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Applications of a Fluidic Artificial Hand in the Field of Rehabilitation

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1. Introduction

Since the early middle of last century, use of artificial robotic hands in the field of rehabilitation has been associated with prosthetic devices used for the therapy of upper limb deficiency. Artificial manipulators of the last century were used in general for industrial applications or for service tasks of telemanipulation.

In the last three decades, service robotics developed very rapidly. In recent years, robotic systems which are able to complete service tasks in direct cooperation with humans became popular [Yuta et al., (2006)].

Modern robotic rehabilitation devices are intelligent systems used for movement assistance, physical support and indoor navigation, physical rehabilitation, vocational rehabilitation, and interactive entertainment [Bien, Stefanov (2004)].

Dextrous manipulation has become the subject of research for many scientists around the world and artificial hands are used in a wide area of applications [Venkataraman, Iberall (1990)].

Investigations of hand construction, artificial design, and manipulation abilities resulted in the development of different hand prototypes for service robotics, prosthetics, and rehabilitation [Muzumdar (2004); DeLaurentis et al., (2000); Pons et al., (1998); Pons et al., (2000); Lee et al., (2000); Light, Chappell, (2000); Weir et al., (2001); Kyberd et al., (2003); Walker (2003); Boblan et al., (1999); Plettenburg (2002); Hirzinger et al., (2004); Jacobsen et al. (1986); Townsend (2000)].

In view of the dexterity of natural hands, it may be assumed that there are problems in the development of dextrous artificial hands, including controllability, hand geometry, hand functionality, development and placement of sensors; sensory fusion, and the need for better actuators [Subramanian T. Venkataraman, Thea Iberall (1990)].

As regards the different criteria related to artificial manipulators, which were discussed in research literature, we share the opinion that acceptance of robotic devices by the user plays a very important role in the development of manipulator constructions. Safety and simplicity of usage are no less important aspects of device architectures. Universality of components, their modularity and changeability should be taken into account and can allow for reducing the energy consumption and production costs of whole systems.

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This chapter will highlight applications of an artificial robotic hand actuated by flexible fluidic actuators developed at the Forschungszentrum Karlsruhe (Karlsruhe Research Centre, Germany) [Kargov et al., 2006].

Flexible fluidic actuators were developed as an alternative to other actuation principles of today, such as electromotors, shape memory alloys, or McKibben muscles.

Up to date, fluidic actuators have impeded the design of artificial actuation systems due to their relatively high weight and low power. Modern fluidic actuators have already been identified as being particularly suitable for macrorobotics, compared to other actuator technologies and considering several criteria, including stress improvements, bandwidth, intrinsic compliance, packaging, good power to weight ratio, and high dynamics [Hollerbach et al., 1992].

2. Fluidic artificial hand

2.1 System components and mechatronic design

Since 1999, a multifunctional artificial hand has been developed at the Karlsruhe Research Centre that meets modern technical standards. This development was based on the invention of new flexible fluidic actuators [Schulz et al., 1999]. The construction of first actuators was easy. They were built of thin plastic films in a very compact manner as a two-layered body with two separated chambers which contained a small pipe for fluid supply. The elastic chambers were expanded when the pressure was applied to the actuator. This expansion behaviour was taken into account by a new concept of an artificial finger joint, which was presented in 2000. The functional principle of such artificial joints consists in converting the energy of chamber inflation into a rotational movement between two thin plates that are connected to each other (Fig. 1a,b). Different prototypes of fluid actuators based on this principle have been built by the Institute of Applied Computer Science up to date [Schulz et al., 1999].

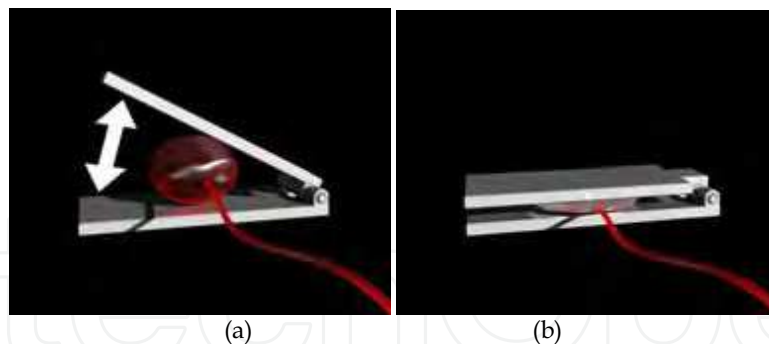


Fig. 1a,b. Functional principle of flexible fluidic actuators.

The current model of an artificial finger joint consists of a flexible fluidic actuator made of a reinforced flexible bellow. Both fronts of the actuator are attached to solid fittings mounted on the joint, which transmit the pulling force of axial expansion to the joint (Fig. 2.). A special tissue covers the bellow and reduces the radial expansion of the actuator under pressure.

Two major advantages of these actuators are their low weight and inherent compliance. Each actuator weighs only 2.6 grams and is built of lightweight materials. In comparison

with fluid cylinders, flexible fluidic actuators can transmit energy in the same manner, but have a higher power-to-weight ratio at the same pressure and volume. Small dimensions of actuators of 12 mm in diameter and 12 mm in length allow for an integration directly in the artificial finger joint. A torque of up to 0.8 Nm can be achieved for such joint at 6 bar pressure.



Fig. 2. Flexible fluidic actuator with artificial joint.

The development of artificial joints led to the design of a multi-articulated artificial hand (Fig. 3.). Biometric data of a natural hand were used to design the prototype of this robot hand. Made of lightweight aluminium with high tensile strength properties, the basic construction consists of the 5-fingered durable and stable mechanical framework with a natural appearance. The artificial metacarpus with the fingers is made up of artificial bones and joints. The number of joints can be varied for other prototypes and optimised for special applications without almost any losses of the anthropomorphic appearance of the hand, its dexterity, functioning, and high dynamics.



Fig. 3. Current prototype of a fluid hand

All joints and actuators in the hand are constructed identically. This makes the hand construction modular, actuators can be interchanged with each other, and the number of degrees of freedom can be changed. Consequently, redesigning of the end manipulator and the whole reconstruction of the system are not necessary.

Current prototypes of a fluid hand have 8 active actuated joints and 3 passive joints which are not actuated. The index and middle fingers have four active joints. The ring and small fingers have one actuated joint and one passive joint each. The thumb is actuated by two joints. The base joint of the thumb is placed perpendicular to the middle joint to achieve an opposite movement.

Other important components of the fluid hand are electronic valves and the control unit (Fig. 4.), which are integrated in the artificial metacarpus. Valves and electronics are custom-made, as suitable commercially available devices are lacking.



Fig. 4. Electric valve and control unit.

Valves are operated according to the mono-stable principle. They supply the fluid for fluidic actuators and keep the fluid pipeline closed, if no current is applied. In this way, the position of fingers can be saved during grasping. Small dimensions of valves of 23x11x13 mm allow for their integration in the hand. Low power consumption of the valves of 1 Watt saves energy and a flow rate of 14 l/min (by air) ensures a high dynamics of hand movements.

The electronic unit is built by SMD technology, except for some few discrete components, and arranged on a four-layered circuit board. With the dimensions of 51 mm / 40 mm / 9 mm, it consists of a programmable microcontroller PIC16F877 by Microchip (Microchip Technology Inc., USA), drivers for the valves, an integrated analogue-digital converter which can digitize 8 signals collected by positioning, pressure, and tactile sensors as well as mini connectors which allow for the direct connection of all periphery units to the electronics. Sensors can be integrated optionally in the hand and use analogue/digital ports to communicate with the control unit. Additionally, the electronics offers I2C, CAN, and SPI interfaces to interact with external robotic devices, such as the robot arm and an RS232 interface for programming the control unit and diagnosing the whole control system from a PC.

