semantically described as robot object handling methods like "pour and serve a drink", "prepare and serve a meal", "fetch and handle a book". The interaction with the user is performed through a HMI which handles different user input commands. These tasks can be performed either autonomously or they may be directly controlled by the user of FRIEND. In autonomous mode the robot dynamically recognizes the environment by interpreting the sensor signals with respect to the task and plans the robot's next actions and movements. In the so called *shared control mode* the user can take over direct control at any time and command the robot at different abstraction levels, that is, the user may submit high level commands through the HMI or may adjust the robot's movement directly.

Task execution in FRIEND may also be assisted by smart components placed within the environment in which the robot operates. These components are sensors and actuators used to simplify robot task execution. For example, in the case of "preparing and serving a meal" the doors of different containers (e.g. fridge, microwave) are opened by remote control commands from the robotic system. To support eating, a smart tray is introduced which measures the position and weight of objects with short sampling time and provides faster and more reliable measurements then the vision system, thus reducing control task complexity.

4 Project approach

FRIEND builds the basis for the implementation of complete chains of support scenarios in complex environments. It can be used as a platform technology for further research and development or rehabilitation tasks and as a support system available for end users.

FRIEND is presently designed mainly for the assistance of patients suffering spinal cord injury with lesion above vertebra C5 or for persons with similar handicaps and has been developed for three basic support scenarios. It is characterised by modular and user-oriented design to facilitate seamless integration into smart homes and adaptation to specific user requirements. However, small modifications of the HMI adjust the system to the requirements of the elderly. To prove the benefit of FRIEND and show the usefulness to prospective users, three basic support scenarios were implemented and tested at different levels:

- *All day Living (ADL scenario)*: The ADL scenario 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.
- *Working at a library service desk*: The second support scenario is a working scenario where the user is working at a library desk equipped with a laser scanner for reading IDs of books and customer IDs. The task of the FRIEND 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.
- *Functional check of work pieces*: The third support scenario considers working in a maintenance workshop. Here the FRIEND user has to perform quality control tasks like checking of electronic keypads for malfunctioning. For this purpose a special workshop desk containing different smart tools was built. The keypads are placed into a keypad magazine from which the user can extract one after the other with the

robot, inspect it visually and then test the electric functions.

5 Results

The FRIEND robot uses results from eight years of intensive research carried out at IAT and the joint research of the AMaRob consortium for four years.

The acquired sensors information is used within the robotic system to plan the movement of the manipulator for object grasping and handling [8]. The visual data is provided by the ROVIS vision system [2].

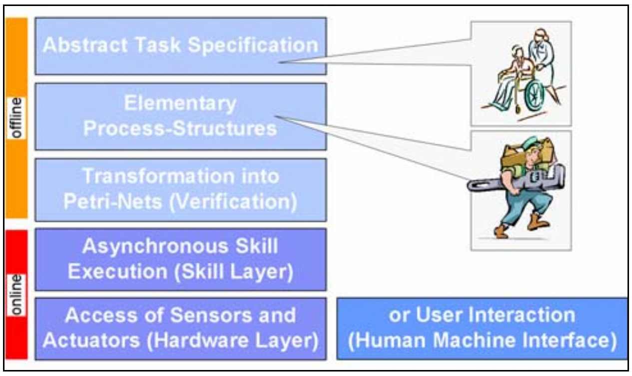

Figure 3: Multilayer structure of the MASSIVE software

The FRIEND robot represents a combination of various hardware components controlled via the MASSiVE architecture. The hardware components are:

- *7-DoF Light Weight robot Arm* (LWA) capable of handling objects up to 5 kg; it is equipped with a gripper and sensors (e. g. force torque sensor, anti-slipping mechanism);
- *Stereo camera system mounted on a 2-DoF PTH* used for acquiring stereo images for environment understanding through the ROVIS framework;
- HMI capable of handling different input technology:
  - All kind of available and specific control inputs like chin joystick, force joystick used as input devices for users which still have certain degree of movement of neck and/or arm or fingers (incomplete Spinal Cord Injury);
  - *Speech synthesizer and speech recognition* system;
  - BCI used to derive the robot input commands directly from the brain waves of the user [17]. This HMI approach is suited for persons that lack any movement of limbs or neck;
- *Intelligent wheelchair tray* located in front of the user for precise measurement of position, shape, size and weight of objects placed directly in front of the user;
- *TFT-Display with touch panel*, used as visual output device for the user and as input device for care giving personnel;
- Communication with appliances via remote (wireless) utilities (e.g. infrared, Bluetooth, RFID etc.).

