ROBONAUTS NEED LIGHT-WEIGHT ARMS AND ARTICULATED HANDS

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ABSTRACT

The paper describes recent design and development efforts in DLR's robotics lab towards a new generation of "mechatronic" ultra-light weight robots with articulated hands. The design of fully sensorized joints with complete state feedback and the underlying mechanisms are outlined. The second light-weight arm generation is available now; in the same way the second generation a most highly integrated 4 finger-hand is near completion. Thus it is hoped that big steps towards a new generation of space as well as service and personal robots have been achieved.

1 INTRODUCTION

When comparing human skills with those of present-day robots of course human beings in general are by far superior, but when comparing the skill of an astronaut in a clumsy space-suit with that of the best available robot technology, then the differences are already going to disappear, the more if there is a remote control and monitoring capability on ground with arbitrarily high computational and human brain power. For IVA activities a robot basically would have to compare with the full human skill and mobility; to be honest, many of the manual operations to be done in a space-laboratory environment are fairly simple standard operations, like handling parts, opening and closing doors, pulling drawers, pushing buttons etc. which have to be done just by stepping through extensive, written procedures. Real intuition and manual skill is particularly requested in non-nominal situation and repair situations. Although it is not clear today when a multi-fingered robot hand might be as skilled as the human hand and when (if ever) a robot might show up real intelligence and autonomy, it nevertheless is obvious that even with today's technology and the available telerobotic concepts based on close cooperation between man (e.g. the ground operator) and machine there are many tasks in space, where robots can replace or at least augment human activities with reduced cost from a mid-term perspective.

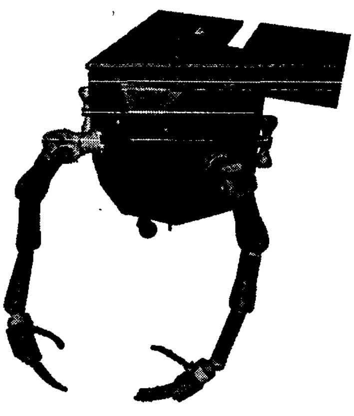

Fig. 1 DLR's Robonaut concept for a free-flying robot satellite with two arms and two articulated hands

What we definitely need for space (as a technology driver) **but** also for the wide variety of future terrestrial service robot applications, are sensor-controlled light-weight arms (in contrast to the stiff and heary industrial solutions) and articulated, multifingered hands, which come closer and closer to the delicate human performance. Two of these arms combined with an arrangement of a stereo camera pair tends to provide such a system with humanoid appearance and thus provokes the "robonaut" terminology (Fig. I). NASA has recently presented remarkable results in this context.

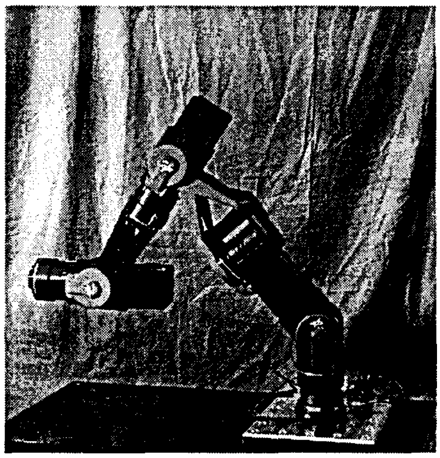

Fig. 2 DLR's second light-weight robot generation

2 ARM MECHANICS

The design-philosophy of DLR's light-weight-robots is to achieve a type of manipulator similar to the kinematic redundancy of the human arm , i.e. with seven degrees of freedom, a load to weight ratio of better than 1:2 (industrial robots ≈ 1:20), a total system-weight of less than 20 kg for arms with a reach space of up to 1,5 m, no bulky wiring on the robot (and no electronics cabinet as it comes with every industrial robot), and a high dynamic performance. As all modem robot control approaches are based on commanding joint torques, joint torque control (allowing programmable impedance, stiffness and damping) was a must for us.

Another must for us has been the use of precise motor position sensing, and link angular sensing.

Taking these requirements into account; we started a kinematic simulation to determine the best joint configuration. Based on the kinematics and desired payload, the required dynamic joint torques were calculated. Suitable motors and gears were chosen to obtain the desired joint torques.

The design of the mechanical parts and the integration of all electronic components was done by using modem 3D-CAD techniques. This resulted in a virtual prototype of the new light-weight robot, which could be easily manufactured and assembled.

2.1 Kinematic Simulation

Based on the number of joints (7), the payload (up to 8kg), the overall length (lm) and the tasks to be performed, the kinematic simulation should provide an optimal joint configuration. In our simulation we have chosen a trajectory consisting of three perpendicular spirals (Fig. 3). As a result, it was suggested to equalize the distances between joint 2-4 and to use 3 perpendicular pitch joints for joint 2-4.