2.2 Control architecture and functioning

Communication and data transfer between the controller and external devices take place via serial CAN, SPI, I2C or RS232 interfaces. In general, control signals, such as the joint number, angles for positioning the joints or a number of programmed grip types are transmitted from the external control system to the fluid hand in this way.

A fluid hand works as follows: the controller collects external control signals and operates four mono-stable valves via the respective driver modules. Microvalves provide the corresponding flexible fluidic actuators with external air pressure. The actuators are inflated under pressure, forces of expansion are generated, and the flexion movement of hand digits is achieved. The extension movement is performed by a spring element.

2.3 Performance and functionality

Due to the use of fluidic actuators and the possibility of controlling each joint separately, a large operating range of hand motion is achieved. Every digit of the hand with an active base joint can be flexed by up to 90°. All actuators can be flexed independently of each other.

The possibility of moving each finger joint or joint group separately during grasping is a very important advantage of artificial hands with an anthropomorphic appearance and functionality. Using this benefit, artificial manipulators can perform in general all basic grasping patterns of human hands.

Different tasks of daily life, such as grasping and manipulating differently sized household objects, can be performed using a large number of combinations of movable joints. A cylindrical power grasp, precision grasp, tripod grasp, hook grasp, and spherical grasp can be performed. (Fig. 5.). The important functions of the index finger, such as pressing a key or operating a switch, can be implemented as well.

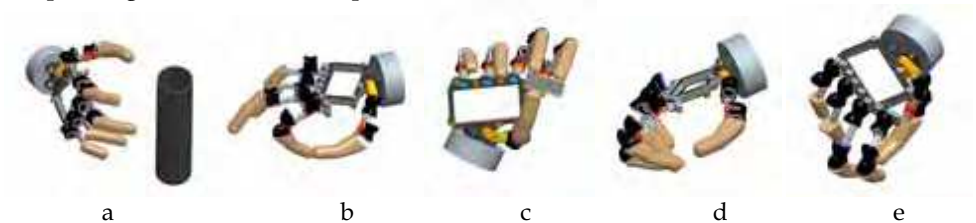


Fig. 5. Grip types which can be performed by the fluid hand. a - cylindrical power grasp, b - precision grasp, c - tripod grasp, d - hook grasp, and e - spherical grasp.

A multiple number of degrees of freedom (DOF) and compliance of the fluidic actuators and elastic finger pads give rise to a fluid hand with the specific feature of adaptive grasping. Artificial fingers conform to the shape of an object when grasping it. Additionally, the self-adapting properties of the hand provide for a correct distribution of contact force when grasping and manipulating objects, which is similar to that of natural hands.

2.4 Technical characteristics

The technical characteristics of the hand are presented in Table I. Small-sized and low-weight components were used for the mechanical construction of the hand, resulting in a low total weight of 350 g. The weight of the skeletal framework is 245 g, including 8 fluidic actuators and the elastic finger pads.

Prehension forces are distributed over a large contact area during grasping and stable holding with low grip forces is possible. Hence, a cylindrical object simulating the handle of a suitcase can be held with a maximum of 110 N in a hook grasp.

Using the custom-made valves, the hand can be closed within two seconds.

The fluid hand has different interfaces and can be integrated in different systems for service robotics and rehabilitation, which use different control interfaces.

The fluid hand requires an external power supply of 7.5V up to 12 V and air pressure supply of 6 bar.

3. Applications of a fluidic artificial hand

3.1 Humanoid robot for the household environment

3.1.1 System overview

The humanoid robot ARMAR-III [Asfour et al., 2006] has been developed within the German Humanoid Project (SFB 588: Collaborative Research Center on Humanoid Robots). The goal of this project is the development of humanoid robots which safely coexist with humans, interactively communicate with humans, and usefully manipulate objects in built-for-human environments. In particular, it is focussed on the integration of motor, perception, and cognition components, such as multimodal human-humanoid interaction and human-humanoid co-operation in order to be able to demonstrate robot tasks in a kitchen environment. Designing the robot is aimed at obtaining a humanoid that closely mimics the sensory and sensory-motor capabilities of the human being. The robot should be able to deal with a household environment and the wide variety of objects and activities encountered in it. Therefore, the robot must be designed in a comprehensive manner, such that a wide range of tasks (and not only a particular task) can be performed.

The humanoid robot ARMAR-III (Fig. 6) has 43 mechanical degrees of freedom (DoF): the head has a total number of 7 DoFs, the waist has 3 DoFs, each arm has 7 DoFs, each hand has 8 DoFs. The mobile platform has 3 DoFs. In addition, the hands consist of 16 DoFs. From the kinematics control point of view, the robot consists of seven sub-systems: head, left arm, right arm, left hand, right hand, torso, and a mobile platform. The upper body has been designed to be modular and light-weight while retaining a size and proportion similar to those of an average person. For locomotion, a mobile platform is used, which allows for holonomic movability in the application area. The head has seven DoFs and is equipped with two eyes.

The eyes have a common tilt and can sway independently. The visual system is mounted on a four-DoF neck mechanism. Each eye is equipped with two digital colour cameras (wide and narrow angle) to allow for simple visual-motor behaviours, such as tracking and saccadic motions towards salient regions as well as for more complex visual tasks, such as hand-eye co-ordination.

The head features human-like characteristics in motion and response, that is, the neck and the eyes have a human-like speed and range of motion. Furthermore, the head is equipped with a microphone array, consisting of six microphones (two in the ears, two in the front, and two in back of the head). This is necessary for 3D acoustic localisation.



Fig. 6. The humanoid robot ARMAR-III in the demonstration environment (kitchen). The robot consists of seven sub-systems: head, left arm, right arm, left hand, right hand, torso, and a mobile platform.

The main goal of our research is to build humanoid robots which support people in their daily life. The main component of such a robot for handling objects is its manipulation system. The design of the arms is based on the observation of the motion range of a human arm. From the mechanical point of view, the human arm can be modelled by a first-order approximation as a mechanical manipulator with seven DoFs.

The sections of the arm are linked by one-DoF rotational joints, each specifying a selective motion. Consequently, the arms have been designed in an anthropomorphic way: three DoFs in the shoulder, two DoFs in the elbow, and two DoFs in the wrist. Each arm is equipped with a five-fingered hand with eight DoFs ([Schulz et al., 2004]). The goal of performing tasks in human-centred environments results in a number of requirements on the sensor system, especially on that of the manipulation system. To achieve different control modalities, different sensors are integrated in the arm. Each joint is equipped with motor encoders, axis sensors, and joint torque sensors to allow for position, velocity, and torque control. Due to space restrictions and mechanical limitations, the sensor configuration differs. For example, a sensor fitting into the elbow will most likely be too large for the wrist. In the current version of the arms, motor revolution speed, position of axis, and axis torque are monitored in each joint. In the wrists 6D force/torque sensors (ATI Industrial Automation, www.ati-ia.com) are used for position and force control. Four planar skin pads (see [Kerpa et al., 2003]) are mounted to the front and back side of each shoulder, thus also serving as a protective cover for the shoulder joints. Similarly, cylindrical skin pads are mounted to the upper and lower arms, respectively.

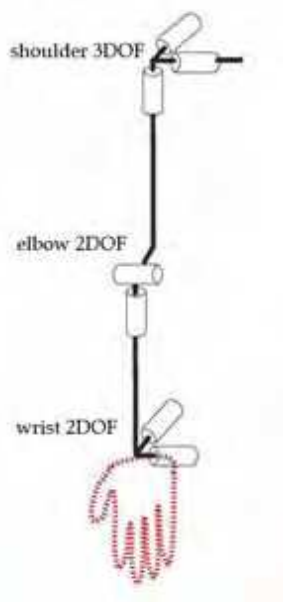


Fig. 7. Kinematics of the arm with 7 DOFs.

