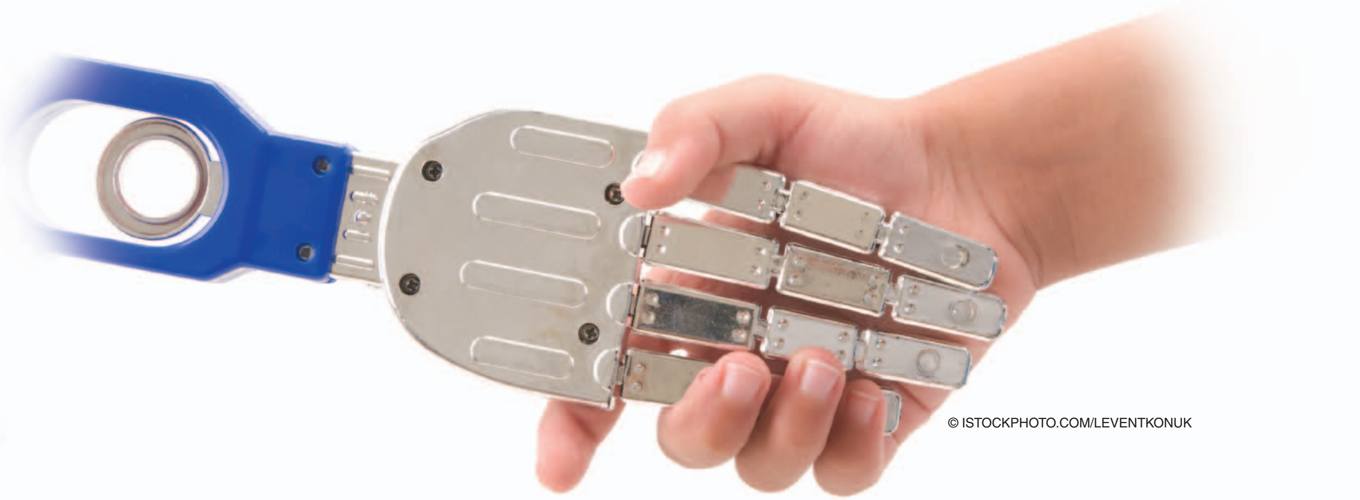
A Supportive FRIEND at Work

Robotic Workplace Assistance for the Disabled



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This article presents the evolution of an assistive robotic system, the Functional Robot with Dexterous Arm and User-Friendly Interface for Disabled People (FRIEND), from a robot supporting disabled people in their activities of daily living (ADL) into a robot supporting people with disabilities in real workplaces. In its fourth generation, FRIEND supports the end user, a quadriplegic individual, to work as a librarian with the task of retrospectively cataloging collections of old books. All of the book manipulation tasks, such as grasping the book from the book cart and placing it on the specially designed book holder for reading by the end user, are carried out autonomously by the FRIEND system. The retrospective cataloging itself is done by the end user. This article discusses all of the technical adjustments and improvements to the FRIEND system that are necessary to meet the challenges of a robot supporting a disabled person working on a regular basis. These challenges concern the shared autonomy between system and user, system effectiveness, safety in interaction with the user, and user acceptability. The focus is on both the vision-based control of book manipulation as a key factor for autonomous robot functioning and on an advanced human–machine interface (HMI), which enables the end user to intervene if the autonomous book manipulation fails. The experimental results of an in-depth evaluation of the system performance in supporting the end user to perform the librarian task are presented. It has been shown that working together, the FRIEND system and the end user had an overall success rate of 95%. These results may help to raise interest in the research field of workplace assistive robotics, establish new projects, and, eventually, supply such systems to the people whose working lives they could greatly improve.

Assistive Robot FRIEND

The assistive robot FRIEND is an intelligent wheelchair-mounted manipulator. The FRIEND has been designed to support severely disabled people (patients with quadriplegia or similar handicaps) in object manipulation tasks in everyday living scenarios [2]. Over the past 15 years, FRIEND has passed

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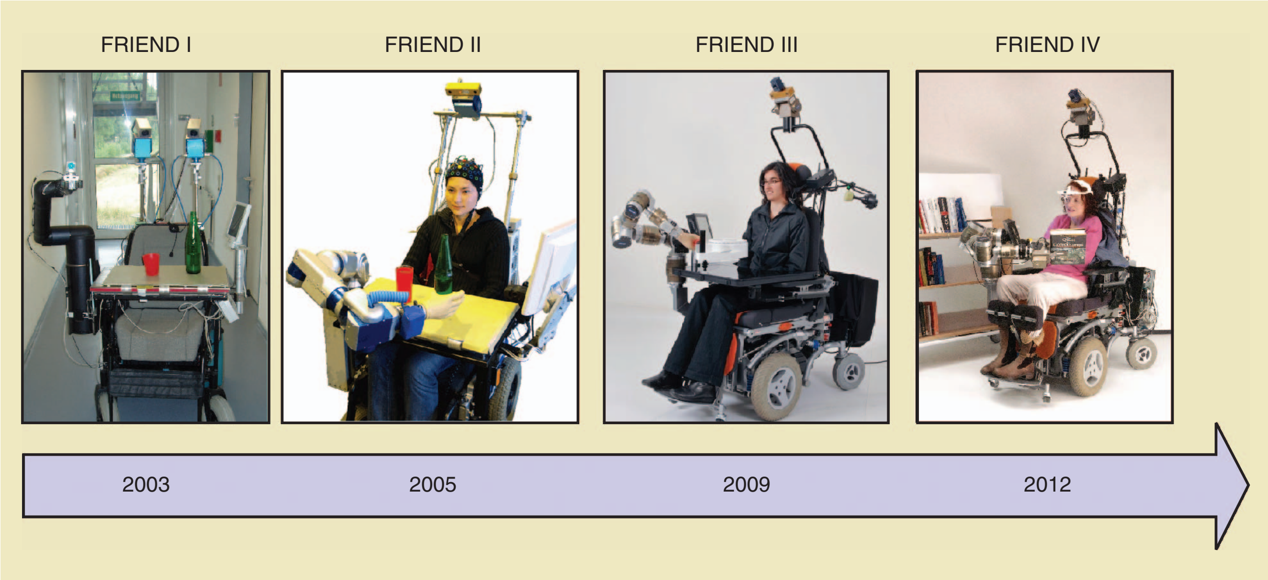

Figure 1. The timeline of the assistive robot FRIEND shows the system's development over the past decade. (Photos courtesy of IAT, Frank Pusch, and Riad Hamadmad.)

through four generations (Figure 1) as technology and experience have progressed, performing increasingly complex tasks.