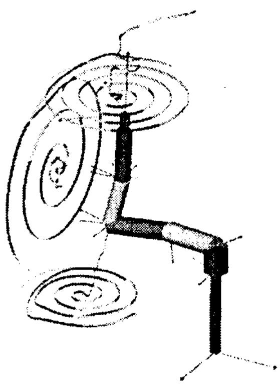

Fig. 3 kinematic simulation

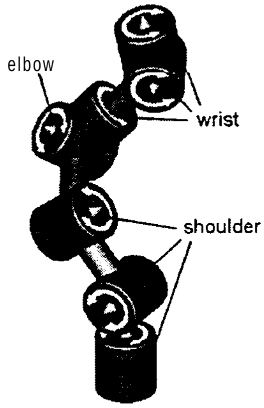

Fig. 4 robot kinematics

2.2 Design of the Light-Weight Structure

Meeting the guidelines of building a robot with a payload of 8kg and an overall weight of less than 17kg requires the design of an extremely light-weight structure. To compensate the joint elasticity, torque sensors are implemented in each joint. They allow various sophisticated control methods like vibration damping and stiffness control.
Furthermore, one has to use motors and gears with a very good output-torque to weight ratio. High performance brushless DC-motors from Kollmorgen and light-weight Harmonic Drive gears seemed both very suitable.

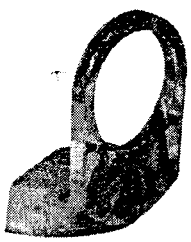

Fig. 5 FEM calculations

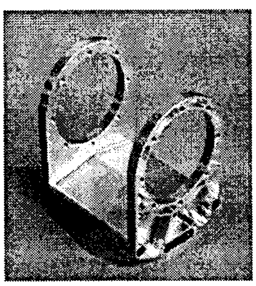

Fig. 6 manufactured part

Due to the light-weight aspect, most structural parts consist of aluminum, the link between joint 2 and 3 is made out of carbon fiber. The usage of extremely light-weight structures requires a close look at the highly loaded mechanical parts. It is necessary to maximize stiffness and strength of the structures while keeping in mind that weight must be reduced. This is done by using Finite Element Methods (FEM) (Fig. 5). The main structure is non-modular with modular subassemblies. Despite of having a variety of different housings, this turned out to be a reasonable way to maximize the payload to weight ratio.

2.3 Virtual prototype

The light-weight robot is designed using a modem 3D CAD system. All mechanical parts as well as the electronic components are shaped in detail and have a density assigned to them forming a so-called virtual prototype.

Fig. 7 mechanical structure

Fig. 8 electronics

Thus it is possible to retrieve masses, centers of gravity and mass matrices for single components as well as for the whole robot. The possibility of getting important model parameters from the model simplifies the identification of the arm significantly. The geometrical data of the electronic components have been obtained via the interface between the mechanical and electronic CAD tool.
The electronics was effectively integrated in the whole design. In addition, the internal structure of the virtual prototype allows an easy animation and visualization.

2.4 Multi-Sensory Joint Design

Each joint contains a torque sensor, a link position sensor and a motor position sensor. Furthermore, all joints are equipped with electromagnetic brakes. All these components, including motor and gear are placed inside the housing to be as space-saving as possible. We use motors without housing, special short and light-weight Harmonic Drive gears and modified electromagnetic brakes with reduced power consumption and decreased weight.

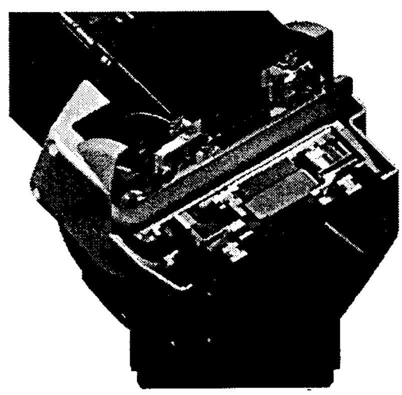

Fig. 9 Cross section of joint 2

The gears are provided with aluminum crafted wave generators and circular splines. All housings are made of aluminum (saving 40 % weight) and are designed to transfer thermal energy from the motor to the surrounding air. All joints are equipped with hollow shafts for the internal cabling.