3.1.2 Control architecture

The control architecture comprises the following three levels: task planning level, synchronisation and coordination level, and sensor-actor level [Asfour et al., 2005]. A given

task is decomposed into several sub-tasks. These represent sequences of actions the sub-systems of the humanoid robot must carry out to accomplish the task goal. The co-ordinated execution of a task requires the scheduling of the sub-tasks and their synchronisation with logical conditions, external and internal events.

Fig. 8 shows the block diagram of the control architecture with three levels, global and active models, and a multi-modal user interface [Asfour et al., 2005]:

- The task planning level specifies the sub-tasks for the multiple sub-systems of the robot. This level represents the highest level with functions of task representation and is responsible for the scheduling of tasks and management of resources and skills. It generates the sub-tasks for the different sub-systems of the robot autonomously or interactively by a human operator. The sub-tasks generated for the lower level contain the information necessary for the task execution, e.g. parameters of objects to be manipulated in the task or the 3D information about the environment. According to the task description, the sub-system's controllers are selected here and activated to achieve the given task goal.

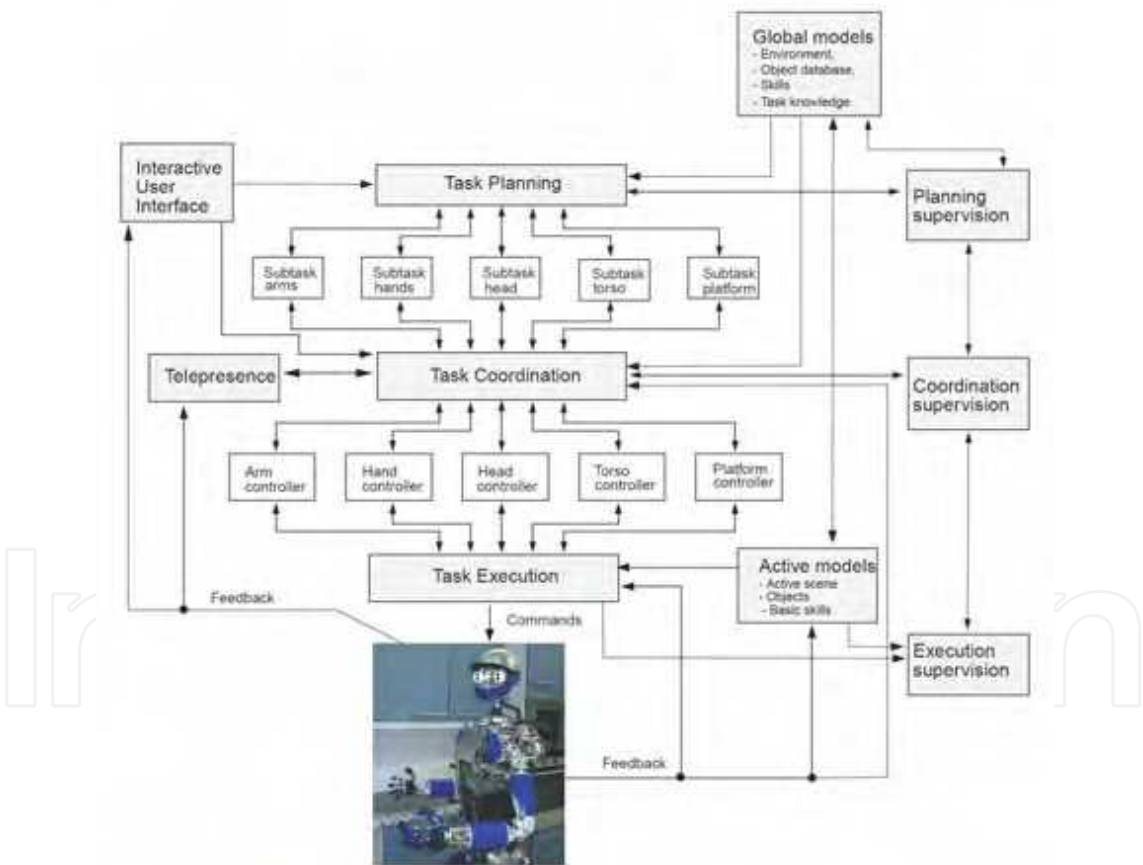


Fig. 8. Hierarchical control architecture for co-ordinated task execution in humanoid robots: planning, co-ordination, and execution level.

The task co-ordination level activates sequential/parallel actions for the execution level in order to achieve the given task goal. The sub-tasks are provided by the task planning level. As on the planning level, the execution of the sub-tasks in an appropriate schedule can be modified/reorganised by a tele-operator or user via an interactive user interface.

- The task execution level is characterised by control theory to execute specified sensor-motor control commands. This level uses task-specific local models of the environment and objects. Hereinafter, these models shall be referred to as *active models*.
- The active models (*short-term memory*) play a central role in this architecture. They are first initialised by the global models (*long-term memory*) and can be updated mainly by the perception system. The novel idea of the active models, as they are suggested here, is their independent actualisation and reorganisation. An active model consists of the internal knowledge representation, interfaces, inputs and outputs for information extraction, and optionally active parts for actualisation/reorganisation (update strategies, correlation with other active models or global models, learning procedure, logical reasoning, etc.).
- Internal system events and execution errors are detected among local sensor data. These events/errors are used as feedback to the task co-ordination level in order to take appropriate measures. For example, a new alternative execution plan can be generated to react to internal events of the robot sub-systems or to environmental stimuli.

In addition to graphical user interfaces (GUIs), the user interface provides the possibility for an interaction using natural language. Telepresence techniques enable the operator to supervise and tele-operate the robot and, thus, to solve exceptions which can arise for various reasons.

3.1.3 Integrated grasp planning and visual object localisation

As a first step towards a complete humanoid grasping system, an integrated approach to grasp planning has been developed [Morales et al., 2006]. The central idea of this system is the existence of a database with the models of all the objects present in the robot workspace. Based on this central fact, two necessary modules are developed: a visual system able to locate and recognise the objects and an offline grasp analyser that provides the most feasible grasp configurations for each object. The results provided by these modules are stored and used by the control system of the humanoid to decide and execute the grasp of a particular object. Fig. 9 gives an overview of the grasp planning system.

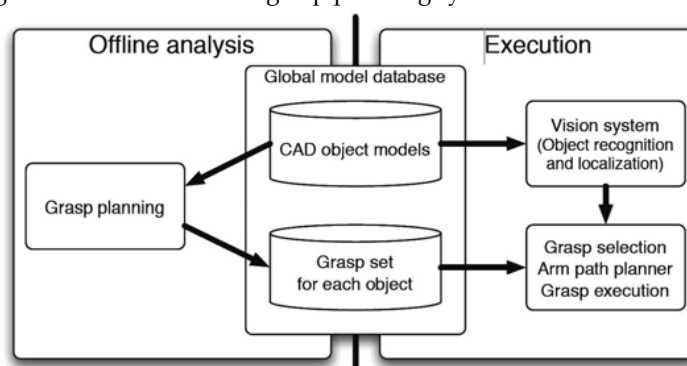


Fig. 9. An overview of the grasp planning system.

