Proceedings of the 2000 IEEE
International Conference on Robotics & Automation
San Francisco, CA • April 2000

A Mechatronics Approach to the design of light-weight arms and multifingered hands

**G. Hirzinger, J. Butterfaß, M. Fischer, M. Grebenstein,
M. Hähnle, H. Liu, I. Schaefer, N. Sporer**

DLR Oberpfaffenhofen
German Aerospace Center
Institute of Robotics and Mechatronics
D-82234 Wessling
Gerd.Hirzinger@dlr.de

Abstract

The paper describes recent design and development efforts in DLR's robotics lab towards a new generation of 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, as well as the second generation of a worldwide most highly integrated 4 finger-hand is available now. Thus we hope that important steps towards a new generation of service and personal robots have been achieved.

Introduction

The importance of robot actuators and mechanisms has often been underestimated in the past, especially in those days when artificial intelligence concepts promised to be capable of solving all crucial robotic problems. The truth is that only via very small steps we seem to approach the human arms and hands more and more, while typical industrial robots still are able to carry around only 1/10 or even less of their own weight. In particular even today industrial robots try to guarantee precision purely by heavy masses and high stiffness. And in nearly all applications robots are still purely position controlled devices with may be some static sensing, but far away from the human arm's performance with its amazingly low *own weight against load* ratio and its online sensory feedback capabilities involving mainly vision and tactile information, actuated by force-torque-controlled muscles. However particularly for the growing field of service robots (e.g. articulated arms on mobile platforms) a huge market for smart light-weight robots seems to arise.

Although a number of engineers are searching for alternative actuation principles as are shape memory alloys or even biological actuators, we believe that even after years of research and development in electromagnetical actuation combined with gear reduction a final state has not been reached so far.

DLR's light weight robot concepts

The design-philosophy of DLR's light-weight-robot concepts 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 between 1:3 and 1:2, 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 modern robot control approaches are based on commanding joint torques, the first carbon fibre type arm version (Fig. 1) showed up an inductive (13 bit, 1 KHz bandwidth) torque-measurement system that was an integral part of an extremely compact double-planetary gearing system with the high reduction rate of 1:600. A full inverse dynamics (joint torque) control system including a neural net learning system for compensating gravity modelling errors made use of it (see below).

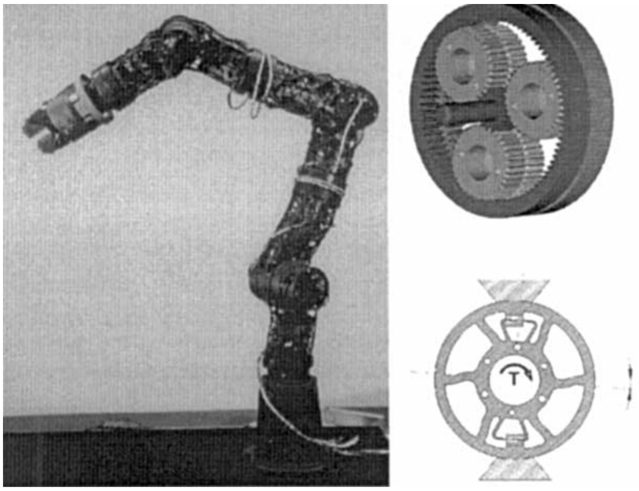


Fig. 1. DLR's first light-weight-robot with integrated signal and power electronics, double planetary gearings and inductive torque sensing (right)

However the double-planetary gears (Fig. 1) with their extremely high reduction rate were difficult to manufacture. Meanwhile a new light weight robot prototype (Fig. 2) is available in our lab which tries to make optimal use of all the experience gained with the above „reference" model. Its joints are based on special light-weight harmonic drives.