3 ELECTRONIC COMPONENTS OF THE LIGHT-WEIGHT ROBOT

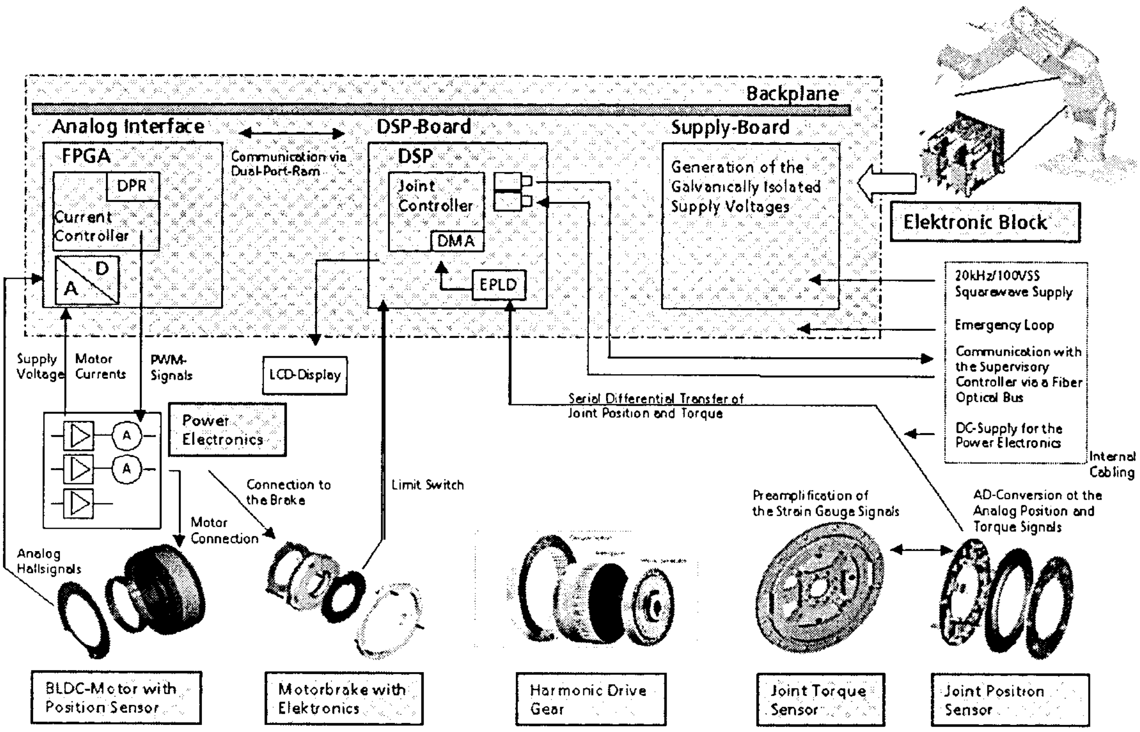

Fig. 10 Components of the light-weight robot

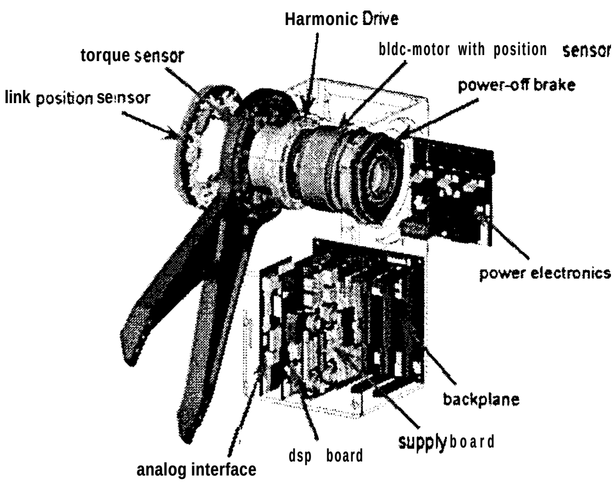

Fig. 11 The intelligent joint

For setup and maintenance reasons we have decided to use a backplane concept for the main electronic boards (Fig. 11).
One backplane is designed for carrying electronics for two joints. Joint 7 and 6, Joint 5 and 4, Joint 3 and 2 share each one electronic block, which is integrated in the robot structure. The electronics for joint 1 is located in the base of the robot.
The electronic block is built up with a backplane, a supply board, two DSP boards and two analog interfaces. The electronics of the whole robots consumes less than SOW. The 20 KHz/100 V power supply (galvanically decoupled) had successfully been used already in the ROTEX mission (Ref. I), the first remotely controlled space robot.

The robot joints communicate via a fiber optical bus system. The standardized SERCOS protocol, which is a real time bus system, is used. The desired and actual motor position, link torque and link position are transmitted every millisecond. Status and supervisory signals like temperatures, voltages and error messages are transferred by means of the acyclic channel, which is defined by SERCOS as well.

On a joint-integrated DSP, the joint torque control algorithms run with 3 KHz and artificial joint impedances may be commanded from the external PC-based Cartesian controller.

3.1 Power Electronics

The power electronics has been developed for three-phase motors. The MOS-fets are thermally coupled with the structure of the joint in an ideal manner (Fig. 12). Two phase currents and the bridge voltage are measured galvanically isolated. A miniaturized, temperature compensated current sensor was developed in our lab. A sophisticated temperature compensation circuit leads to an accuracy of better than 1% over a temperature range from 0°C to 85°C. The size of the whole board is 65mm x 50mm x 25mm.