The grasp planning system consists of three components (see [Morales et al., 2006]):

- The **global model database**. It is the core of our approach. It does not only contain the CAD models of all the objects, but also stores a set of feasible grasps for each object. Moreover, this database is the interface between the different modules of the system.
- The offline **grasp analyser** that uses the model of the objects and of the hand to compute in a simulation environment a set of stable grasps. The results produced by this analysis are stored in the grasps database to be used by the other modules.
- A **online visual procedure to identify objects in stereo images** by matching the features of a pair of images with the 3D pre-built models of such objects. After recognising the target object, it determines its location and pose. This information is necessary to reach the object (see [Azad et al., 2006]).

Once an object has been localised in the work scene, a grasp for that object is selected from the set of pre-computed stable grasps. This is instanced to a particular arm/hand configuration that takes into account the particular pose and reachability conditions of the object. This results in an approaching position and orientation. A path planner reaches that specified grasp location and orientation. Finally, the grasp is executed. These modules are not described in this paper, since they are still under development.

3.1.4 Outlook

The robot represents a highly integrated system suitable not only for research on manipulation, sensor-motor co-ordination, and human-robot interaction, but also for real applications in human-centred environments that make higher requirements on perception and action abilities of the robot. These are different scientific and technical problems, such as navigation, humanoid manipulation and grasping with a 5-finger hand, object recognition and localisation, task co-ordination as well as multi-modal interaction. The term multi-modality includes the communication modalities intuitive for the user, such as speech, gesture, and haptics (physical contact between the human and the robot), which will be used to command or instruct the robot system directly. Concerning the co-operation between the user and the robot - for example in the joint manipulation of objects - it is important for the robot to recognise the human's intention, to remember the acts that have already been carried out together, and to apply this knowledge correctly in the individual case. Great effort is spent on safety, as this is a very important aspect of the man-machine co-operation.

An outstanding property of the system is its ability to learn. As a result, the system can be led to new, formerly unknown problems, for example to new terms and new objects. Even new motions will be learned with the aid of the human and they can be corrected in an interactive way by the user.

3.2 Rehabilitation wheelchair system / Rehabilitation robot FRIEND-II equipped with the FZK hand: dexterous and safe manipulation

3.2.1. System description

The rehabilitation robotics system FRIEND developed by the Institute of Automation of the University of Bremen (IAT) can be used by disabled people, for instance, with upper limb impairments, to act more autonomously in daily life as well as in the working environment. For the detailed description of this robotics system, its main components, and envisaged functionalities see another chapter in this book about FRIEND I+II.

Service robots in general and rehabilitation robots in particular have to act in the real world and not in a specially installed working cell, i.e. an artificial world, as common industrial robots. To act safely and effectively in a real unstructured environment, this kind of robots requires dexterous manipulators with at least 7 joints (degrees of freedom or DoF) like a human arm. The effects of the limited motion repertoire of “Manus”-ARM, the 6-joint kinematic structure of which corresponds to that of an ordinary industrial robot, were demonstrated during the experiments with FRIEND-I [Martens et al., 2001]. The next generation of this rehabilitation robotics system, FRIEND-II (Fig. 10), therefore is equipped with a dexterous lightweight robot arm with 7 joints [Ivlev et al., 2005]. This electrically driven robot arm was developed by *amtec robotics*, Berlin (www.amtec-robotics.com) with the functional specification given by the IAT. To implement humanlike kinematics, the arm is composed of a series of turn and pan joints with perpendicular axes. The combination of a turn-pan-turn-joint is kinematically equivalent to a spherical joint like the human shoulder or the wrist joint. The middle (4th) pan joint corresponds to the elbow (Fig. 11). At the wrist, a multi-axis force/torque sensor of the type Gamma by ATI-Industrial Automation (NC, USA) is integrated. To increase the grasping capabilities, the arm may be equipped optionally with a 5-finger artificial fluid hand instead of a conventional two-finger gripper. In this way, the range of objects which can be grasped is extended and manipulation safety is improved thanks to the hand compliancy. Although it operates very closely to the user, this “soft” hand is safe and cannot harm a human or objects in the workspace. FRIEND-II also is equipped with a stereo pan-tilt-zoom camera system and a “smart tray” which is able to detect objects. The rack shown in Fig. 10, on which the cameras are mounted, was chosen to determine the optimal location of the cameras and will later be exchanged for a more ergonomic rack. The multi-processor control PC is mounted at the rear of the wheelchair.



Fig. 10. Rehabilitation Robot FRIEND-II with fluidic Hand.

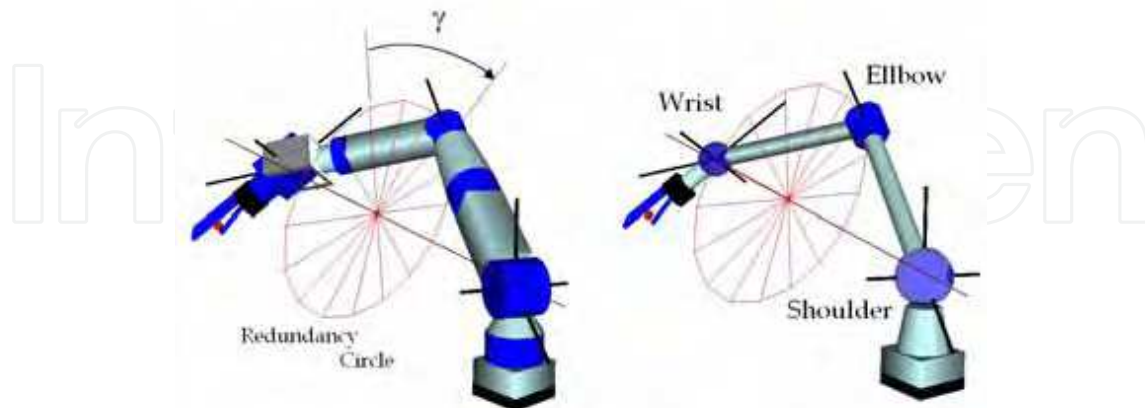


Fig. 11. Kinematic structure of a 7-joint manipulator and its self-motion manifold.

3.2.2. Grasping cases and dexterous arm control

Similar to a human arm, a dexterous manipulator with humanlike 7-joint kinematics allows for changes of the Cartesian elbow position in space without influencing the hand location. This feature is called *self-motion* and characterises in general the manipulative manifold of dexterous robots. In a 7-joint robot arm a manipulative manifold is a circle – the so-called redundancy circle, with the centre on the line connecting the intersection points of the shoulder and wrist joints (Fig. 11). The elbow position on the redundancy circle usually is determined by the redundancy angle γ . By varying γ , the arm configuration is changed without changing the hand location. This feature is utilised by the configuration control of dexterous 7-joint manipulators [Seraji, 1989]. Compared to conventional 6-joint kinematics, however, kinematic dexterity causes significant control problems, because dexterous kinematic structures with more than 6 DoFs are described by an underdetermined systems of non-linear algebraic equations.

For the successful and practically useable control of dexterous manipulators, a new control concept, called Kinematic Configuration Control (KCC), has been developed [Ivlev et al., 2000]. The concept combines the advantages of the kinematic control paradigm, enabling exact regulation of tool motion and typically used by conventional robots with 6 DoFs, with the possibility of precisely controllable changes of the robot configuration.

The standard algorithm of kinematic control is based on the following vector equation:

$${}_{(s)}\mathbf{g} = \mathbf{f}({}_{(n)}\mathbf{q}), \quad (1)$$

which describes the relationship between the n -dimensional joint variables vector ${}_{(n)}\mathbf{q}$ and the s -dimensional vector ${}_{(s)}\mathbf{g}$ representing the location of the end effector (hand) in the workspace. The non-linear vector function \mathbf{f} consists of s scalar functions specifying the kinematic structure of the robot as an open kinematic chain.