During the different stages of research and development of FRIEND, different user support scenarios in ADL have been considered. Starting from a simple drink-serving scenario in FRIEND I, more advanced scenarios requiring advanced manipulative skills were developed with the next generation of the prototype, FRIEND II, including extended drink-serving and a meal-serving scenario. Within the German national project AMaRob [3], it was demonstrated that FRIEND III could provide 90 min of independence from personal support. This was enabled by the improvements in robot software architecture, supporting autonomous execution of a sequence of actions, the integration of an advanced HMI, robust vision-based robot control, and collision-free path planning. Within the AMaRob project, the first trials with disabled individuals who used FRIEND III in a work environment were performed as well. The focus was on research of methods for vision-based manipulation control in the autonomous performing of tasks such as handling outgoing and returned books placed on the library desk [18] or testing telephone keyboards [3]. Although the scenarios in these trials were realistic, they were of a rather laboratory character and the involvement of the end-user was mainly in starting autonomous subtasks and rating the HMI and success of the tasks executions. It was recognized that using FRIEND in a real workplace would require a much higher success rate than the one achieved with the FRIEND III system. The main characteristic of the development of the FRIEND in its fourth generation is its transformation from a robot supporting disabled people in their ADL into a robot for supporting disabled people in real work environments, which have much greater task variability and much more stringent requirements in the success rate of tasks. This article presents the necessary enhancements of the FRIEND system needed to achieve this transformation.

These enhancements are user driven. The central role of the end user is a key aspect of the design, which poses new, significant challenges to FRIEND, covering issues related to shared autonomy between the system and user, system effectiveness, safety in interaction with the user, and user acceptability. The technical adjustments and improvements are, however, only one part of the process. Finding and convincing an employer, the recruitment of an employee, and clarification of details with other organizations such as the department of employment, integration agency, and insurance companies are also critical, although they may not be the primary interest or field of expertise of the research organization.

A scenario net consists of a set of individual tasks that are arranged in a flowchart and may contain loops and branches.

Usage Scenario

The presented enhancement of the FRIEND system started with the identification of a usage scenario. To define the usage scenario, two interest groups were identified:

- the employer, an institution that has an appropriate task to be carried out and has the resources and willingness to employ an individual with physical limitations that would usually be considered as a significant hindrance to employment
- the employee, an end user who, with the help of robotic assistance, could overcome the obstacles posed by quadriplegic

disability and who is willing to be a pioneer in using a robot in the workplace. The employee must also have the professional skills necessary to fulfill the job role at the workplace.

The State and University Library of Bremen agreed to be the employer. After finding the employer, the position was announced on several appropriate Internet sites for disabled people. Also, experts in the department of employment who are familiar with the abilities, disabilities, and wishes of many disabled individuals were consulted. Through the department of employment, a quadriplegic female end user was identified who agreed to move to Bremen and to start her integration into professional life with the help of the FRIEND system as part of the Bremen Integration Agency project ReIntegraRob [4].

The FRIEND system usage scenario, i.e., the end user job description, was developed in cooperation with the University Library of Bremen and consists of the retrospective cataloging of collections of old books. These books are currently not included in the online catalog, and therefore it is not possible to locate and find details of them using an Internet search, a problem that nearly all large libraries face. To make the information about such books accessible to online users, it is necessary to catalog and include them in the online catalog retrospectively. This means that the conventional book index cards have to be transferred into the machine-readable format of the online catalogs. For this, the librarian has to open each book, find the bibliographical information, and enter it into the library's online catalog.

The robot control based on speech recognition as the control input has proven to be very exhausting for the user, whereas the BCI has been very slow.

In the FRIEND usage scenario, the FRIEND end user is the librarian. The books to be cataloged are taken from the archive by a library worker, and they are brought to the librarian on a book cart. All of the subsequent manipulative tasks during the cataloging are carried out by the FRIEND system: it takes the next book to be cataloged from the top shelf of the book cart and puts it onto a specially designed book holder placed in front of the FRIEND end user. The cataloging is done by the FRIEND end user, who enters the cataloging information into the library software, PICA, using speech recognition. After cataloging is completed, the book is closed, grasped again by the manipulator, and put back onto the lower shelf of the book cart. Hence, the autonomous book manipulation consists of grasping books from the book cart, transferring them to the book holder, and grasping them again to transfer them back to the shelf of the book cart. The autonomous book grasping is based on vision-based control of FRIEND's manipulator. The development of robust robot visual perceptual capabilities has been an important aspect of the improvement of FRIEND's capability for reliable autonomous functioning over its different generations.

Although the goal has been to develop general methods for vision-based reconstruction of objects to be manipulated, in different robot working scenarios, different object-specific image processing methods had to be developed, and different vision-based control structures had to be adopted [19]. The vision-based control of book manipulation is a key factor for autonomous functioning of FRIEND IV in the library workplace scenario. The experimental results presented in this article demonstrate that the interaction between the user and the robot's autonomous procedures enabled a success rate that was acceptable for the work environment.

Related Work

To the best of our knowledge, the first robotic system supporting a disabled person to work with books was the robot RAID, which was developed at the Swedish Rehabilitation Engineering Research Center and was designed to assist in picking out books from a bookshelf, carrying documents, and serving drinks in an office environment [13]. RAID did not have sensors to provide autonomous robot functioning, and manipulation of the robot gripper to grasp the books was controlled directly by the user, imposing a significant mental load on the user. The robot ProVAR [14], which incorporated force sensors and different interface modes, allowed people with high cervical spinal cord injuries to function more independently in a workplace setting by helping them perform office tasks such as delivering documents, diskettes, video tapes, and so on.

The technically more advanced robotic system CAMP, proposed in [15], was designed to work in an offsite shelving facility. The books in the facility were equipped with bar codes for identification, and the location of each book was saved in the system database. The end user requested a specific book through an Internet interface in response to which the mobile system navigated to the target location. Using a bar code reader mounted on the robot gripper, the book was identified, grasped by a specially designed parallel gripper, and delivered to the user. A major drawback of this system was the empty area needed around each book (40 cm on both sides). A similar system was presented in [16], where books are identified by special labels using an optical character recognition (OCR) system. The grasping operation is achieved by integrating visual and force sensing, where the vision system is responsible for detecting the book and identifying its approximate location and the force torque sensor on an industrial parallel plate gripper is responsible for detecting the exact position of the book borders.