In the robot working scenarios a large number of action sequences are implemented to fulfil the user's demands. MASSiVE, illustrated in Fig. 3, as a *shared control framework*, interacts with the user through the HMI which operates at user interaction level. The HMI is interconnected with the *Sequencer*, the core of MASSiVE. The Sequencer plays the role of a *Discrete Event Controller* (DEC) that plans sequences of operations by means of predefined tasks knowledge [18]. For safety reasons, the Sequencer commands are verified using a generated PN task description. The MASSIVE architecture builds the basis for the control of the robot and the environment and also the basis for reliable software development, simplified model based code maintenance and software components modularity.

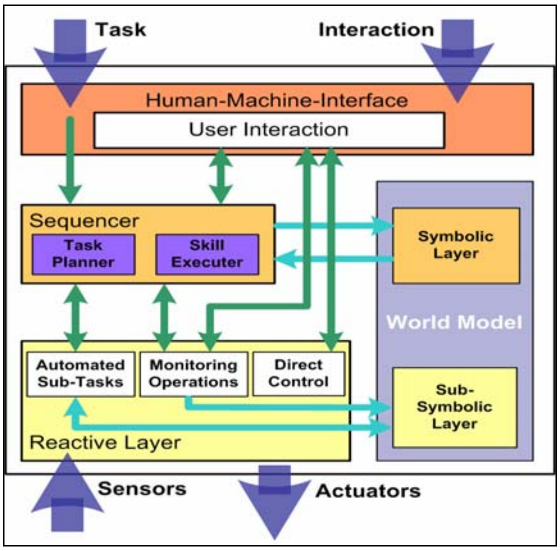

Figure 4: Multilayer structure of the MASSIVE software

The user commands are acquired through the HMI [17, 23] and translated further into machine language for interpretation [15]. The algorithm that converts a user request into robot actions resides in the *Reactive Layer*. Here, the data collected from different sensors, such as the stereo cameras and the intelligent tray, are processed in order to "understand the environment". The data is further converted into actions by the available actuators, such as the 7-DoF manipulator. The computed data is shared between modules with the help of the *World Model*. The World Model defines the information produced and consumed by the operations in the Reactive Layer. During online system operation task parameters can be viewed with the help of a *Graphical User Interface* (GUI) available on a display system mounted on the wheelchair in front of the user.

The surrounding environment of the robot is understood by the ROVIS vision system, illustrated in Fig. 5. The ROVIS objective is to provide reliable vision information to manipulative skills for appropriate autonomous object grasping and handling. One major problem in robot vision is robustness with respect to illumination changes. The novelty in ROVIS, which provides a certain degree of robustness

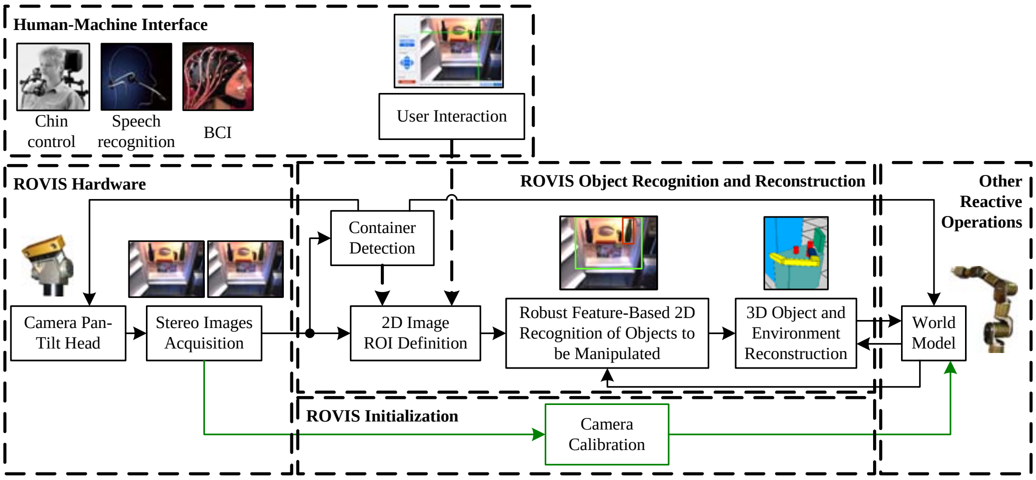

Figure 5: ROVIS architecture within the FRIEND system.

with respect not only to variable illumination, but also to external disturbances that act on the machine vision system, are proposed closed-loop control methods included at image processing level [11]. The goal of these methods is to automatically adjust image processing parameters according to a measure of image processing quality result, thus avoiding the usage of constant operating parameters which provide a good output only in fixed reference illumination conditions.

The development of the complex MASSiVE architecture, along with ROVIS, was possible using a *Model Driven Development* (MDD) approach which increases the visibility of the overall software structure and provides a highly transparent framework suitable for a large software development community. Published results from different fields of research in FRIEND can be found in [1-23].

