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Abstract
In this paper we will present the design of the dexterous DLR Hand II and experiments performed with it so far. In various experiments and demonstrations we could show the abilities of our articulated hand and gain a lot of experience in what artificial hands can do, what abilities they need and where their limitations lie. We discuss the achievements and the shortfalls of DLR Hand II in comparison to the human hand and show possible improvements. The physical force of this hand is similar to the power of an average human hand, but the size of the artificial hand is still larger. In order to grasp and manipulate objects typically used by humans it is necessary to further reduce the size. We need new concepts to keep the hand as powerful as DLR Hand II.

Keywords: Dexterous Hand, Experiments, Teleoperation, Grasping, Manipulation, Integration.

1. Introduction

Hands and arms are powerful tools of humans to interact with the environment. Manipulating grasping and carrying a wide variety of objects, using tools to perform desired tasks, catching and throwing objects are basic abilities we need our arms and hands for. As robots start to serve men as „service robots“ or prolonged arms in a priori unknown environments and partly unknown tasks, it is straightforward to equip robots with artificial hands in order to achieve abilities as mentioned above. The current developments on this field at DLR aim at future robonaut systems for space applications on one side and at the terrestrial use of arms with articulated hands on mobile platforms on the other side. In this paper we present the design of our current hand version DLR Hand II and show the design path to the next generation. In the last few years, lots of robotic hands have been developed [4, 9, 10]. Different control strategies for robust and stable grasps were implemented and their efficiency is demonstrated in more or less complicated experiments. But still there are not too many hands that do at least some part of the things that man can do with his hands. We designed two generations of anthropomorphic hands so far. In various experiments and demonstrations we could show the abilities of our hands and gain a lot of experience in what artificial hands can do, what abilities and features they need and where their limitations lie. In the following we would like to give an overview over the design, the applications and experiments performed with DLR Hand II, this hands abilities and the things that need to be improved. The result is a system that is both compact and easy to use. The hand system has been structured as modular as possible in order to provide easy access to measured data, simple maintenance and quick replacement or enhancement of the system to adapt to new needs.

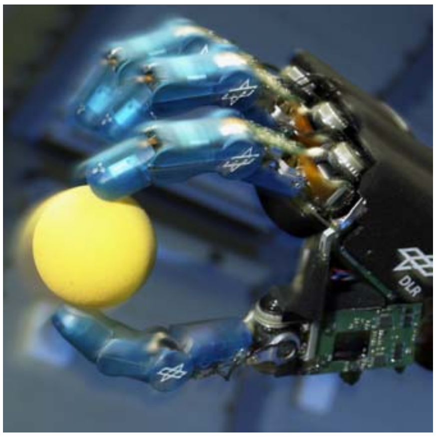

Fig. 1: DLR Hand II

2. Design of DLR Hand II

The main aspects in developing DLR Hand II were maximum flexibility and performance to improve autonomous grasping and fine manipulation possibilities and the use of fully integrated actuators and electronics in the hand itself. This is the only possibility to use an articulated hand on different types of robots which are not specially prepared. Hands with forearms [4] or hands with just grasping abilities allow a much smaller design due to the possibility of using the additional space in the forearm for actuators and electronics, but restrict the usability with e.g. industrial robots. Farther displacement of those components as known from the MIT-Utah Hand [9] nearly disables the use on mobile robots. Furthermore the hand must be easy to maintain and use.

2.1 Kinematic Design of DLR Hand II

The design process started on an anthropomorphic base by evaluation of different workspace/ manipulability measures like those of Salisbury [5] or Yoshikawa [6] to get optimal ratios of link lengths of one finger. The desired objects to be manipulated and technological restrictions resulted in absolute link lengths. The second step was to get suitable hand kinematics. The design was based on performance tests with scalable virtual models. Soon we realized the need to being able to change the position of the 4th finger and the thumb as well. To perform power grasps the best position of the second, third and forth finger is parallel. On the other hand performing precision grasps and fine manipulation requires huge regions of intersection of the ranges of motion. For this reason we chose an additional degree of freedom which enables to switch the hand between two configurations. This is realized with a tiny motor and a spindle gear. Realizable kinematics were calculated and imported to the two virtually found configurations and optimized unless the actual configuration with a total of 13 DOF was found.