Another mobile system was presented in [17]; it is a system that does not use any preknowledge of the books and in which distant users can browse books in a library through an Internet interface. The user defines the category of the desired book, and the robot then navigates to the corresponding shelf and positions itself perpendicular to it. The vision system of the robot uses a laser scanner mounted on the robot to segment the edges of the books on the shelf. The system then computes the thickness for each book and identifies the book being targeted. The published performance evaluations of the presented systems [15]–[17] are rather limited, which perhaps explains the lack of recent published results about these systems in real library environments. The robotic systems [15]–[17] were designed to serve the end user in manipulating books where he/she was not necessarily a person with physical disabilities. As such, these robotic systems did not face the challenges of being adjusted to the needs and capabilities of an end user with severe disabilities, which means that the robotic system has to have an HMI containing input devices adapted to the physical limitations of the end user and that the end user is not involved in low-level robot control.

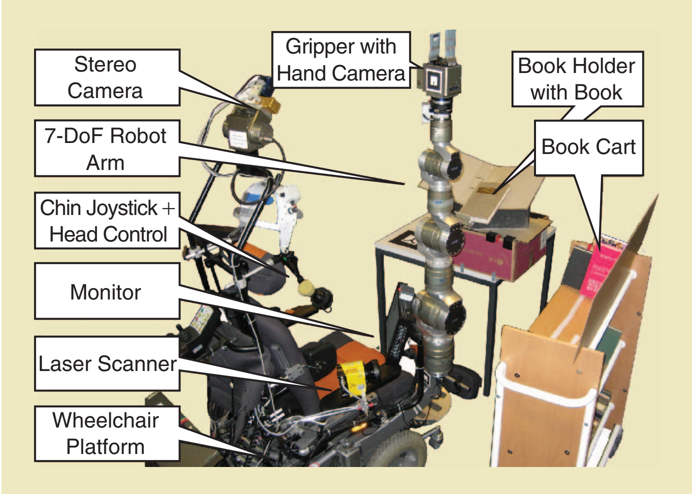

Figure 2. The robotic system FRIEND is shown in a library environment.

The systems described in [13] and [14] provided an increased level of independence for people with disabilities in a workplace settings. The independence provided is, however, offset by the systems' cost and complexity, which imposed a significant mental and physical load on the user as he/she was involved in low-level robot control, with the result that these workplace robotic systems had only limited success and were not extensively developed after the achievement of the first results [1]. In contrast to these systems, the assistive robotic system FRIEND requires only high-level commands from the end user to perform its tasks. In addition, in the fourth generation of the FRIEND system described in this article, the user gives high-level commands only for initializing the sequence of tasks and not for starting the tasks one after another, which was the case in previous FRIEND generations [2] as well as in the system described in [17].

Early results on using FRIEND to support disabled people in a real library workplace were published in [9], where it was shown that vision-based manipulation control was able to achieve a success rate in book grasping of up to 80%. Such a result has been considered rather poor, as the goal has been to develop a robotic system that achieves the highest rate of success to enable the end user to effectively complete the retrospective cataloging task. Thus, the need for an appropriate HMI has been identified to give the end user an easy interface to control the robot manually in cases where the robot fails to complete its task. Unlike the early work [9], [10] where individual system modules were considered and evaluated, this article presents a more in-depth evaluation of the performance of the complete FRIEND system in running the full usage scenario with the integration of the user through the HMI.

FRIEND in a Library Workplace

Environment and Hardware

The environment of the assistive robot FRIEND IV in the library usage scenario consists of a book cart and a book holder placed on a table in front of the user, as shown in Figure 2.

The FRIEND system consists of a seven-degrees-of-freedom (7-DoF) manipulator mounted on an electrical wheelchair and a computer-based manipulator control. The robot's end-effector is a standard industrial parallel gripper slightly modified for book manipulation. To perform autonomous book manipulation—grasping books from the book cart, transferring them to the book holder, and grasping them again to transfer back to the shelf of the book cart—the system is equipped with various sensors needed for task execution support. The vision sensors that provide visual information about the robotic system's environment as required for manipulator control are a Bumblebee stereo camera system attached to a 2-DoF pan-tilt head unit on a rack behind the user and an eye-in-hand camera mounted on the robot gripper. Two vision sensors are needed because of the geometry of the scene. On the one hand, the distance between the stereo camera and the book cart is ~1.5 m, so the stereo-based environment reconstruction would have low accuracy and is not suitable for determining the book grasping point directly. On the other hand, the hand camera, which is much closer to the books, does not provide reliable information in all cases because of shadows and, in addition, it cannot provide the depth information required for the grasping point. Hence, a merging of vision information from the two systems is needed.

For the HMI, FRIEND IV is equipped with a chin joystick in combination with a head control panel, specially designed and developed for the FRIEND end user. In the previous generation of FRIEND, several input devices were tested and used to control the human–robot interaction, such as speech recognition and a brain–computer interface (BCI) [7]. The robot control based on speech recognition as the control

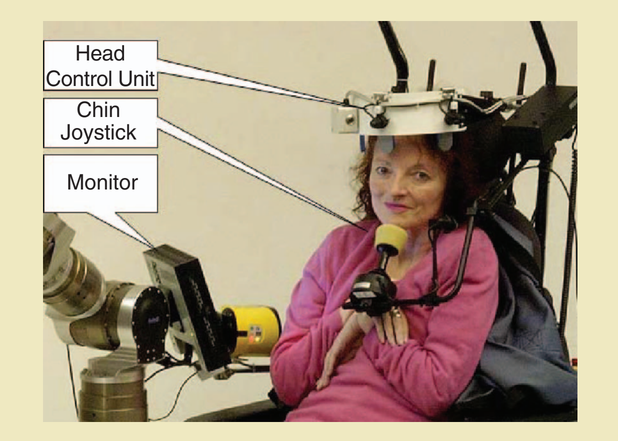

Figure 3. The control of the FRIEND's HMI is suitable for tetraplegic end users. (Photo courtesy of Riad Hamadmad.)

input has proven to be very exhausting for the user, whereas the BCI has been very slow. Therefore, the chin joystick was selected for the library workplace usage scenario. In the early phase of FRIEND development, the mouse cursor on the graphical user interface displayed on a small monitor was controlled directly by the chin joystick of the wheelchair, and mouse clicks could be done through additional buttons next to the chin joystick by moving the chin to that direction. Because of the limited neck flexibility of the end user, these buttons cannot be reached. Hence, a new head control unit with three buttons (Figure 3) was developed and tested, allowing the end user to simulate a mouse click, to stop the robot arm immediately in a critical situation, or to pan the chin joystick aside, each selectable by small head movements, respectively, to the front, right, or left. The head control unit was designed in such a way that it can be adapted easily to individuals with different body heights and head sizes.