Features:

- supply voltage — up to 80V
- nominal output current — 15A
- switching frequency — 40kHz
- nr. of half bridges — 3
- two phase currents are measured galvanically isolated
- DC-supply voltage is measured galvanically isolated

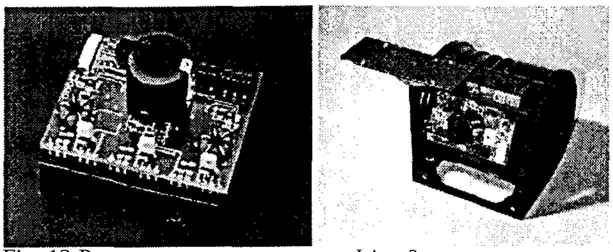

Fig. 12 Power converter Joint 2

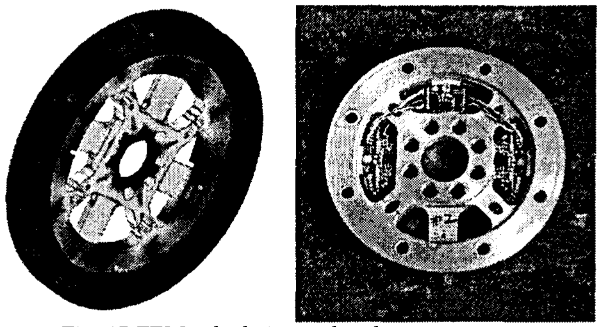

Fig. 15 FEM calculation and real torque sensor

3.2 Brushless DC-Motor with Position Sensor

To get a high performance drive unit it is essential that the motor position can be exactly controlled.

Two analog hallsensors are integrated into the motor to measure the magnetic field of the rotor. Thus we were able to meet the challenging space restrictions. The two sensors have a displacement so that their outputs correspond to a sine and cosine signal. With the sine and cosine the motor position is calculated.

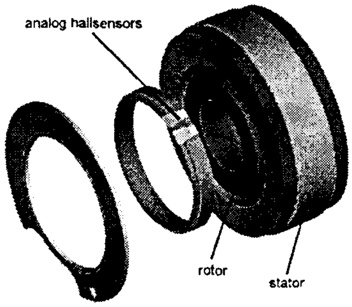

Fig. 13 motor with integrated position sensor

3.3 Safety Brake

Each joint is equipped with a safety brake. An intelligent drive electronics reduces the power dissipation of the brake by the factor of IO. As a result the brake could be redesigned in collaboration with the manufacturer. The total mass went down from 28 1 g to 155g.

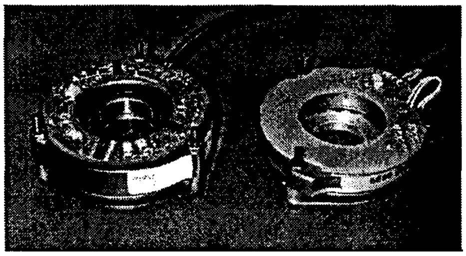

Fig. 14 Original and redesigned safety brake

The control electronics. and a limit switch circuit are directly mounted on the brake - another good example for the mechatronics approach.

3.4 Torque Sensor

The deformation of radial beams is measured by strain gauges. The resistance variation of the strain gauges is proportional to the applied torque. By using eight strain gauges temperature effects and transverse forces can be compensated.

Special efforts were made to find the optimal shape of the beam, the placement of the strain gauges and to make the sensor insensitive to overloads. Four different sensors have been designed with load ranges from 30Nm up to 200Nm. The boards for preamplifying the strain gauge signals are integrated in the sensor mechanics. The mechatronics concept saved space and weight, while the performance of the sensor could be increased.

3.5 Link Position Sensor

The link position sensor is able to measure the off-drive position with an accuracy of 0,01°. As the absolute position is measured no reference sequences have to be performed during the power up of the robot. The sensor has a flat shape and allows the use of a huge hallow shaft. The analog joint position sensor signal as well as the torque signal are digitized and transferred via a serial, high speed, differential communication to the DSP-board.

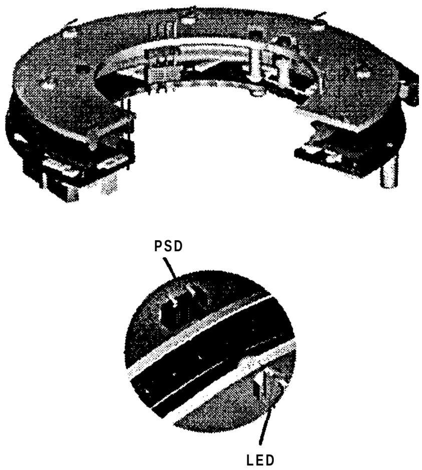

Fig. 16 link position sensor

4 ROBOT CONTROL (impedance control)

Considering the application fields for which this robot was designed, a main focus obviously had to be the ability to perform compliant manipulation in contact with an unknown environment. The robot should be able to guarantee the safety of humans interacting with it not only at the TCP, but also along the entire robot structure. This was one of the main motivations for introducing torque sensors in each joint, allowing not only gravity compensation (thus emulating outer space conditions), but also stiffness and impedance control.