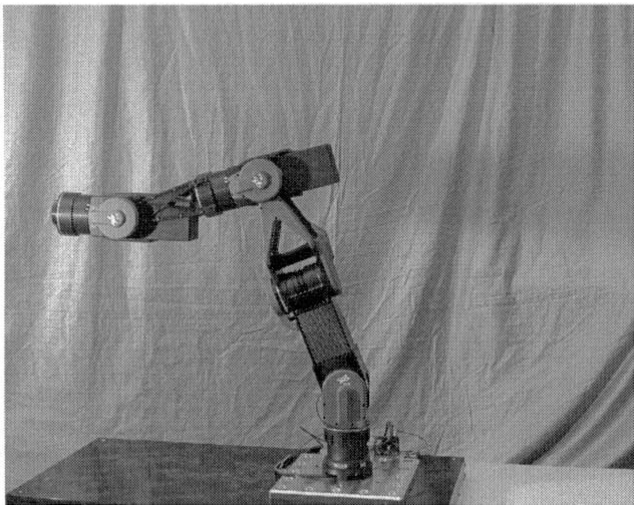


Fig. 2. DLR`s second light weight robot LWR2

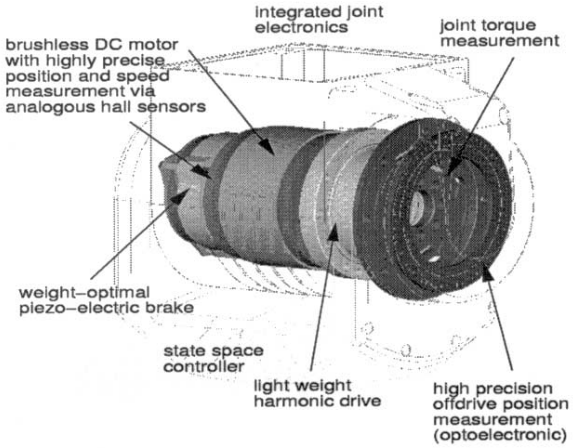
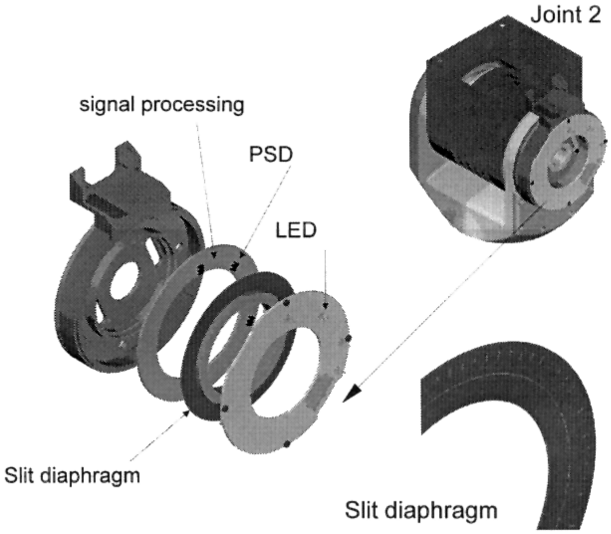
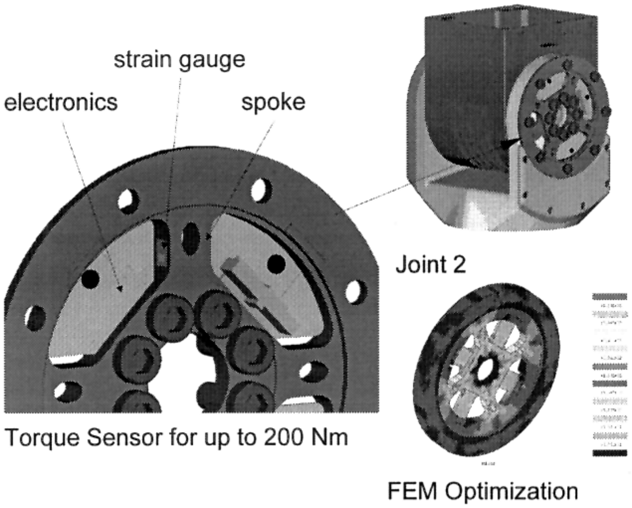


Fig. 3. Mechatronic components of DLR's new intelligent robot joint

In the drives (Fig. 3) we are measuring all relevant state variables, i.e. off-drive position, torque, motor position and speed (Fig. 4a and 4b). For torque measurement we went back to strain gauge based systems.



a) Off-drive joint angle sensor (resolation 0,01 degrees)



b) joint torque sensor Not shown here are the hall sensors used for motor position measurement.