To obtain a manageable system and to reduce the complexity of the manipulation for the opening, closing, and turning over the pages of the books, an automated book holder is used. Since all of the currently available solutions do not fulfill the necessary requirements of the defined usage scenario, a novel automated book holder with a device to turn pages using low pressure was developed. The book holder works autonomously but can also be manipulated by the user through the user interface to open or close the book or turn over a page. The open page of the book is imaged by the robot's hand camera, and the image is displayed on a monitor placed next to the user so that she can read the pages and extract the bibliographic information. To enable the autonomous placing of the books onto the book holder so that they can be opened, the books are arranged in a special manner on the book cart so that the spine of the book is facing inward. Additionally, the books are arranged so that horizontal and vertical placement is alternated, as shown in Figure 4. The latter provides enough space for positioning the plates of the gripper when grasping the book (which is always the right-most book on the upper shelf of the book cart). Such an arrangement of the books reduces the complexity of the book grasping procedure and the complexity of the gripper, so that important resources are conserved to implement solutions for the remaining tasks.

To guarantee the safety of the user and to ensure permanently safe operation, two certificated laser scanners have been attached to the FRIEND system in such a way that the user area is strictly separated from the workspace of the manipulator.

Human-Machine Interface

From the end user's point of view, the FRIEND's HMI is its most important system element since it enables the communication of the end user with the system: through the HMI, the end user gives the commands to the system and receives feedback. The user gives high-level commands for initializing a sequence of tasks or for executing a particular task in a sequence of necessary actions to be performed. In previous FRIEND generations, the user had to start the subtasks one after another [2]. To reduce the amount of user interactions and to avoid unnecessary workload for the end user in working with the system, a new level of abstraction was added to the existing concept of FRIEND IV. The five tasks in the sequence of the library usage scenario have been combined into a so-called *scenario* net:

- new book cart
- take book from book cart
- put book on book holder
- catalog book
- put book on book cart.

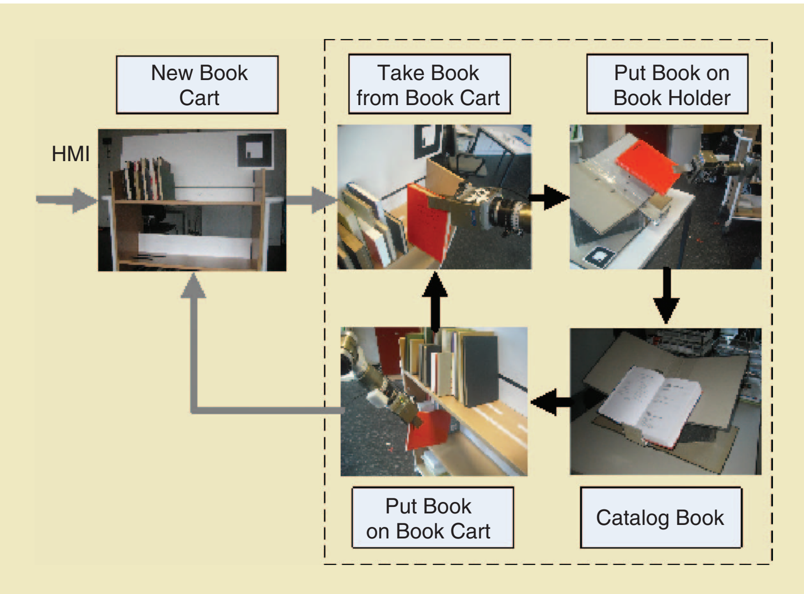

Figure 4. The scenario net for book cataloging.

A scenario net consists of a set of individual tasks that are arranged in a flowchart and may contain loops and branches. The tasks are arranged in a double nested loop, as shown in Figure 4, where the outer loop (gray arrows) relates to all tasks of manipulation of books placed on the book cart, and the inner one (black arrows) relates the cataloging of one book. The user initializes the task's sequence execution by giving the initial high-level command "new book cart"; after this, the further execution of the inner loops also has to be confirmed, i.e., the end user has to decide after one successful cataloging whether the system should continue with the manipulation of the next book on the book cart. In the case of reliable autonomous robot functioning, the end user does not need to interfere after initializing the execution; the end user just monitors the autonomous execution while waiting to perform the cataloging herself.

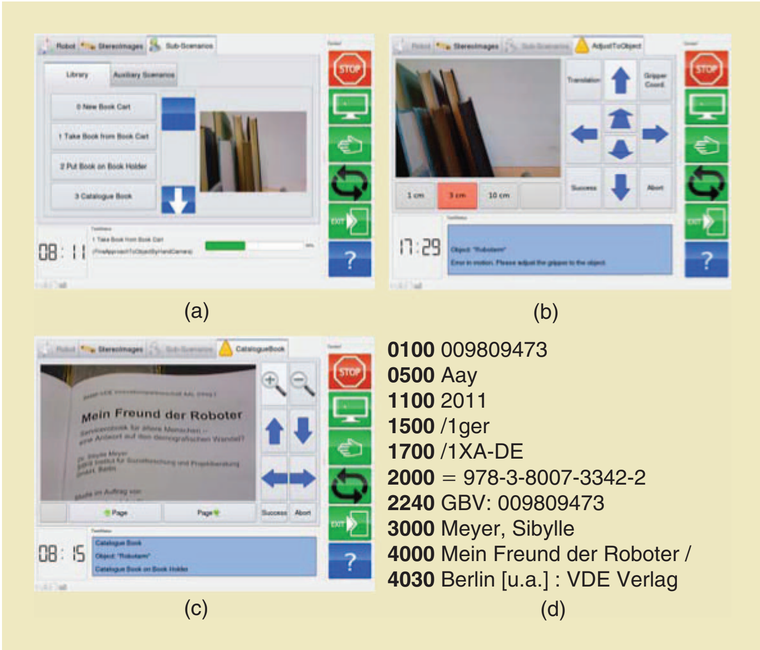

Figure 5. The FRIEND's HMI: (a) scenario initialization, (b) user interaction when autonomous execution fails, (c) book cataloging, user's view, and (d) cataloging data as inserted by FRIEND's end user. (The bold numbers indicate fields in the database, and the text following the bold numbers is the bibliographic information inserted by the user.)

The end user can monitor the current task execution either by direct visual observation or, when the scene is partially hidden behind the robot arm, by looking at the live camera images displayed in the HMI [Figure 5(a)]. This enables the user to detect possible critical situations in which the user should interrupt the execution of the task.

The book taken by the robot from the book cart is placed on a special book holder in front of the user's wheelchair. Because of the distance to book holder, the book cannot be read directly by the end user. Therefore, the hand camera of the robot is used to provide live images of the opened book. After the book is placed on the book holder, the robot arm is moved automatically in front of the opened book such that the book is partly inside the field of view of the hand camera [Figure 5(c)]. Using buttons displayed next to the live image, the end user can zoom in and out or can move the robot to any direction to read the whole page and to extract the information necessary for the cataloging, which is the real professional task of the end user supported by FRIEND. The cataloging data are inserted by the end user into the library software using speech recognition. The result of the cataloging is shown in Figure 5(d).