Another challenging control problem results from the lightweight design of the robot, which inherently leads to increased joint elasticity. Since the links can be regarded as rigid compared to the joints, a flexible joint robot model can be assumed. This implies a fourth order model for each joint. Therefore, by measuring the motor position q_m and the joint torque τ and by computing the numerical derivatives dq, and $d\tau$, the complete joint state can be obtained. Our control strategy is to use the available sensors to implement the desired task behavior as well as to compensate the effects of joint elasticity.

The first stage in the controller development was a joint state feedback controller with compensation of gravity and friction (Fig. 17).

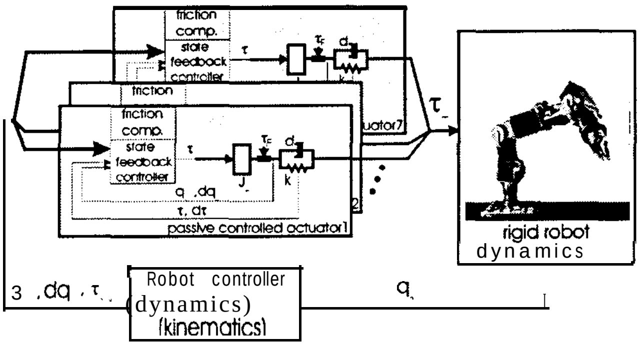

Fig. 17 state feedback controller with gravity compensation

In our opinion, this structure represents, the minimal configuration that can provide both positioning accuracy and effective oscillation damping. The controller constitutes a direct extension of the PD controller still used in most industrial robots to the case of manipulators with joint elasticity. It is proven to be passive and global asymptotically stable for a wide range of parameters (Ref. 2, Ref. 3).

An important feature of this controller structure is that, by a suitable parameterization, it can be used to provide a position, a torque, as well as an impedance controller. In fact, the position and the torque controllers are implemented as special cases of the impedance controller, for maximal and zero stiffness respectively. The gains are computed online, to provide the desired joint stiffness and damping. The state feedback controller is implemented in a decentralized manner on the signal processors in each joint, with a high sampling rate (3kHz).

Using joint parameter identification and CAD modeling of the rigid robot components, an accurate robot model was obtained, which was subsequently used for the design and simulation of model based controllers (Ref. 3).

The Cartesian position. control uses a singularity robust inverse kinematics module for redundant manipulators. It enables collision avoidance and the optimization of additional task dependent criterions (Ref. 6, Ref. 7, Ref. 8)

Our next steps try to continuously reduce weight by using a self-developed, specialized external rotor motor, a new piezo brake (weighting only 30g), more carbon fiber technology and higher joint modularity. As a central goal we try to further optimize the joint performance index I as defined and proposed in (Ref. 5).

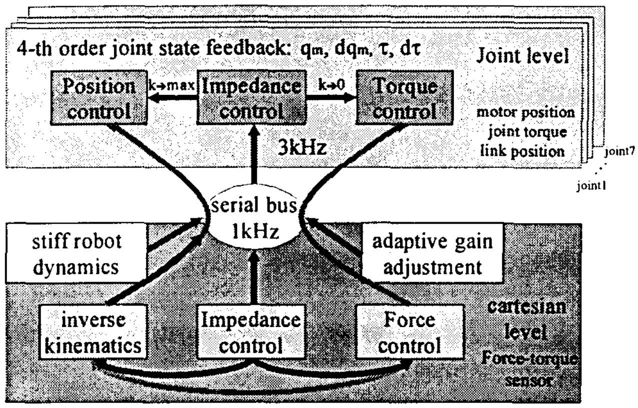

Fig. 18 controller architecure

5 ROBONAUT HANDS

In 1997 DLR developed one of the first articulated hands with completely integrated actuators and electronics (Fig. 19),(Ref. 9, Ref. 10).

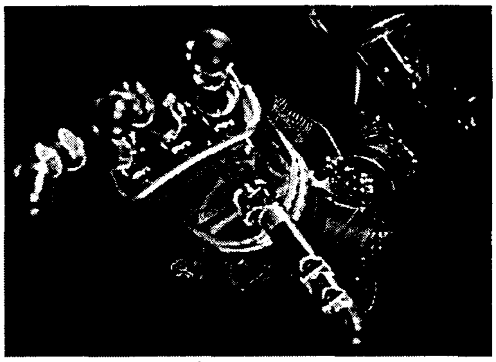

Fig. 19. DLR's Hand I.