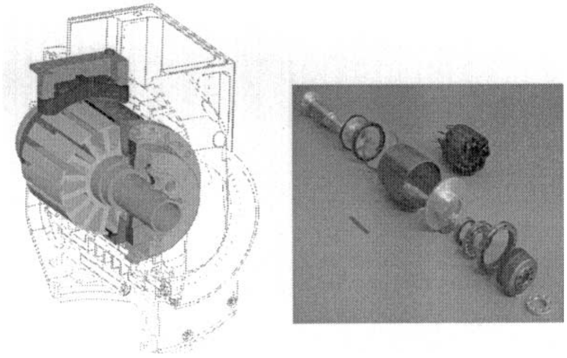
Fig. 4. Joint angle (a) and torque (b) sensors in DLR's second light weight robot (Fig. 2)

A first version of this new arm uses socalled INLAND motors which were redesigned by us to provide hollow axes where all cabling is fed through (Fig. 2).

A next version as designed presently will presumably use a new motor concept (Fig. 5) as developed in our lab, the optimized external rotor motor (OERM), as well as new type of piezo brakes.

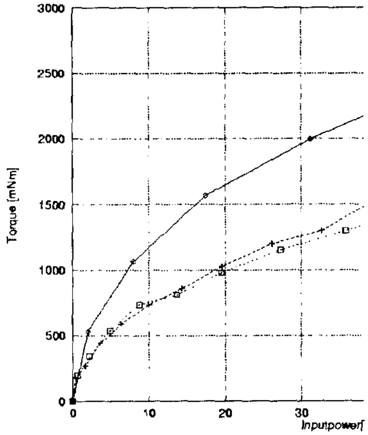
The electromagnetic torque generation to be delivered over a wide rotor speed range is realized by a multipole stator assembly interacting with rotor permanent magnet poles in a non-symmetrical configuration to virtually eliminate cogging effects. The dynamic performance is significantly enhanced by means of a special commutation control technique based on a single coil winding technique.

In view of the limited heat exchange to be realized with a compact design, the key design requirement is a large stall-torque-to-input-power-ratio. This number can be significantly enhanced as compared to conventional designs by careful tuning of geometrical dimensions and electromagnetic design parameters using magnetic field computations supporting a lumped parameter optimization process.



a): Joint 2 with OERM and piezo controlled brake

b): OERM with Harmonic Drive



c) Stall torque OERM vs. the best commercial motors

Fig. 5. The Optimized External Rotor Motor (OERM) just needs about 38% of the stall torque input power which has been required by the best commercial motor used since, and moreover yields 50 % higher torques.

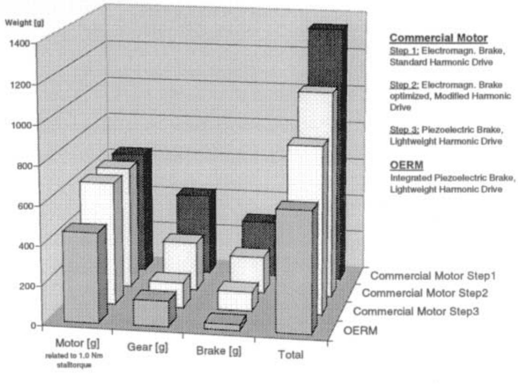


Fig. 6. The history of weight reduction in DLR's LWR-Drive Units

The tedious history of weight reduction over the last two years is depicted in Fig. 6.

In the first step the (in our opinion) best commercially available high- end brushless DC- motor was combined with a slightly modified Harmonic Drive gear and a commercially available robot- safety-brake.

In the next steps the total weight was diminished by reducing weight in the Harmonic Drive's circular-spline and the development of a weight optimized, modified version of the original, commercially available electromagnetic brake, which has been replaced recently by DLR's new piezoelectric brake with a weight of less than half the original brake. Considerable further decrease of the drive-unit masses was reached by providing the Harmonic Drive with a new aluminum crafted wave generator and circular spline as developed in close cooperation with the company Harmonic Drive, so that it finally came out with only 40 % of the weight of the original part.