An autonomous execution of the sequence of tasks cannot be guaranteed all the time. This is, for example, the case when a book cannot be detected autonomously by the vision system due to shadows or other very poor illumination conditions that cannot be avoided at the workplace. Another case arises if the trajectory for the manipulator cannot be calculated because the target is out of the working space of the robot and therefore unreachable. In such a case, the end user is requested to intervene. The system request is displayed in the HMI [Figure 5(b)]. This request allows the end user to control the robot manually using configuration space control to move it to the desired target position. (Here, *manually* is meant figuratively. The user can interfere via the user interface but not with her hands, which are paralyzed.). After that, the end user can confirm successful autonomous task execution (success) or can abort the execution (abort) if the task cannot be completed. In the latter case, the execution of that task has to be started again. This concept of shared autonomy allows a successful task completion when a fully autonomous concept fails.

Safety of the User

Safety has been an important consideration during the development of FRIEND through its different generations. The safety hardware and software concept comprises a watchdog, an electronic emergency switch, reduced power supply if the arm operates close to the user, and a virtual safety curtain between the user and robot realized in the system software. However, in the previous generations, FRIEND was tested either by able-bodied persons or by disabled individuals with low levels of disability. In the presented application, the FRIEND user has quadriplegia and is paralyzed from the neck down. In addition, she works for several hours at a time with FRIEND. Therefore, safety becomes even more important than it was in previous FRIEND generations. The complete safety strategy and safety system realization was reconsidered. Hazard and operability analysis (HAZOP) and failure mode and effect analysis (FMEA) are two commonly used methods to analyze safety critical situations [5], and they were used to analyze the system safety in an iterative systematic approach.

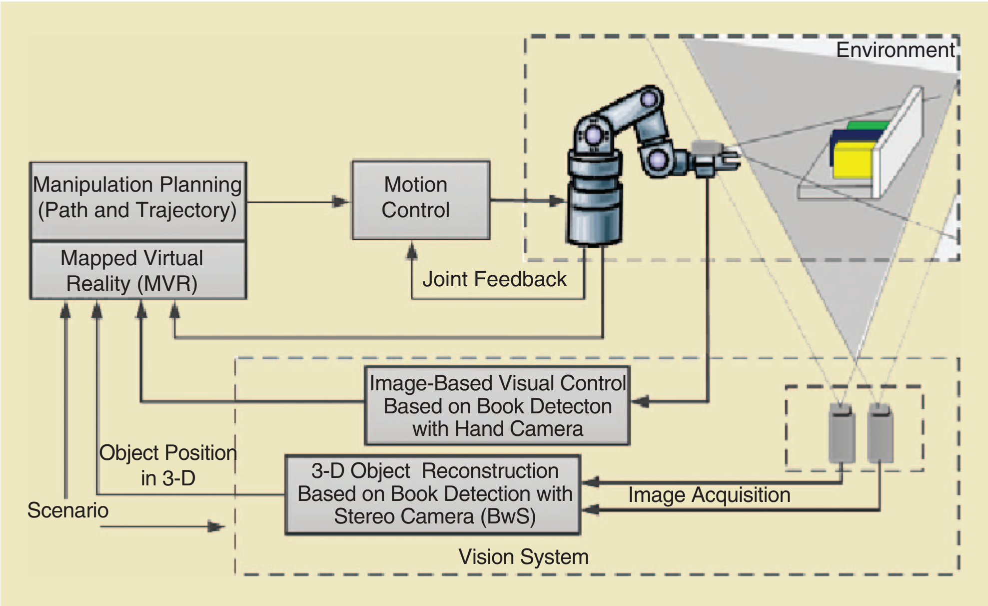

Figure 6. The block diagram of vision-based robot control.

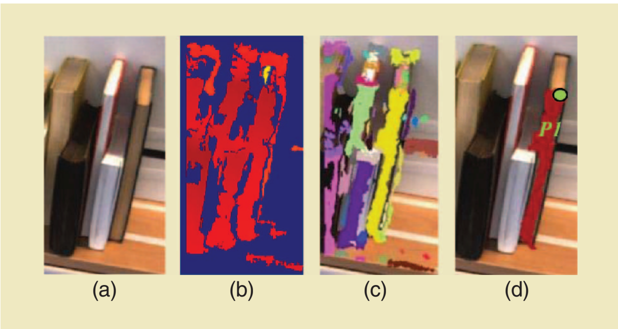

Figure 7. The book detection using stereo vision: (a) left stereo camera image (cropped), (b) the corresponding disparity map based on both stereo images, (c) segmented planar regions, and (d) the reprojected point of the upper-right book corner.

The preliminary safety analysis from the ReIntegraRob project showed that the safety functions implemented in the previous FRIEND generation could not provide adequate protection from some potential hazards, e.g., the potential hazards arising from a short circuit in the drive control unit of the robot arm. The result of the HAZOP analysis for the library scenario identified the two most critical hazards that must be mitigated through external safety functions:

- robot arm collision with the user
- robot arm collision with objects in the environment.

The causes of these hazards are found systematically via FMEA analysis. For the most critical hazard, collision with the user, the user area is separated from the robot workspace and monitored via two laser scanners. The protected zone is monitored by the certified safety laser scanners (one for upper body and one for lower body). The laser's beam is configured such that a protective plane is scanned by infrared light in front of the user's body. In normal mode, the robot control software ensures that the robot does not penetrate the safety curtain. Any penetration of an object (e.g., the robot arm) through this plane is seen as a critical safety issue and will cause an interruption of the power supply to the robot arm and stop each movement immediately. The same occurs if the mounted force-torque-sensor on the gripper measures an unexpected force during movement of the robot arm in free space.

The other hazards that may occur due to the robot systems' critical malfunctions (e.g., short circuit) or software control errors (these causes are obtained from FMEA) are mitigated via an additional high-level safety controller (a safety microcontroller) that monitors these malfunctions and powers off the robot arm whenever these critical malfunctions occur.

Additionally, a safety checklist is prepared that considers the safety precautions before system startup. Each item on the list has to be checked and marked, and finally, the whole checklist has to be signed by the person responsible for the system start-up, e.g., a care person who accompanies the user to the workplace. The checklist is used each time the user is seated in the wheelchair. Items on the checklist are, e.g., checking that the safety laser scanner is in its correct position and that it is powered on.

Vision-Based Control of Book Manipulation

The FRIEND's manipulator control structure to control the robot arm for book manipulation is shown in Figure 6.