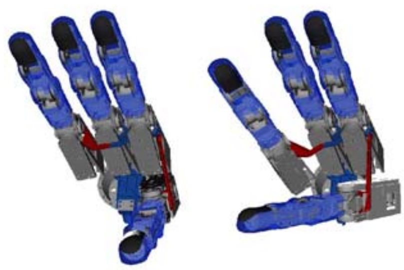

Fig. 2: The two hand configurations

2.2 Actuator System

DLR Hand II consists of four identical fingers with three independent joints and one additional coupled joint each. The actuation system basically consists of brushless DC motors, tooth belts, harmonic drive gears and differential bevel gears in the base joint. The differential joint allows to use the full power of the two actuators for flexion or extension. Since this is the motion where most of the available torque is needed, it allows to use the torque of both actuators jointly for most of the time. Thus we can utilize smaller motors. The motor in the medial joint has less power than the motors in the base joint, however there is an additional reduction of 2:1 by the transmission belt. So we achieve the torque which corresponds to the torque of the base joint actuators for a force of 30 N at the finger tip. In all joints we use identical harmonic drives, since the smallest appropriate type can stand the torque in both joints.

2.3 Sensor Equipment

A dexterous robot hand for autonomous operation and teleoperation needs at least a set of force and position sensors. We use other sensors additionally to this basic scheme of strain gauge based joint torque sensors and specially designed potentiometers in each joint. Besides the torque sensors we designed a tiny six dimensional force torque sensor for the finger tip [3]. The potentiometers would not be absolutely necessary, since one may calculate the joint position from the motor position, however they provide a more accurate information and eliminate the need of referencing the fingers after power up. The potentiometer provide a joint angle resolution of 1/10°. Speed sensors improve the controllability of the actuators. They are basically position sensors, where the speed can be calculated by differentiation of the position signal. For this reason each motor has two linear Hall effect sensors which are used for the commutation as well. The position within the magnetic cycle of the motor can be derived from these two sinusoidal signals with a phase shift of 120°. Temperature sensors for monitoring and compensation complete the sensor equipment.

2.4 Force Torque Fingertip Sensor

A tiny six dimensional force torque sensor (20 mm ∅, 16 mm in height) with digital output has been developed for the fingertip. The measure ranges are 30 N for the forces and 600 Nmm for the torques. Also a 200 % mechanical overload protection is provided in the structure. With internal electronics the sensor can provide force and torque data at very high bandwidth and with very low noise. The sensor is based on foil strain gauge bridges and delivers digital values of forces and torques applied to the sensor. All analog signal conditioning and the A/D converters are within the sensor's metal body (fig 3).

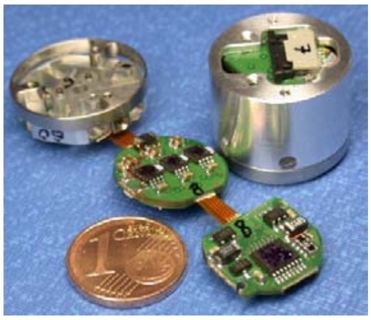

Fig. 3: Force torque sensor

2.5 Communication Architecture

The hand is controlled by an external computer. In order to use the hand freely on different manipulators and to reduce the amount of cables and noise, we designed a fully integrated serial communication system. Each finger holds one communication controller in its base unit. The controller collects the data of five ADCs per finger with together 40 channels of 12 bit resolution and transmits them to the communication controller in the hand base and distributes the data from the controller scheme to the actuators for finger control. The communication controller in the hand base links the serial data stream of each finger to the data stream of the external control computer. By this architecture we are able to limit the number of external cables of DLR Hand II to a four line power supply and an eight line communication interface.