This well known hand has been in use for several years and has been a very useful tool for research and development of grasping. The main problems remaining were maintenance and the many cables (400) leading out from the Hand. The experiences with Hand I accumulated to a level that enabled us to design a new hand according to a fully integrated mechatronics concept which yields a reasonably better performance in grasping and manipulation and therefore accelerates further developments.

6 The DLR HAND II

6.1 Open Skeleton Design

Due to maintenance problems with Hand I and in order to reduce weight and production costs the fingers and base joints of Hand II were realized as an open skeleton-structure. The open structure is covered by 4 semi shells and one 2-component fingertip housing realized in stereolitography and vacuum mold (Fig. 20). This enables us to test the influence of different shapes of the outer surfaces on grasping tasks without redesigning finger parts.

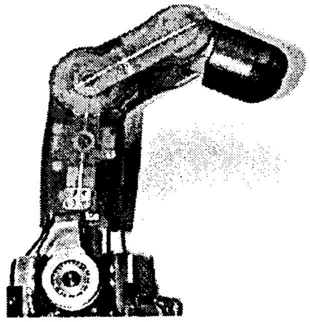

Fig. 20 Finger with semi shell housings and rubber skin fingertip.

6.2 Grasp-oriented Design of DLR's Hand II

The main target developing Hand II from the beginning has been the improvement of the grasping- performance in case of precision- and power-grasp. Therefore the design of Hand II was based on performance-tests with scalable virtual models as seen in Fig. 2 1.

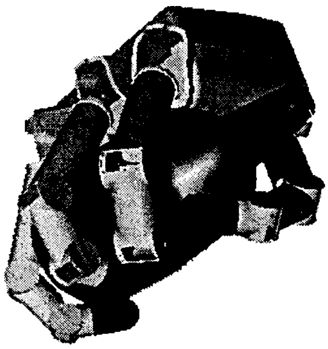

Fig. 2 1 Optimization of kinematics with scalable hand model.

Soon it turned out very important to be able to change the position of the 4th finger and the thumb as well. To perform power-grasps it is absolutely necessary to have a nearly parallel position of the second, third and fourth finger as seen in Fig. 22

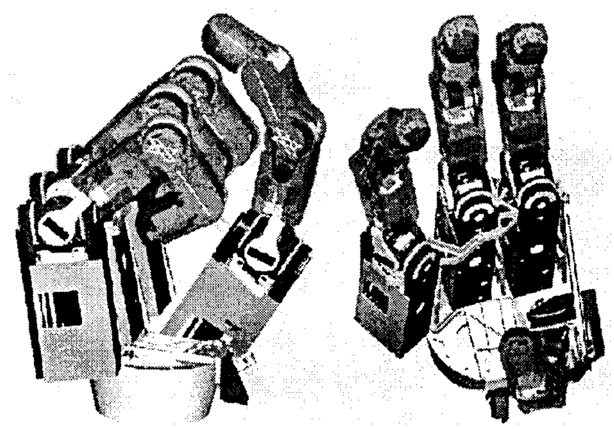

Fig. 22 Simulation of Hand II in power grasp and tine manipulation configuration.

On the other hand performing precision-grasps/fine-manipulation requires huge regions of intersection of the ranges of motion and the opposition of thumb and ring-finger (Fig. 22). Therefore Hand II was designed with an additional minor degree of freedom which enables to use the hand in 2 different configurations. This degree of freedom is a slow motion type to reduce weight and complexity of the system. The motion of the first and the fourth finger are both realized with just one brushed dc actuator using a spindle gear. The realized finger positions for both types of grasping were designed virtually. Optimized configurations were found using interactive grasping tools as seen in Fig. 23 and mapped to each other using the positions of 2nd and 3rd finger.

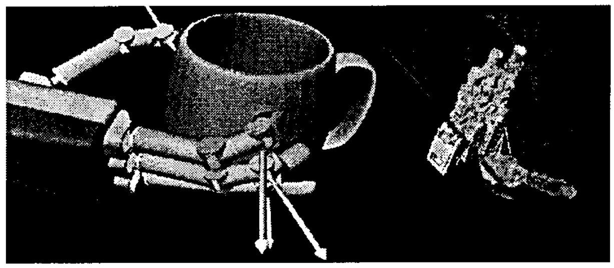

Fig. 23 Interactive grasp and manipulability simulation tools.

Realizable kinematics were calculated and imported to the two virtually found configurations and optimized unless the actual configuration with an overall number of 13 DOF was found (Fig. 22).