It uses the robust vision methods that provide reliable information on the robot's environment in combination with the built-in sensors of the 7-DoF robot arm. The built-in sensors of the robot arm provide precise information on the position of all of the robot joints. The main modules of this structure are described briefly in the following. The focus is on vision-based book detection modules, as they are different from vision modules in FRIEND's ADL scenarios [19] concerning the manipulation of objects different from books. In ADL, the objects to be manipulated were different household objects such as bottles, glasses, and meal trays [3].

Vision-Based Book Detection

The books that FRIEND IV has to manipulate in the cataloging are uniformly and nearly identically colored and not marked or labeled. They are arranged on the book cart as explained in the section "Environment and Hardware" and as shown in Figure 7.

Two novel algorithms were developed and implemented to ensure robust and reliable book detection and grasping. The first one, called *book detection with stereo camera (BwS)*, is based on stereo vision and planar segmentation. It calculates the three-dimensional (3-D) coordinates of the upper right corner of the book to be grasped, which is the first book from the right in the cameras' images. The second algorithm, called *book detection with hand camera (BwH)*, performs two tasks: improvement (fine tuning) of the upper right corner of the first book, which is calculated by BwS, and the determination of the slope of the book with respect to the gripper.

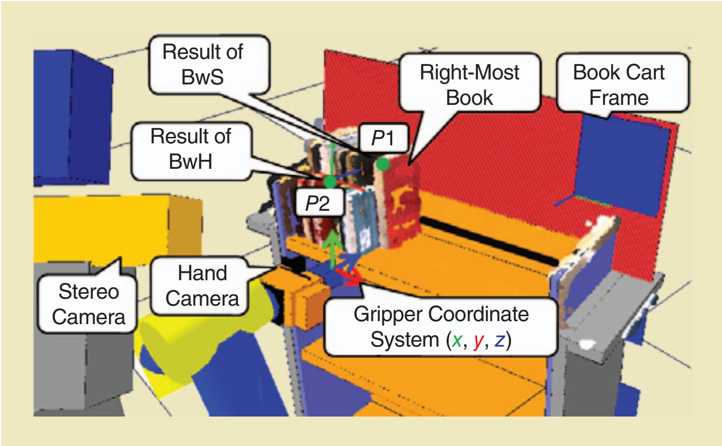

Figure 8. The MVR of the robot created using ImageNets showing the point cloud of the books on the shelf; points $P1$ and $P2$ are computed from BwS and BwH, respectively.

Book Detection with Stereo Camera

The BwS method was developed to overcome the problems of standard image processing operations such as edge detection, line segmentation, and parallelogram extraction and to cope with a cluttered scene and quite a large distance between the stereo cameras and the book cart. The BwS method is based on the fact that each book consists of several planar surfaces representing its sides. Because of the placement of the books on the book cart and due to the relative position of the robot with respect to the book cart, up to three planar surfaces of a book are visible: the top, front, and right side. The exact number of visible book surfaces and their sizes depend on the exact camera position with respect to the books on the cart. The development of this method is supported by ImageNets, a graphical framework developed in house [6]. The main idea behind ImageNets is the rapid and correct development and user-friendly implementation of image processing algorithms. Figure 7 shows the steps of the proposed image processing algorithm.

Using the stereo camera system of the robot, the stereo correspondence between the left and right stereo image is computed. The resulting disparity map is segmented into its primitive planar surfaces, where each planar region represents one possible side of a book in the scene. The segmented regions are analyzed based on their size, 3-D plane orientation, and location with respect to the book cart in 3-D; and candidate objects with 3-D plane orientation parallel to the back of the book cart and perpendicular to the shelf plane are initialized, where each candidate object represents the front of a book on the shelf. The book to be manipulated is then extracted from the object candidates, and the upper right corner ($P1$) of the extracted region is computed in 3-D [9]. Figure 7 shows $P1$ in 2-D, and Figure 8 shows the same point in the 3-D representation of the robot's environment, which is called mapped virtual reality (MVR) [8].

Book Detection with Hand Camera

The calculated point $P1$ resulting from BwS is sent to the path and trajectory planning module, which provides input to robot motion control module. Thus, the manipulator is moved so that its end-effector reaches the 3-D target point with the X and Y coordinates of the calculated $P1$ and predefined Z coordinate in front of the book cart, as shown in Figure 8. After reaching the target point, the hand camera is initialized. The image captured by the hand camera is at first preprocessed to reduce noise. The processed image is then converted to an edge image using Canny's algorithm. Books appear as regions in the edge image and are separated by their contours from other books. The applying of a contour-detection algorithm onto the Canny edge detected

Autonomous book grasping is based on vision-based control of FRIEND's manipulator.

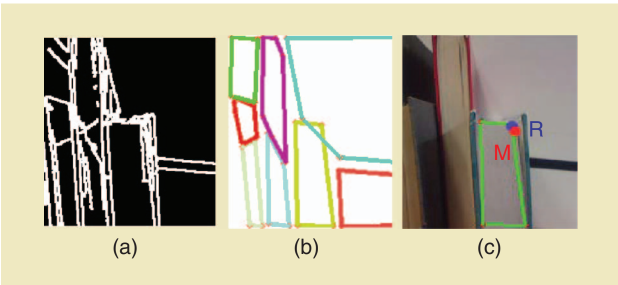

Figure 9. The main steps of book detection with the hand camera: (a) the Canny edge detected image, (b) the detected book candidates, and (c) the original image with detected right-most book.

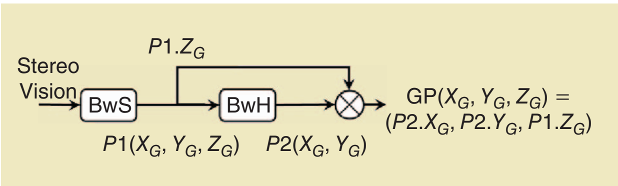

Figure 10. The combination of both BwS and BwH algorithms.

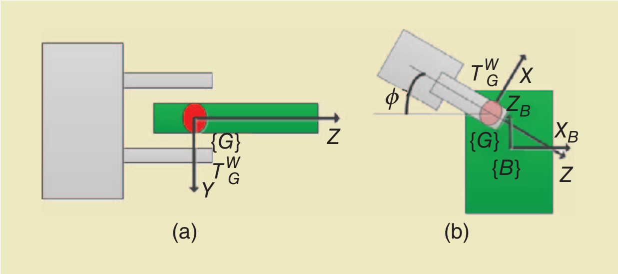

Figure 11. The book grasping: (a) the parallel gripper and gripper coordinate frame $\{G\}$ and (b) the book coordinate frame $\{B\}$ and the angle Φ for book placing.

image yields a set of possible book candidates. Candidates are analyzed based on different selection criteria such as form, size, and geometry and are merged when they belong to the same book [10]. An example of the result of the presented algorithm is shown in Figure 9. The first book from the right in the camera view is then extracted from the book candidates, and the upper right corner of the segmented book is computed [point R in Figure 9(c)]. The robot end-effector tracks the point R using image feature-based visual servoing until R is positioned in the center of the image [point M in Figure 9(c)] and the gripper is aligned with the book slope. The output of BwH is the position of the robot end-effector in 3-D (point $P2$ in Figure 8).