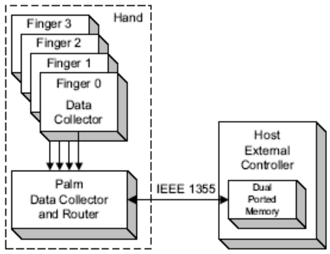

Fig. 4: Communication architecture

2.6 Customized Tool Adapter

The DLR Hand II is equipped with a specially designed tool adapter for quick mounting. This adapter can be used to exchange the hand for a different tool. Also, to provide higher availability, the hand can be replaced by a spare hand. The adapter itself consists of a robot-side fixture and a tool-side plug. It is designed to not only attach DLR Hand II but also other tools used with our robots. It is based on a commercially available mechanical coupling which has been modified implementing 32 electrical connections. The hand uses twelve of them leaving capacity for other tools. The communication runs via four differentially transmitted signal lines. The four power supply lines include two lines of DC power for the actuators and two lines of AC power for the electronics. For the latter, we use 50 V, 20 kHz and tiny transformers to provide the voltages needed. Completing this concept, our Light Weight Arms provide internal cables for the hand. To replace the hand, one simply has to turn the motor power supply off, open the latch of the tool adapter, replace the hand, close the latch, and turn on the motor power supply again.

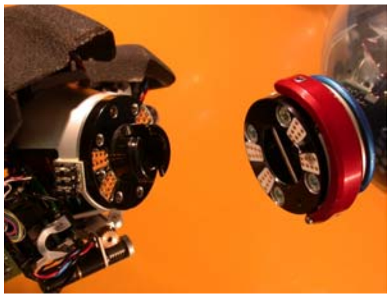

Fig. 5: Customized tool adapter

2.7 Features of the DLR Hand II

The following features enable the hand to be used in the different experiments, applications and demonstrations of section 3. ***1) Fingers Can Be Bent Backwards:*** Although this feature introduces singularities in the Cartesian mode it increases the grasping abilities very much: While usual finger designs only offers point contact at the finger tips in case of precision grasps, bending the fingers backwards permits much more robust line contact with a so-called pinch grasp. ***2) Palm Design and Shape:*** For power grasps the palm design is crucial, as the palm is essential to the stability of a power grasp. We used rapid prototyping to optimize the shape. In terms of power grasp planning, palm design is still a topic of research. ***3) Reconfigurable palm:*** One design feature of the DLR Hand II is the reconfigurable palm. Similar to human hands the DLR Hand has an additional DOF in the palm to adapt the hand pose to the actual need: For power grasps, a "flat" palm is needed, while for precision grasps and fine manipulation we wish to have a configuration with opposing fingers. We can switch between these two hand configurations. ***4) Speed:*** The joint speed of about 360 °/s enables the hand to perform actions where high speed is necessary. This holds especially true for the piano playing demonstration as well as for the ball catching [8]. In our view this speed is sufficient. ***5) High Degree of Integration:*** Especially when putting together more complex robotic systems as e.g. a mobile platform with DLR Arm and DLR Hand II mounted on it, easy integrability is very important. The fact that there is no need for additional hardware except from a control computer and the customized tool adapter proved to be a major advantage**.** ***6) Flexible Control Software Architecture:*** One important feature of our hand is the flexible control software architecture [2]. We can quickly realize new applications and consistently switch between controllers and applications in real-time from an external interface. At the same time an operator can interrupt each action using a graphical user interface. ***7) Motion Teaching:*** Pre-planning of grasps and grasp movements is one possibility to plan finger trajectories. In practice, however, there is the need of teaching finger trajectories or hand poses manually. Thus we realized a motion and pose teaching facility. We can store trajectories or given hand poses which can be teached either using a data glove or a zero torque control mode of the fingers.