6 Innovation and Exploitation

The fundamentals for the innovation process have been established by the cooperation of therapists at NRZ and researchers from IAT. The ideas of exactly what activities of disabled people can realistically be supported by robotic manipulation have been born in fruitful discussions of the team members, mostly driven by the requirements of the care providing personnel at NRZ.

An additional useful impact in the outcome of design of the robot was also brought from other cooperation partners within different funded FRIEND projects, such as the AMaRob project funded by *The German Ministry for Research and Education* (BMBF). An essential criterion for the acceptance of a robotic system in sensitive environments like at NRZ is connected with the looks, the sound and the HMI of FRIEND. A profound design approach has therefore helped to make FRIEND a user friendly robotic system inspiring confidence to both user groups: the disabled patients as well as to the care personnel and therapists.

The system integrating partners have added major efforts to achieve another aspect for the acceptance of FRIEND by its users: dependability. FRIEND has reached the goal of providing more than 90 minutes of full autonomy for the disabled patients. In all experiments the mechanical, electrical and control components had to be proof for stability and performance. This includes a minimum power consumption and dependable function of the innovative LWA, the MASSiVE and ROVIS architectures, the grasping instrument, wheelchair, etc.

Also, care providing robots need to be highly customizable. Each user has individual requirements and desires and in many cases very different abilities to communicate with an automated machine like a robot. The partners have therefore integrated a complete set of different HMI devices ranging from hand and chin joysticks and speech control to BCI.

Commercially, FRIEND is now available as a completely integrated system or in a component fashion comprising functional subsets of FRIEND (like a stereo vision system on a PTH, the wheelchair Nemo and the reconfigurable LWA). The system is targeting for use in rehabilitation research areas. Beside this the partners are going to promote FRIEND as a dependable and durable testbed for supervised tests by disabled patients. The responsibility for marketing FRIEND in these areas has been granted to SCHUNK. Customers are found in rehabilitation centres and robotic research institutions. The goal of the consortium is to place 20 systems in the research market within the next 3 years.
FRIEND has already had many presentations and shows, e.g. CeBIT 2008 (Hannover, Germany), Rehacare 2009 (Duesseldorf, Germany) and the *2009 Int. Conf. on Intelligent Robots and Systems* (IROS, St. Louis, USA). The next opportunities are the SCHUNK Expert Days 2010 in Hausen, Germany, as well as the *Hannover Trade Fair* and the ISR *Robotik Int. Conf.* in Munich, Germany. Part of the

marketing concept includes the presentation of FRIEND within the ECHORD research programme funded by the EC. Further information related to FRIEND can be found at www.friend4you.eu.

The consortium partners have contributed to the development of FRIEND in different ways (hardware, software, conceptual work, drawings and tests). The concept of handling the intellectual properties therefore is adapted to this situation. Each partner has agreed on the marketing agenda treated as one important outcome of AMaRob, the last project funding for FRIEND. The agenda includes the marketing events for the years 2009 and 2010 as well as a reasonable pricing for the system. The manufacturing partners for the robot's hardware are going to produce and sell their parts after reception of purchase orders by customers. They will also provide after sales service to the customers. The partners with intellectual properties will be rewarded with license fees based on the number of sold FRIEND systems.

A comprehensive part of research and development work is the MASSiVE software necessary to control FRIEND. It is clear that most of the support work after sales is connected with further software development. For research institutes customers an *Open-Source General Purpose License* (GPL) is granted. For researchers and system engineers who would like to implement new algorithms, training and the support model is provided. Based on scientific exchange programs (e.g. Erasmus), interested researchers will receive a full introduction and training, under the GPL, in learning the FRIEND's architecture and algorithmic solutions for problems like visual scene understanding and reliable robot control.

The exploitation of FRIEND at first in research area, and some time later for end users, has been an objective right from the start of the AMaRob project. The innovation process itself was strongly driven by the cooperation of researchers, therapists and engineers. The direct outcome of the FRIEND development is clearly to be seen in the improved living and working conditions of the disabled test persons. At the same time therapists were able to find new ways to assist the rehabilitation process. The care giving staff has reported about improved working conditions, since the test persons gained autonomy and quality in life.
Researchers and engineers have taken advantage from new strategic developments with enormous requirements. Several Phd, diploma and master theses are also a secondary result of the cooperation.

Industrial partners in the AMaRob consortium like SCHUNK, Otto Bock and Meyra will strengthen their efforts to establish the market of service and personal robots even more. The chances for robotic applications in rehabilitation have seriously improved with the technical expertise gained in the FRIEND development and technology transfer.

The ongoing process of introducing the FRIEND platform to customers in research and rehabilitation will establish a strong relationship between the developers and the industrial partners. It is expected that many new ideas and requirements will occur in the introduction phase. The various customer contacts of the industrial partners are therefore strongly beneficial for the cooperation with the researchers and will lead to further mutual developments.

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