To define the grasping point, the outputs of BwS and BwH have to be merged, as shown in Figure 10. Suppose $P1(X_G, Y_G, Z_G)$ is the output of the BwS algorithm, where $X_G, Y_G,$ and Z_G refer to the gripper coordinate system, which is located in the middle of the gripper plates (Figure 8). $P1$ is passed to BwH algorithm, which in turns tracks the exact position of the upper right corner of the right most book and the output of BwH is $P2(X_G, Y_G, Z_G)$, the 3-D position of the robot end-effector where the upper right corner of the first book is in the center of the image received by the hand camera.

Let GP refer to the final grasping point, then $GP(X_G, Y_G, Z_G) = (P2.X_G, P2.Y_G, P1.Z_G)$. In other words, the X and Y coordinates of the grasping point are equal to the X and Y coordinates of the point $P2$, whereas the Z coordinate of GP is equal to the Z coordinate of $P1$.

Manipulation Planning

The result of vision-based book detection is used to update the workspace representation, which is implemented into FRIEND as an MVR (Figure 8). In addition, the visual information on books to be manipulated, the models (location, size, and orientation) of both the book cart and the book holder are obtained by marker-based 3-D reconstruction method. The MVR is constantly updated by the output of the vision-based book detection as explained above, and the manipulation planning in all tasks of book manipulation, grasping books from the book cart, placing them onto the book holder, and placing them back to the shelf of the book cart is done in updated MVR.

For any kind of motion done by the robotic arm, it is necessary to define a target frame T_G^W, where $\{G\}$ is the gripper and $\{W\}$ is the world-origin coordinate system placed at the basis of the robot arm. The target frame should be computed, so that a suitable collision free target configuration can be calculated through the inverse kinematics. This configuration is given to the path planning algorithm that is going to deliver a collision-free and user-safe path executed by the robot. The algorithm used in this article is called CellBiRRT [11], and it is a sampling-based approach. The calculated path is finally tracked by the robotic arm as realized by motion control (Figure 6).

The manipulation planning determines a sequence of actions needed to be done in order for the task to be executed autonomously. Grasping the book from a platform, the book cart, is done in cooperation with the vision system as explained, while placing an object back onto the cart platform is done using knowledge from previous tasks, e.g., the relative location between the gripper and the grasped book.

Figure 11 shows the pose of the end-effector of the robot arm in book grasping. The calculation of the gripper orientation is important for grasping. In this article, a parallel gripper is used, and the orientation is calculated as Figure 11 shows, using the formula

$$T_G^W = (T_B^W \cdot T_G^B), \tag{1}$$

where T_G^B is a relative frame between the gripper and the book, which is computed geometrically, so that the gripper plates lie between two books. The position adjustment of the gripper is done by the vision system using the BwH and BwS algorithms as explained. To achieve appropriate orientation for placing, additionally the angle $\Phi \in [0, \Phi_{\max}]$ in Figure 11 is calculated. Its value depends on the ability of the robot arm to be tilted appropriately. Introducing the angle Φ simplifies the placing of book at the book holder, especially because of distance between book holder and robot (Figure 12). The location of the gripper is now known, the book can be grasped, and the relative location between the gripper and the book is stored for further usage.

The placing of a book either on the book cart or on the book holder (Figure 12) is done similarly by

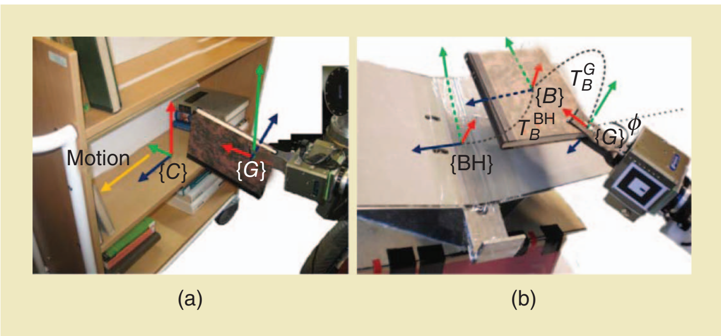

Figure 12. (a) Placing a book on the book cart. (b) The coordinate frames and the angle Φ for placing a book on the book holder.

calculating the necessary frames. The gripper location is calculated, so that the book is aligned to be parallel to the $\{C\}$ frame, e.g., the book cart's frame. If T_C^W is the book cart/book holder frame, obtained from MVR, the alignment of the book is done using again a similar form such as (1), that is, $T_B^W = (T_C^W \cdot T_B^C)$. The frame T_B^C relates the orientation of the book with the book cart/book holder. It can be extracted either by a database or geometrically. The gripper frame can be calculated using (1). In general, for each case the calculation of the relation T_B^C between the gripped book and the container, where it is going to be placed, is the first step. Since a relative frame T_G^B is assigned to each gripped object, the pose of the end-effector can be extracted.

Table 1. Success rate of the manipulation of 100 books in the FRIEND library workplace scenario.

Execution	Task 1	Task 2	Task 3	Task 4	The Complete Sequence of Tasks
Autonomous	84%	83%	89%	84 %	62%
With user interaction	99%	96%	99%	100%	95%

Table 2. User questionnaire results.

Questions	Possible Answers	Average Answer in User Acceptability Test of the FRIEND III	Answer of the FRIEND IV End User
1) What is your first impression about FRIEND?	Positive Negative Scary Strange	Positive	Very positive
2) Can FRIEND be supportive in your daily activities?	Very supportive Yes A little No	Yes	Very supportive
3) Is FRIEND better in assistance than care-personnel?	Yes No	No	Neither … nor
4) Could FRIEND replace the care-personnel?	Yes No	No	No
5) Is FRIEND user-friendly?	Yes No	Yes	Yes
6) Could you imagine using FRIEND once it is on the market?	Yes No	Yes	Yes

Performance Evaluation

To evaluate the performance of FRIEND IV in executing the usage scenario, an intensive test consisting of 100 consecutive runs was performed. In each run, the complete sequence of manipulation tasks was executed, which includes grasping the book from the book cart (Task 1), putting the grasped book on the book holder (Task 2), grasping the book from book holder after the user has completed the cataloging (Task 3), and returning the book on the lower shelf of the book cart (Task 4). In the case of the system failure in autonomous execution of a specific task, the end user was asked to complete the task through the HMI. Once the task was executed by the user, the system executed the subsequent task(s) autonomously. The experimental results show that executing the scenario through the execution of the sequence of individual tasks helped the end user control the system manually in case of failure in autonomous task execution.