3. Experiments

In the context of a robotic hand there are mainly two independent fields of applications. In the first area, an operator controls a robotic hand and arm to perform tasks at places he cannot be present himself for various reasons. In the second area, the robotic system performs autonomous tasks, that were previously taught with a number of parameters to adjust to the actual environment.

3.1 Teleoperation Experiments

1) Experiments with a data glove: The most intuitive way to control a robotic hand is by making it follow the movements of a human hand, e.g. by the use of a data glove. However, a robotic hand differs kinematically from human hands. Thus, a mapping between the measured postures of the human hand and the desired posture of the robotic hand is needed like proposed in [11]. Here the goal was to map tip positions of the human and robotic hand, neglecting posture of the links. This approach is feasible for grasping objects by precision grasps. However, it depends on the training set of the neural net and thus on the user it was trained for. It is not suitable for power grasps, since the position of the links is not directly controllable. Another approach to map joint angles is suitable for power grasps and is intuitively and easily adjustable to different users.

2) Telemanipulation using stereo vision, data glove and force feedback: In one setup used in several demonstrations an operator was several 100 km away from the robotic environment. The goal was to prove the suitability of DLR Hand II and DLR Arm II to perform every day tasks via telemanipulation. The operator could control position and orientation of the arm using a control ball. The hand was controlled using a data glove as described above with a VTI Cybergrasp exoskeleton to create one dimensional force feedback per finger. The data connection was routed to an ISDN line, connecting the remote operator's site to the robotic scenery in our lab (fig. 6). The remote operator was provided with visual stereo feedback transmitted via ISDN or a satellite link. Different tasks were performed as e.g. pouring a glass of wine from a bottle, opening and closing drawers, grasping objects, switching light switches etc. There are several requirements experienced in this setup. First of all the hand needs to be able to perform power grasps for handling large objects as bottles and boxes. For this type of grasp a soft finger surface with sufficient friction is useful in order to improve adjustment to the object's surface and keep required normal forces small. Additionally, sufficient power is required because the usual gravitational load put on the hand is about 2-3 kg and enough reserve is required to apply internal forces to hold the object by friction. Restrictions occurred when handling tiny objects.

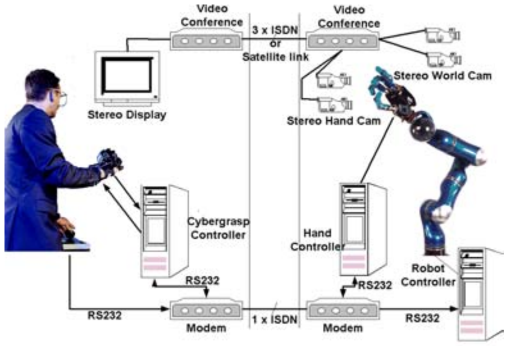

Fig. 6: Telemanipulation setup

3.2 Task Level Programming Experiments

The following experiments consist of multiple operations fulfilling a higher order task. The experiments were performed in a relatively autonomous manner with a task level programming system.

1) Catching a Softball with DLR Arm II and DLR Hand II: As a demonstration of efficient programming, control system design and velocity we developed a setup that tracks and catches a soft ball thrown by any volunteer. Parts of the experiment has been published in [8]. Hereby two cameras track a thrown ball. The trajectory of the ball can be predicted by using an extended Kalman Filter. Optimizing the intersection of the trajectory with the robot's catching region returns a desired catching point. Examinations showed an average available time span for closing the hand before the ball bounces off again of about 50-80 ms. Restrictions occurred in the size of the ball. Experiments to catch a soft soccer ball right in the flight did not work reliable due to large size as well as experiments with small soft balls that could not always be retained by the hand. Requirements for this experiment was the capability of the system to withstand moderate impacts of a thrown object, a deterministic behavior of the control system and a sufficiently high velocity of the fingers.

Fig. 7: Catching a softball.