For non-redundant robots with $n=s$, the equation system (1) can be solved in a closed form: ${}_{(s)}\mathbf{q} = \mathbf{f}^{-1}({}_{(s)}\mathbf{g})$. For each end effector location ${}_{(s)}\mathbf{g}$ within the robot workspace $W \in \mathbb{R}^s$, this solution yields a finite number of possible configurations. In the case of redundant kinematics $n>s$, the equation system (1) is underdetermined and can be solved in a so-called functionally closed form, when the inverse functions $\mathbf{f}^{-1}({}_{(s)}\mathbf{g}, {}_{(r)}\mathbf{q})$ contain $r = n - s$ joint

variables as parameters. In order to fully specify the equation system (1), r additional conditions (scalar equations) are needed.

In the case of 7 DoF kinematics $n=7$. The dimension s of the vector ${}_{(s)}\mathbf{g}$ depends on the manipulation and/or grasping task. If the manipulation task follows a fully defined trajectory in the 3D Cartesian working space $W \in \mathfrak{R}^3$, the three Cartesian coordinates as well as the hand orientation angles are specified unambiguously and the vector is ${}_{(6)}\mathbf{g} = [X, Y, Z, Yaw, Pitch, Roll]$ with $s=6$. The same condition results when grasping objects of parallelepiped shape, as for example a book (Fig. 12a). The hand location here may also be considered as having been determined completely, because the object may be gripped in the middle for equilibrium reasons. In this case, $s=6$ as well. Therefore, just one additional condition to resolve the redundancy will be needed for such kind of manipulation and grasping tasks.

However, such a fully defined specification of the hand location is encountered rather rarely in service and rehabilitation robotics. Figures 12b and 12c show two other typical grasping cases. If a cylinder (e.g. a glass or a bottle) must be grasped, the orientation angle Yaw cannot be defined precisely: in general, it may have an arbitrary value between 0° and $\pm 180^\circ$. In this case, ${}_{(5)}\mathbf{g} = [X, Y, Z, Pitch, Roll]$ with $s = 5$ and for redundancy, two additional conditions are required. When grasping a ball-shaped object, such as an apple or an egg, all three orientation angles are free, ${}_{(3)}\mathbf{g} = [X, Y, Z]$, $s = 3$ and three additional conditions already will be needed to resolve the redundancy.

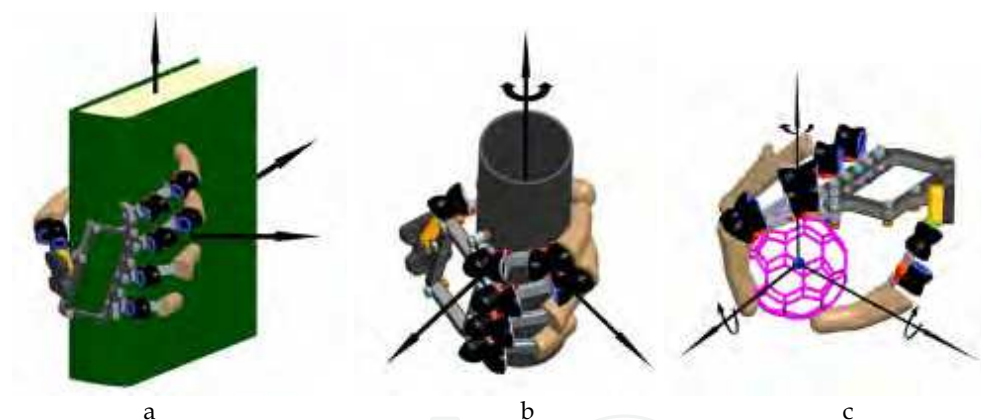


Fig. 12. a - completely defined hand location when grasping a book ($s=6$), b - Partly defined hand orientation when grasping a glass ($s=5$), c - Undefined hand orientation when grasping a ball ($s=3$).

The main idea of resolving redundancy in KCC in contrast to other concepts of closed solutions for 7-joint kinematics [Dahm 1997, Asfour 1999] is to control the robot arm relative to the actual robot pose (spatial posture) instead of the actual configuration, as it is typical of other control methods. The difference between a robot configuration and a robot pose is defined as follows: a pose is the placement of robot links and joints in the 3D Cartesian working space, while a configuration is a set of joint angles – i.e. a point in the 7D configuration space for a robot arm with 7 joints.

To control the robot arm relative to the current pose, the kinematic chain with a number of additional virtual (imaginary) links [Ivlev et al., 1997, Ivlev et al., 1999] is applied, such that

the constrained kinematic structure becomes non-redundant – this means that the number of degrees of freedom becomes equal to the working space dimension. For the case of ${}_{(6)}g = [X, Y, Z, Yaw, Pitch, Roll]$, just one imaginary link will be needed. In the case of 7-joint kinematics, it connects the robot elbow with the Cartesian point, where the elbow was placed by the previous control cycle (Fig. 13). For this kinematic structure, the kinematic equations can be solved analytically – like for conventional robots with 6 joints, and the desired hand position can be achieved with high accuracy.

The optimised KCC algorithm described in [Ivlev et al., 2000] allows to calculate exactly the elbow position E_{min} on the redundancy circle with the minimal distance to the previous elbow position E' – say, with minimal length of the imaginary link. The implemented routine contains only 21 multiplications, 11 additions as well as 1 square root and, hence, is very fast: the calculation requires only 40 μs on a PC with a 1 GHz Intel processor [Ivlev et al., 2004]. Within a typical robot control cycle of 16 ms, enough time remains to simulate the variation of the elbow position on the redundant circle and to generate other valid robot configurations. After this, the best robot pose considering the current spatial situation can be selected.

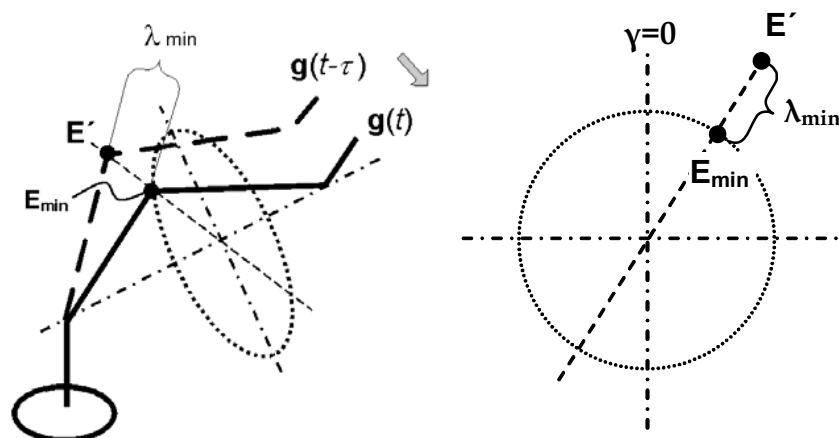


Fig. 13. Method of redundancy resolving in KCC.

In the grasping cases with $s=5$ and $s=3$, the new kinematic structures with two and four imaginary links, respectively, have to be assembled and the new inverse functions generated. In these functions, one or three parameters (lengths of imaginary links), respectively, must be chosen according to the current spatial situation. Alternatively, the inverse functions for the case $s=6$ (i.e. the fast optimised KCC algorithm) can be used. In this case, one (*Yaw*) or all three hand orientation angles *Yaw*, *Pitch*, and *Roll* (Fig. 12b and Fig. 12c) have to be varied in the hand location vector ${}_{(6)}g = [X, Y, Z, Yaw, Pitch, Roll]$ in addition to variations of the elbow position on the redundancy circle.