6.3 Actuator System

The three independent joints (there is one additional coupled joint) of each finger are equipped with appropriate actuators. The actuation systems essentially consist of brushless dc-motors, tooth belts, harmonic drive gears and bevel gears in the base joint. The configuration differs between the different joints. The base joint with its two degrees of freedom is of differential bevel gear type, the harmonic drive gears for geometric reasons being directly coupled to the motors. The differential type of joint (Fig. 24) allows to use the full power of the two actuators for flexion or extension.

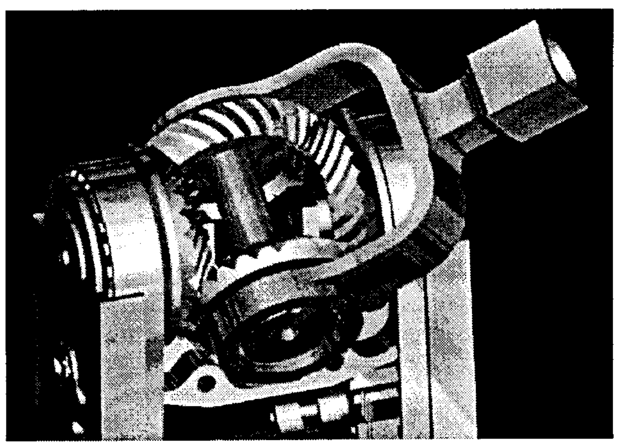

Fig. 24 Differential bevel gear of the new basejoint.

Since this is the motion where most of the available torque has to be applied, it allows to use the torque of both actuators jointly for most of the time. This means that we can utilize smaller motors. The actuation system in the medial joint is designed to meet the conditions in the base joint when the finger is in stretched position and can apply a force of up to 30 N on the finger tip. Here the motor is linked to the gear by the transmission belt (see Ref. 11 for advantages). 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. Thus we achieve the torque which corresponds to the torque created by the two motors in the base joint for an external force of 30 N on the finger tip. The harmonic drives used are of the same type for all joints, since the smallest appropriate type can stand the torque for both types of actuation.

6.4 Sensor Equipment

A dextrous robot hand for teleoperation and autonomous operation needs (as a minimum) a set of force and position sensors. Various other sensors add to this basic scheme. Each joint is equipped with strain gauge based joint torque sensors and specially designed potentiometers based on conductive plastic. Besides the torque sensors in each joint we designed a tiny six dimensional force torque sensor for each finger tip which will be explained more precisely in 6.5. The potentiometers, each with an analogous filter of third order, would not be absolutely necessary, since one may calculate the joint position from the motor position, however they provide us with a more accurate information of joint position, and they can by the way eliminate the necessity of referencing the fingers after power up. In case of not using the potentiometers one would have to consider the elasticity of the transmission belt and the harmonic drive. With the potentiometer we achieve a resolution for the joint angles of 1/10°, this means approximately 10 bits for the joint.

6.5 Force Torque Fingertip Sensor

A tiny six dimensional force torque sensor (20 mm in diameter and 16 mm in height) as shown in Fig. 26 with full digital output has been developed for the fingertip. The force and torque measure ranges are 10 N for F_x and F_y, 40 N for F_z, 150 Nmm for M_x, M_y and M_z respectively. Also a 200 % mechanical overload protection is provided in the structure.

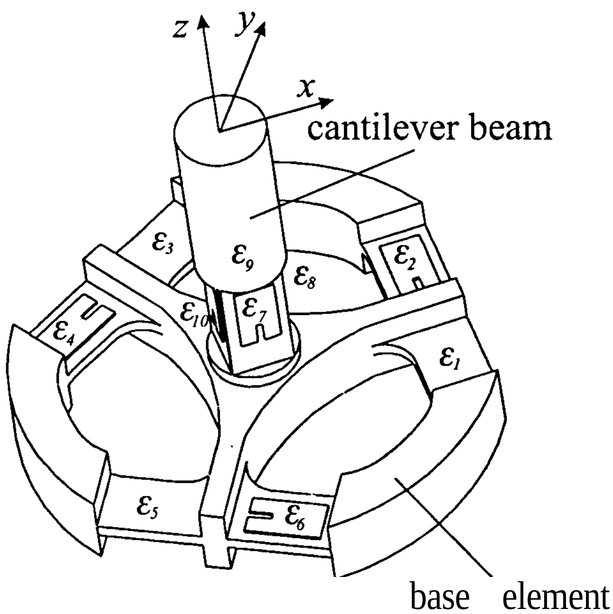

Fig. 25. Mechanical structure of six dimensional fingertip force torque sensor.