In the performed 100 runs, the robotic system together with the end user was able to successfully complete the sequence of four tasks in 95 (95%) runs. In 62 runs, the system was able to execute the sequence of all four tasks autonomously. In 29 runs, the system failed in the autonomous executing of one task only, whereas in four runs the system failed in the autonomous execution of more than one task. Table 1 summarizes the experimental results. As evident, the average success rate for the autonomous execution of individual tasks is 85%, while this rate increases to 98.5% for the execution with the end user interaction.

The success in the autonomous execution of Task 1, grasping the book from the book cart, depends mainly on the results of the applied image processing algorithms. In the performed experiments, the implemented vision method was able to detect the grasping point of the book to be manipulated correctly in 90 runs. The correct detection means that the vision-based detected point was between the gripper plates in the so-called tolerance area, as defined in [9]. However, in some cases, the cause of the failure was an inability to grasp the book. This happened, for example, when the horizontally placed second book on the shelf of the book cart (the book next to the vertically placed book to be manipulated) was too thin (less than $\sim$1.7 cm, which is a width requirement for reliable book grasping as detailed in [9]), so that the robot was not able to insert the left plate of the gripper in the gap between the first book (book to be manipulated) and the third book in a row, which was also vertically placed. This resulted in the collision of the gripper with the third book. In such cases the user was asked to align the gripper manually between the first and the third book using the HMI. Some of the failures in execution of Task 2, putting the grasped book on the book holder, were due to the inaccurate computation of the book size, which resulted in misplacement of the book on the book holder. Two common reasons that negatively affect executing all four tasks are 1) the physical limitation of the robot arm to reach the target configuration, which requires the user to move the wheelchair closer to the desired target object and redo the task, and 2) the inaccuracy in calibrating the robot with its surrounding environment.

In the current state of development and six months after the end user started work as librarian with the assistance of FRIEND IV, the execution time of all the four tasks without user interaction is ~5 min. For the cataloging process itself, the end user needs, on average, between 12 and 14 min. One of the goals in further FRIEND development is to improve the software and hardware implementation so that the time for autonomous execution can be significantly reduced. The time the end user needs for completing the cataloging of one book depends on her experience as a librarian and in working with speech recognition software. With increased experience, this time is expected to become much shorter.

The book holder works autonomously but can also be manipulated by the user through the user interface to turn over a page or close the book.

User Acceptability

The robotic system FRIEND III was part of a study of user acceptance of service robots [12]. In the qualitative part of that study, several service robots from different areas of application, including FRIEND III, were introduced to 20 elderly people. With this study, FRIEND was the only robot that obtained the highest possible rate of acceptability. The reason for such a high acceptance rate is that for the interviewed people, who were mainly healthy and fit elderly, the vision of having a robotic system as a support to their independent life at home instead of being dependent on conventional personal care is of high importance. The performance of FRIEND III in ADL scenarios confirmed that such robotic assistance is possible.

Further measuring of the acceptance of FRIEND III was done during a system test with patients in the Neurological Rehabilitation Centre, Bremen, and during the presentation of FRIEND III at the REHACARE fair in Düsseldorf (2009). For this purpose, individuals who tested FRIEND were asked to fill in a questionnaire, the results of which are shown in Table 2. The same questionnaire was used for evaluating the user acceptability in the library workplace scenario described in this article. The feedback of the FRIEND IV end user is shown in Table 2 in comparison with the user acceptability test results of FRIEND III. It is important to note that the individuals involved in the acceptability test of FRIEND III had less severe disabilities than the FRIEND IV end user.

The data from user questionnaire suggest that the acceptance of FRIEND IV is higher than that of FRIEND III. The higher acceptance recorded may partially be explained by the fact that the more severely disabled user of this system has inherently greater readiness to accept automated assistance.

In addition to the FRIEND IV end user, two of her assistants were asked to measure the acceptance of FRIEND IV. Without any technical background on FRIEND, both assistants needed less than half an hour of introduction. They had very positive impressions and emphasized the easiness of control of FRIEND. They also stressed the importance of FRIEND in giving independence to the end user in performing a professional task with which the care personnel cannot help.

Apart from answers to the survey questions, the FRIEND IV end user has given her positive impression on how her professional life has been changed. She is very happy to find a job after 11 years without work in which she can finally use her intellectual skills. She believes that once the development is finished and FRIEND is available on the market in the future, it can be significant support to her in doing her tasks in the library and to other people with disabilities working in different workplaces.

Conclusions

The research and development of the assistive robot FRIEND started about 15 years ago. In its first and second generations, different user support scenarios in ADL were considered. The first trials on supporting disabled people in a work environment were performed with the third generation, FRIEND III. In the dissemination process of the FRIEND III, it was decided to focus on supporting the integration of disabled people into professional life. The reason is twofold: first, the integration of people with disabilities into professional life increases their self-confidence and life satisfaction; second, the successful implementation will increase interest in such systems from both employers and financial supporters of development. It is nonetheless recognized that implementing FRIEND in a work place increases the complexity of the assistive robotic system because the possible adaptations of the work place environment are limited.

This article discusses the steps that were necessary to transform FRIEND into a system that supports a quadriplegic end user at work on a daily basis. These steps do not concern only the technical adjustments and improvements of the system but also the overcoming of reservations from employers, care personal, and disabled users. Clarification of details with other organizations such as the department of employment and insurance companies are also critical. The robot usage scenario presented in this article is the support of a quadriplegic individual working as a librarian retrospectively cataloging collections of old books. All the tasks concerning book manipulation such as grasping the book from the book cart and placing it at the specially designed book holder to be read by the end user are carried out autonomously by the system FRIEND, while the cataloging itself is done by the end user using speech recognition. The technical adaptation of the FRIEND system has been driven by the requirement that the robotic system should be very reliable, with little need for unplanned user intervention, and by the requirement that an appropriate standard of safety should be achieved. However, the autonomous functioning of the robot based on vision-based object manipulation cannot always be guaranteed due to a variety of external influences. In the case of failure of the autonomous robot's task execution, the end user intervenes using an advanced HMI. A thorough evaluation of FRIEND's performance in supporting the end user demonstrated that a success rate of 62% was reached for successful fully autonomous task execution, i.e., in 38% of cases, a user intervention was necessary. With the end user intervention, an overall success rate of 95% was achieved. This success rate is an encouraging measure of how FRIEND is able to successfully support the end user in a realistic working scenario.

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