To simulate these variations and to choose a suitable hand orientation as well as an elbow position, the working environment, including the grasping object as well as the relevant obstacles, has to be mapped. To select a collision-free hand location and arm pose during the simulation process, the distances between obstacles and robot arm, including hand, have to be calculated permanently. In FRIEND, this problem has been solved by the so-called Mapped Virtual Reality (MVR) which models the spatial situation in an extremely simplified form and, at the same time, reflects the main spatial correlations [Feuser et al.,

2005]. The objects from the real world – obstacles, objects to be grasped as well as robot arm and hand - are mapped into this virtual reality as simple shapes covering the real objects. Only three simple 3D bodies are used in the MVR: cuboid, cylinder, and sphere. By combining these basic bodies, nearly any complex structure can be assembled. For object-oriented design, a base-class body is introduced, which provides the attributes all 3D bodies have. These are the position and the rotation. For the three simple 3D bodies, three classes are introduced, which all inherit from the base-class body: Cuboid, Cylinder, and Sphere. These classes add attributes which are needed for the description of the corresponding 3D body. For the cuboid, these are height, depth, and width, for the cylinder, height and radius, and for the sphere, only the radius.

For modelling robot links, a class CLink is used, which holds information about the transformation with respect to the previous link. This transformation is described by conventional DH parameters. To model the body structure of a link, a list is used, which holds objects of the three simple 3D bodies introduced before. Generally, a virtual robot consists of a certain number of links, where the number of links specifies the robot DoF. Therefore, the virtual robot is modelled by a list of CLink objects, where the order in the list describes the order of the links and their transformations, i.e. the kinematics of the virtual robot. The list and all needed methods are combined in the class CRobotModel.

The virtual obstacles are also modelled by the three simple 3D bodies and their class representatives and are stored in a list. The needed functionality is combined in the class CRobotWorld which inherits from CRobotModel. The result is a class which offers methods and attributes for modelling a robot and its environment.

The information in the class CRobotWorld can be used to calculate distances between the virtual robot and virtual obstacles. For this task, the GJK algorithm [Gilbert et al., 1988] is used. It provides information about the minimal distance between two convex polyhedrons and the minimal distance vector. The GJK algorithm only works with points (vertices) that describe the polyhedrons. For this purpose, a class Distance is introduced, which encapsulates the GJK algorithm and provides for a conversion of the classes describing the simple 3D bodies in a set of points. A cuboid can be described simply by eight vertices points, a cylinder has to be approximated by a set of points. To describe a sphere, it is not needed to approximate its surface by a polyhedron: its centre point and radius are sufficient. After computation by the GJK algorithm, the distance up to the sphere surface can be calculated by subtraction of the radius.

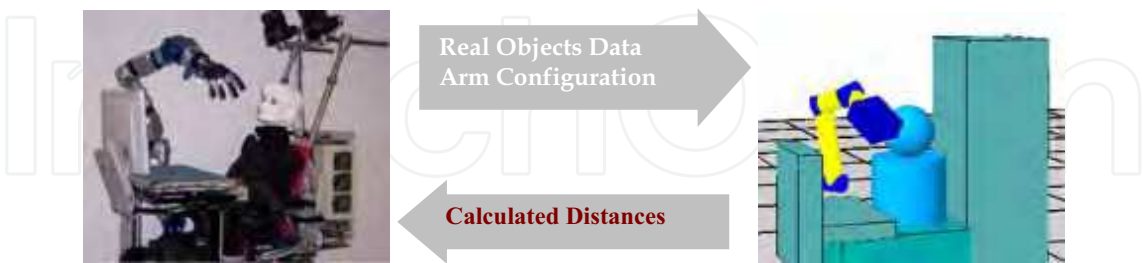


Fig. 14. Concept of Mapped Virtual reality (MVR).

The minimal distance to an obstacle can be obtained by calculating the distance between the obstacle and all body elements of each link of the robot and then choosing the smallest distance.

The classes CRobotModel and CRobotWorld both to render the virtual scene via OpenGL, but the main task of the MVR is to approximate a robot and its environment exactly enough to calculate the distances to obstacles. Therefore, very detailed graphical representation is not desired and not necessary.

In contrast to common VR, the task of which is to reflect the real world as exactly as possible and usually without influencing a situation in the real world, MVR interacts with the real world (Fig. 14). The robot configuration is transferred from the real robot and permanently updated. So, the virtual world reflects the real macro-situation and the distance can be calculated now without any difficulty instead of being measured. The task of external sensors (e.g. cameras) can be reduced to the detection of new objects which have to be mapped into the MVR instead of observing all obstacles in the workspace and measuring distances. Such task distribution increases the safety of manipulation by reduction of technical complexity.

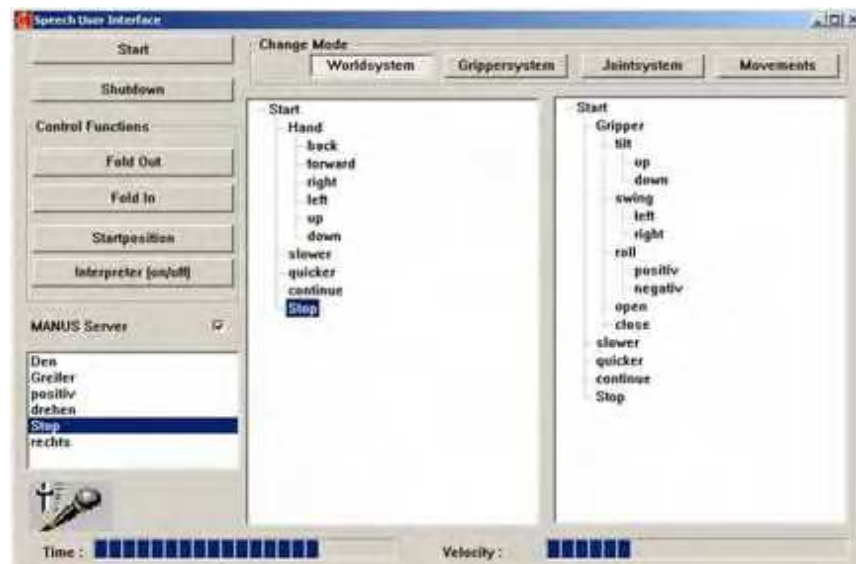


Fig. 15. Man-machine-interface with a speech command tree for the control of hand movements.

3.2.3. User-controlled hand movements

Many specific interfaces adapted to specific handicaps exist to control devices, e.g. devices which are controlled by the chin, tongue, eye position, etc. Speech recognition also is among these devices. An important requirement for the selection of the user interface is the general control philosophy "shared autonomy" which will be used in FRIEND-II [Volosyak et al., 2005]. Shared autonomy means that the robot acts autonomously at any possible time. But to restrict the complexity of the automation system and to enhance the overall robustness, a fall-back level is introduced. If the system detects a situation which cannot be resolved within the system's autonomy, it asks the user actively for support. This means that the system then relies on the mental capabilities of the user. The user can also actively take control of the robot and suspend the automation system. Speech recognition fulfils the requirement of a user interface for shared control. This is the reason why FRIEND-II is

equipped with a speech control interface shown in Fig. 15, which was also used in FRIEND-I [Martens et al., 2001].

The speech processing system translates naturally spoken words into commands. It consists of the two modules of speech recogniser and command interpreter. The speech recogniser consists of the speech recognition software ViaVoice Gold™ by IBM®, which translates naturally spoken commands entered via a microphone into specific words using pre-determined grammar. The recognised words are transmitted to the command interpreter which translates the words or text sequences received into system commands.