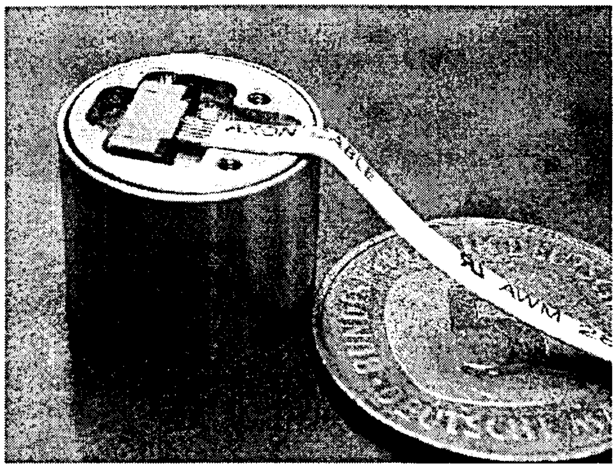

Fig. 26 Six dimensional force torque sensor in fingertip.

6.6 Communication Architecture

All electronics needed locally is integrated into the hand. However the control of the fingers and the hand is done by an external computer. In order to use the hand freely on different manipulators and to reduce cables and the possibility of noise in the sensor signals, we decided to design a fully integrated serial communication system. Each finger holds one communication controller in its base unit (see Fig. 27).

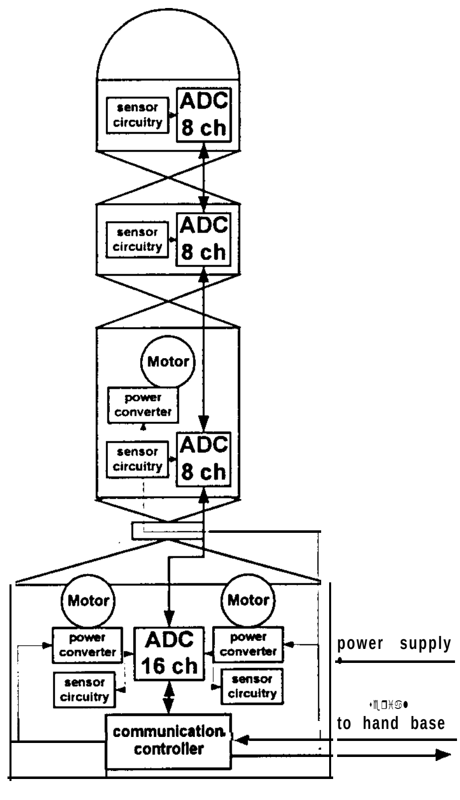

Fig. 27 Electronics and communication in a finger.

This controller is responsible for the collection and distribution of all information of interest. Furthermore it does some reasonable signal processing.

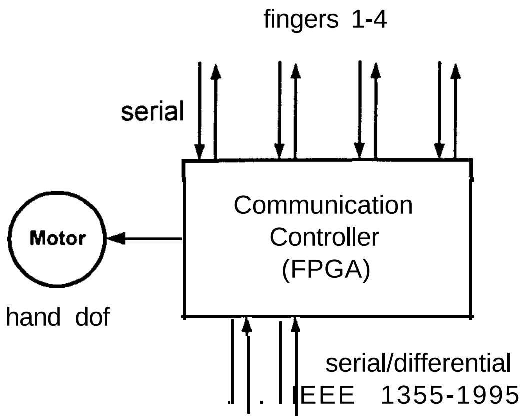

Fig. 28 The communication controller in the hand base links the fingers to external computers.

It collects the data of all five ADCs per finger with together 40 channels of 12 bit resolution each and transmits these data to the communication controller in the hand base (see Fig. 28). On the other hand it distributes the data from the control 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 hardware architecture we are able to limit the number of external cables of DLR's Hand II to a four line power supply and an eight line communication interface since the data is transmitted via differential lines. This interface even provides the possibility of using a quick-lock adaptor for autonomous tool exchange. **Reducing external cabling from 400 (in Hand I) to 12 here, is one of the major steps forward in our new hand.**

6.7 Cartesian Impedance Control

When a robot hand performs any fine manipulation, there is always need that the fingertip should be soft in the direction normal to the contact surface and hard tangential to the contact surface. Thus the impedance should be adaptable to the orientation of the fingertip. Therefore, a Cartesian impedance controller has been developed, where the fingertips behave like a programmable spring.

7 CONCLUSION AND FUTURE WORK

DLR's work on one side aims at the development of robonaut systems for space applications and on the other side at the terrestrial use of ultralight weight arms and multifinger hands on mobile platforms. DLR light-weight robot II and hand II for us are big steps forward in approaching the goal of robot systems with human-like size and performance. The next step will be the integration of our new, mass and power saving motor and piezo brake concepts in the arm, together with extended use of carbon fiber technology in the links. Future hand related work will be a redesign to get the hand ready for manufacturing in a small series und on the other hand to get the hand simplified and qualified for space applications. Parallel to this work various efforts towards autonomous grasping and manipulation with the new hand are in progress.

8 ACKNOWLEDGEMENT

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