2) Tracking and Grasping an Object: One thing that man does with his arm and hands is to pick up moving or still objects. To demonstrate this ability, we realized a visual servoing setup. A pair of cameras was mounted on the hand's wrist. The arm then approaches and tracks a ball and the hand performs a grasping movement to pick it up. When human beings pick up an object, the hand performs a characteristic movement from a resting pose to an open pregrasp pose and finally grasps the targeted object. To mimic this behavior, we derived a distance measure from the visual servoing module and use this measure to interpolate between three given hand poses (rest, pregrasp, grasp). This simple approach leads to an impressive human-like grasping behavior. For the visual servoing module we use a simple Jacobian based approach: We "teach" the desired goal position by bringing the object to be grasped in the desired position, measure its coordinates in the stereo images, move the arm slightly in three orthogonal directions and get the object's coordinates again. From this we can estimate the Jacobian that maps Cartesian deviations to deviations in image coordinates. It is straightforward to use it's inverse to realize a visual servoing facility.

Fig. 8: Tracking and grasping an object.

3) Playing the Piano: To demonstrate the abilities and suitability of our hand to perform tasks in an environment designed for humans we taught DLR Hand II to play a standard piano keyboard. In order to simplify the programming of multiple songs, we taught one complete set of notes and stored these trajectories in a sample file. This file was combined with an arrangement suitable for the hand to present a trajectory for a given piece. We excluded the thumb for kinematic reasons. Restrictions occurred where 4 or more fingers would be necessary. This is one of the few situations, where the kinematic setup and the number of four fingers is not suitable for all occasions. Otherwise for this experiment we required the hand to be easily teachable, have a sufficient accuracy, achieve an adequate speed in finger motions and be able to contact at these velocities with a rigid environment.

4) Service Robot in Human Environments: A major interest of humanoid robotics is to provide assistants for elderly or bodily challenged people. The goal of one of our projects was to realize a mobile platform equipped with hand and arm and to demonstrate the task oriented programming of such a system. A tasks to be demonstrated was to navigate to a designated room, locate the doorknob, open the door, navigate to a table, locate a desired object, and grasp it. The key problem to be solved was the robust contact of hand and arm with the environment and robust grasping under the constraint of world model errors. This could be solved by using impedance control.

4. Lessons Learned

DLR Hand II is a powerful dexterous robot hand. The performance of it with regard to forces is almost similar to a human hand. Also the possible speed is not far from the human abilities. Otherwise DLR Hand II can not actually replace a human hand in a remote environment. One drawback is the missing feel of touch. The human possibilities of haptic perception are so extraordinary excellent that no so far known tactile sensor system can compare to this in the slightest way. Another point is the so far ‘hard’ surface of finger and hand which has to be softened. The size of about one and a half times the size of a common human hand is also an major obstacle in dealing with an environment especially designed for humans. With respect to future applications we have to find a solution with less complexity and a design which can stand problems like intensive dust or the contact with liquids without harm.

5. Conclusion

From our experience in the experiments we found that our hand already can do impressive and useful things, but we also learned about the limitations and possible improvements: Fine manipulation and grasping of small objects is still a difficult task. We think this is not due to the sensor and control quality, but to the finger tip design. Although we use a silicon coating for the finger tips, that finger tips need to be much softer to increase grasp robustness and stability. Our finger tip design already resembles finger nails, but should be much more distinct. We are content with the results of our grasp planners, but integrating a grasp planner in real world systems has its own challenges. Precision grasps are fine in theory, in practice pinch and power grasps are more important. We currently integrate the pinch grasp planning facility in our grasp planner and develop a power grasp planner. Another major issue is creating geometric models of objects to be grasped online and provide them for a grasp planner. We experiment with laser scanner and stereo vision based generation of partial object models. To increase the robustness and stability of grasps we are integrating a grasp force optimization module. One precondition for a grasp force optimizer is the knowledge about the actual contact models and grasp forces. We try to derive the contact model information from position and force/torque sensors. Generally, trying to make artificial hands work in real world situations provides us with a lot of interesting work for the future.

6. References

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