For safety reasons, the set of commands is organised in a hierarchical command tree. To suppress the misinterpretation of commands, such as interpreted noise or misspelled words, a path in the tree must be completed to cause a system action. This minimises the possibility of erroneous interpretations. If the system is in the user command mode and the command interpreter does not receive a permissible command within a fixed period of time, the system automatically returns to a safe state. The entire tree and the current state of the command are represented graphically on the flat screen, because the user can easily recognise the state of the system, if it is presented in the form of pictograms (Fig. 15).

Speech input allows for the control of the robot on different levels of complexity. Low-level commands which control directly a single robot joint or the robot tool (like “gripper up”) are as possible as high-level commands like “pour in a drink”. If the system is not able to recognise objects in the environment or if inconsistent data are retrieved from object recognition, the system may ask the user for support. In this case, the user may control e.g. the pan-tilt heads of the cameras.

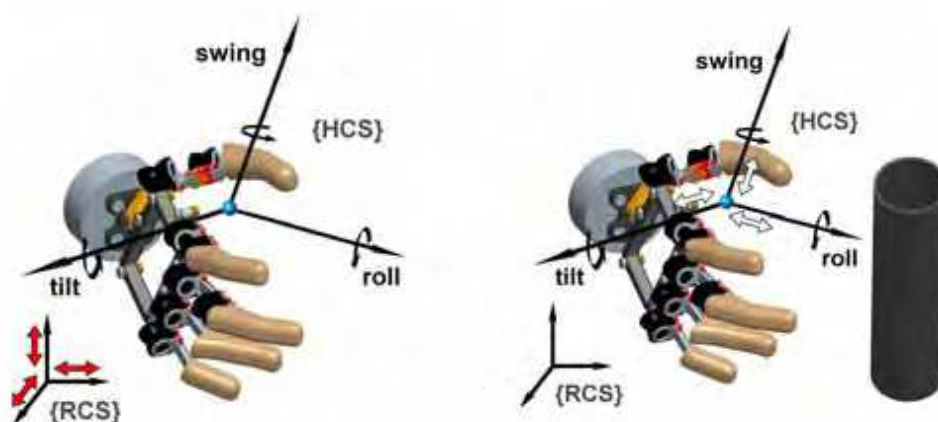


Fig. 16. Different reference coordinate systems during user-controlled hand movements: “mixed” motion directions (left), hand-fixed approaching movements (right).

By means of simple speech commands, the robot may be operated as usual by tele-operation of robot arms with respect to different coordinate systems: a reference coordinate system fixed to the robot arm base (RCS) as well as a coordinate system fixed at the hand (HCS). As shown in [Ivlev et al., 2004], the accuracy and stability of the end effector movements in the tele-operation mode increase due to the use of KCC compared to the so-called resolved-rate control which is used by default for the dexterous manipulator. The individual control of all joints is an alternative control variant and very useful, if complete arm reconfiguration

through the manipulation is required. Such a situation may occur for example during manipulation in a cluster environment, while avoiding obstacles. The pre-condition is that the hand orientation can be changed freely. This means, for example, no filled glass has been grasped before.

In the manual control of some rehabilitation robots, for example “Manus”-ARM (www.exactdynamics.nl), translational Cartesian movement defaults occur relative to the RCS, the rotary ones occur for the HCS. These “mixed” motion directions are shown in Fig. 16, left. If the approaching movement of the hand to an object is commanded, however, the HCS system is significantly more comfortable for the user than the RCS coordinate system, as was found out in the first experiments with FRIEND. Figure 16 (right) shows the directions of the approaching motion to the object.

With the help of the speech control interface, the complete control sequences can be carried out. For example, if the user wants to pick up an object placed on the tray, a possible command sequence might be *Hand right - Hand left - Hand down - Stop - Hand open - Hand forward - Stop - Hand close*. With the last command, the power hook grip can be activated to grasp, for example, cylindrical objects, such as a bottle or a glass (Fig. 12b). To activate other kinds of grips of the dexterous fluidic hand, for example a “precision grip” or a “spherical grip”, special commands can be programmed. Due to the general compliancy of the fluidic hand, however, the majority of relevant objects, such as a book or a ball (Fig. 12a and Fig. 12c), handled by FRIEND can be grasped safely with the power hook grip.

The elbow position on the redundancy circle can be commanded in the same way. Possible commands for this action may be “Elbow left”-“Elbow right” or “Elbow up”-“Elbow down” depending on the current position of the elbow. The first command set corresponds to the situation when the elbow is located close to the upper point of the redundancy circle (i.e. the position with redundancy angle $\gamma \approx 0^\circ$, s. Fig. 17), where the “down” direction is not unique. In all other elbow placements, the second two commands are more convenient from the user’s point of view and can be used for controlling the elbow without loss of safety. Since the user observes the actions of the robot arm continuously, he or she can interrupt its actions in erroneous situations at any moment. As the user is supported by MVR which observes the current spatial situation and anyway stops the arm movement when a collision with the user or the environment may occur, safety of the manipulation processes increases significantly and can be classified as dependable.

The extended manipulatory facility of the dexterous robotic system FRIEND-II in comparison with conventional 6-joint kinematics is illustrated in Fig. 17. In the spatial situation shown, it is possible to grasp the glass without colliding with the bottle only by a skillful use of all 7 joints.

3.2.4. Outlook

FRIEND II is intended to increase the usability of service robots designed for paralysed people with quadriplegia or similar disabilities (paralysis down from the neck due to spinal cord injuries above vertebra C6 and movement of arms, hands, and fingers is impossible). FRIEND II helps to be independent of nursing staff for several uninterrupted hours in professional and private life. To achieve this goal, a range of new technical solutions is introduced. Keywords for the new technology are: manipulative as well as sensory redundancy, shared autonomy, smart devices, and ambient intelligence [Volosyak et al., 2005]. Figure 18 presents the concept of an “intelligent kitchen”. A large

number of different action sequences like “pour in and serve a drink”, “take, prepare, and serve a frozen meal”, “support eating”, “open a drawer”, “fetch and handle a book”, “fetch and handle some tool” are necessary to fulfill the user’s demands, to overcome the complaints about the existing systems, and to give the user a minimum of independence of the nursing staff for several uninterrupted hours. As additional requirements, FRIEND II will have a human-like robustness and flexibility for the autonomous control of unforeseen variations in the environment. Use of the dexterous 7-joint arm with human-like kinematic configuration control and a compliant fluidic 5-finger hand will help at least to solve the problems of manipulative robustness, flexibility in handling objects, and safety.



Fig. 17. Example of dexterous manipulation: a 6-joint arm can’t grasp a glass without collision with a bottle (left); by controllable movement of elbow it will be possible (right).



Fig. 18. FRIEND II in intelligent home environment.

3.3 Upper limb prosthesis

The loss of an upper limb implies a significant restriction of function and the individual has to cope with the stigma of being perceived as incomplete. Currently, upper limb-deficient individuals can either be fitted with a hook-type terminal device that provides good functionality and grasping force feedback, but poor cosmetics that are not accepted by most potential users in Europe. Therefore, most persons are fitted with a purely cosmetic hand or with an electrically driven hand that provides at least some cosmetic, but limited functionality. Since externally driven prostheses have been introduced to the market in the early 1970s an increasing number of patients have been fitted with these hands. However; approximately one third of all limb-deficient persons do not use their prosthesis at all [Atkins 1996]. In the last two decades, some of the achievements in the development of new materials and technologies were integrated in the design of artificial robot hands, resulting in higher dexterity. Artificial hands that are used in prosthetics have only very little in common with robot hands, which will be demonstrated in this chapter.

The following constraints should be considered when designing a prosthetic hand. They are based on the experience of different projects dealing with prosthetic hand design [Keller 1947, Peizer 1969, Weir 2003, Kyberd 2004, Pylatiuk 2007].