The biggest step towards an extremely lightweight construction was the above-mentioned in-house development of the Optimized External Rotor Motor (OERM) with a highly integrated piezoelectric safety- brake. The mass of the motor related to the stall torque at equal power consumption is less than 72% of the originally used high-end motor (Fig. 5) and the weight of the integrated brake (30 g) is just 1/10 of the weight of the commercial brake used in the first step (300g).

The combination of the new Optimized External Rotor Motor (OERM), integrated safetybrake and lightweight Harmonic Drive gear yields an extremely powerful lightweight jointdrive with a related mass of just 55% of the weight of the original high- end drive unit and a joint quality measure of J=250, where we have defined this measure as

$$J = \frac{T}{W} \cdot \frac{V_{\max}}{(180^\circ / \mathrm{sec})}$$

and where

$T[Nm]$ = **output torque (max)**
$W[kg]$ = **weight of joint**
$V_{\max}[^\circ/\mathrm{sec}]$ = **maximal rotational speed**

Indeed it is not trivial to compare the performance of light weight joints, as output torque related to overall weight is meaningless if one does not take in account the joint's maximum rotational speed, which we normalize via 180°/sec, a value which is e.g. a good standard for terrestrial robots.

In summary, we are convinced that the enormous efforts we made to arrive at joints with ≈ 200 Nm output torque, 220°/sec and ≈ 1 kg weight including the brake system will pay out in the near future.

Programmable impedance

From the control point of view the DLR light weight robot belongs to the category of flexible joint robots due to the structure of the gear box and the integrated torque sensor. The dynamic model can be established by applying Lagrange's Equation. For the decoupling of the manipulator dynamics this model is transformed into a new coordinate system in which the joint torque is treated as a state variable instead of the motor position.

This leads to the so-called singular perturbation formulation of the robot dynamics. As a result, the fast motion corresponds to the joint-torque loop and the slow motion corresponds to the dynamic path concerned with the link position. On the higher levels, particularly interesting control results so far have been achieved with a hybrid learning approach, it is based on a full inverse dynamic model providing torque control; but as any model never will be perfect, the remaining uncertainties are learnt via backpropagation neural nets (Fig. 7). An important application is learning zero-torque control, i.e. pure gravity compensation so that the arm is just able to sustain itself against gravity, but reacts softly to any external force without additional force sensing. In addition the arm is provided with programmable impedance. **This means, e.g. when touching it somewhere at the arm structure, it tries to keep the hand frame inertially fixed, but uses its redundancy to yield softly in the arm structure with a given stiffness and damping. In the same way the wrist is provided with an artificial, programmable impedance.**

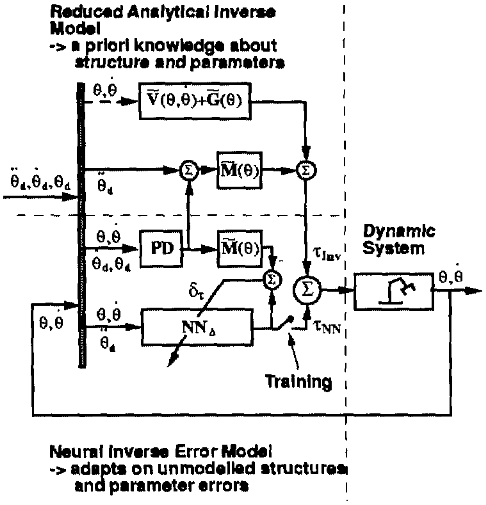


Fig. 7. „Hybrid“ learning control scheme applied to gravity compensation
of DLR's light weight robots