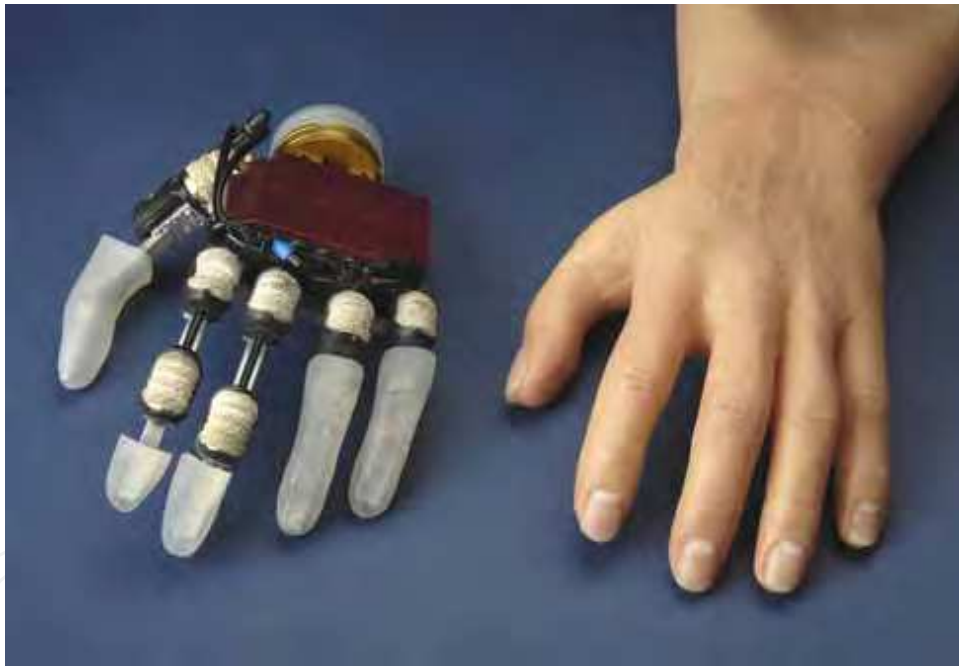


Fig. 19. A cosmetic glove made of silicone rubber covers the mechanics of the multifunctional prosthesis [Schulz 2005]. The thumb can be moved in a plane transverse to the index and middle finger.

- *Weight:* The mass of a prosthetic hand has to be below 500 grams. Otherwise, most users would not accept the technical aid. Every gram is perceived as an external load that must be carried, so the lighter a prosthetic hand is, the better accepted it will be. Although a lightweight design of robot grippers is also

wanted in order to reduce the moments in the joints of the robot arm needed to move the terminal device, most commercial robot hands have a mass that considerably exceeds 500 g.

- *Compact design:* In prosthetic hands a very compact design is needed to allow for the fitting of a maximum number of upper limb-deficient persons. If not all requisite components were within the artificial hand, the large number of individuals with a transradial amputation could not be fitted. By contrast, many robot hands use the space at the forelimb to actuate the hand.
- *Appearance:* As most users of prosthetic hands, especially female users, do not want to attract attention to themselves, the design of a prosthetic hand should mimic a natural hand as closely as possible (Fig. 19). This includes different colours used to match the cosmetic glove to that of the user's skin. The design of robot hands usually is very technical. Additionally, the position of the thumb has a large impact on the appearance of the hand. In most commercial prostheses, the thumb's plane of motion is in direct opposition to the index and middle finger instead of a more natural transverse plane of motion.
- *Sound:* Any sound that originates from a prosthesis may annoy the user and should therefore be avoided. The noise level of commercial prosthetic hands is less than 45 dB at 1 m distance, which is almost imperceptible in surroundings with background noise, like an office.
- *Price:* The resources in most national health care systems are increasingly limited and in clinical practice, health insurance judges the therapeutic effects against the costs of a compensatory aid individually for every patient. In terms of economic efficiency, a prosthetic hand has to be a simple, but functional device, whereas robot hands typically are much more complex and, as a consequence, the expenses may be up to 20 times those of a prosthetic hand.
- *Power consumption:* The energy to process control signals and move the fingers of a prosthetic hand is typically supplied by rechargeable batteries of limited capacity. Therefore, efficient use of the battery energy is required and can be achieved by turning the controller to a stand-by mode when not used as well as by using actuators that do not require energy as soon as an object is grasped.
- *Sensors:* Robot hands need information from sensors about the flexion angle of each joint of the hand and about the occurring grasping forces, whereas commercial prosthetic hands do not have sensors, as the hand position is controlled visually by the user.
- *Grasping patterns:* The human hand is capable of grasping an object reliably with a vast number of different prehension patterns due to its versatility and ability to conform to the shape of an object. Commercial prosthetic hands only have one degree of freedom and, hence, can grasp only with a cylindrical power grasp or with the tip of the thumb, index, and middle finger. Multifunctional hands as described in detail in [Schulz 2005] offer additional prehension patterns (Fig. 20).
- *Grasping force:* A minimum pinch force of 67 N was proposed to enable the users to perform all activities with their artificial hands. If the fingers of a prosthetic hand have more than 1 DOF and, thus, can conform to the shape of an object, the requisite grasping force is significantly lower [Kargov 2004].



Fig. 20. From a neutral position (left), the following prehension patterns can be performed: cylindrical power grasp, index position, tip grasp, lateral grasp, and hook grasp.

- *Grasping speed:* Since their introduction in the 1970s, commercial prostheses have closed the fingers within one second, which can be taken as a benchmark. Just recently, prosthetic hands were introduced, which allow for much more speedy grasping.
- *Sensory feedback:* The lack of sensory information in electrically driven prosthetic hands is one of the main reasons for prosthesis rejection. The user has to estimate the force exerted by the prosthesis while grasping and the posture of the fingers has to be controlled visually.
- *Control:* Prosthetic upper limbs are typically controlled by switches, pressure sensors or myoelectric surface electrodes that are operated by the residual limb in the socket. The control of several independent DOFs has been a challenge, but with the introduction of microprocessors and new methods of biosignal analysis, future control systems will be easier for the patient to be learned and operation of the prosthetic aid will be more intuitive [Reischl 2004, Englehart 2003].
- *Reliability:* Both prosthetic and robotic hand users usually favour a reliable, but simple technical aid to a more sophisticated, independent device that malfunctions regularly. Especially users with a bilateral upper limb loss depend on their prosthetic hands.

Just recently, new prosthetic hands with increased functionality were presented [Schulz 2005, www.touchbionics.com]. For example the multifunctional prosthesis from the Forschungszentrum Karlsruhe, Germany allows for different prehension patterns and also includes sensory feedback [Schulz 2005, Pylatiuk 2006]. It is based on the same actuators described in 2.1 (Fig. 2), but it is driven by a micro hydraulic system (Fig. 4, 21), that is housed within the metacarpus of the hand.



Fig. 21. A custom-made hydraulic pump.

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The coupling of several areas of the medical field with recent advances in robotic systems has seen a paradigm shift in our approach to selected sectors of medical care, especially over the last decade. Rehabilitation medicine is one such area. The development of advanced robotic systems has ushered with it an exponential number of trials and experiments aimed at optimising restoration of quality of life to those who are physically debilitated. Despite these developments, there remains a paucity in the presentation of these advances in the form of a comprehensive tool. This book was written to present the most recent advances in rehabilitation robotics known to date from the perspective of some of the leading experts in the field and presents an interesting array of developments put into 33 comprehensive chapters. The chapters are presented in a way that the reader will get a seamless impression of the current concepts of optimal modes of both experimental and applicable roles of robotic devices.

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