DLR's four-fingered articulated hand I

Impressive dexterous robot hands have been built in the past, e.g. the MIT / UTAH hand, the JPL/Stanford hand, the Belgrade hand, or the hands of the German universities in Karlsruhe, Darmstadt and Munich. However, all of them suffer from one main drawback: if the number of active degrees of freedom exceeds a fairly small number (e.g. 6 dof), there was no chance so far to integrate the drives in the hands wrist or palm: either a number of cables or tubes leads to a separate pneumatic or hydraulic actuator box (e.g. in case of the MIT / UTAH hand) or a mass of bulky motors is somehow mounted at the robot arm, so that the practical use of articulated multifinger hands has often been called into question. Thus, it was our declared goal to build a **multisensory 4 finger hand** with in total twelve degrees of freedom (3 active dof in each finger), **where all actuators (uniformly based on the artificial muscle) are integrated in the hand's palm or in the fingers directly** (Fig. 9 , Fig. 10 and Fig. 11). Miniaturizing the artificial muscle down to a nut diameter of 10 mm in combination with a specially designed brushless DC-motor with hollow shaft was a first important step. Force transmission in the fingers is realized by special tendons (highly molecular polyethylene), which are optimal in terms of low weight and backlash despite of fairly linear behavior.

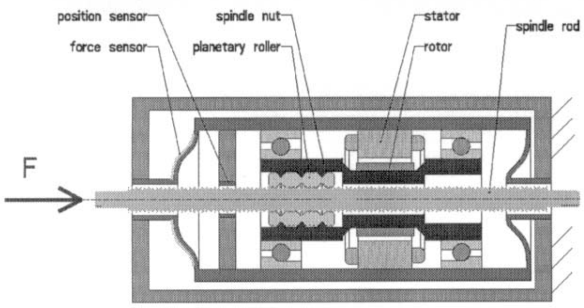


Fig. 8. DLR's planetary roller screw integrated into tiny motors is the basis of the position-force controlled artifcial muscle®; for use in the first DLR hand special position-torque sensors were used

Each finger shows up a 2 dof base joint realized by artificial muscles (Fig. 8) and a third actuator of this type integrated into the bottom finger link (phalanx proximal), thus, actuating the second link (phalanx medial) actively and, by elaborate coupling via a spring, the third link (phalanx distal) passively (Fig. 2). The anthropomorphic fingertips are of crucial importance for grasping and manipulation, thus, they are modular and easily exchangeable with specially adapted versions. Following our mechatronic design principles, literally every millimeter in the fingers is occupied by sensing, actuation and electronic preprocessing technology. **Every finger unit with its 3 active degrees of freedom integrates 28 sensors(!).**

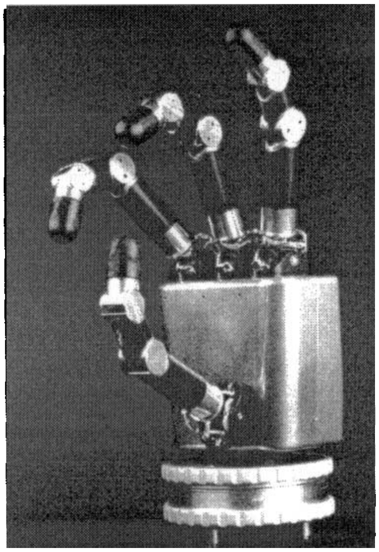


Fig. 9. DLR hand I with 12 dof

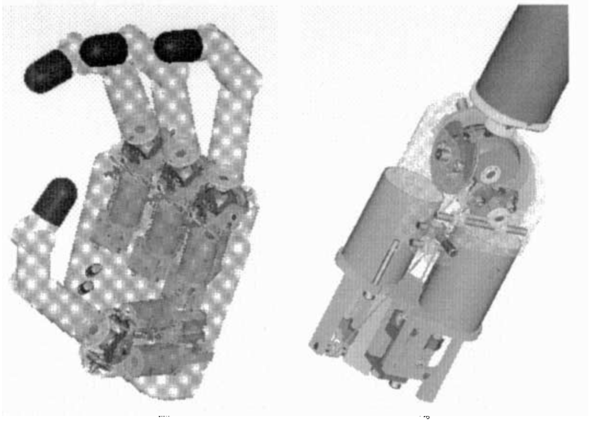


Fig. 10. 3D-CAD-design of the four finger dexterous hand I (12 dof, left) and the base joint (right)

Four tactile foils detecting locus (center) and size of external forces cover all links. They are based on FSR (force sensing resistor) technology and arranged as XYZ pads. The finger tips typically provide a light-projection LED to simplify image processing for the tiny stereo camera system integrated in the hand's palm. Due to the already mentioned modularity the fingertips might be easily exchanged with a version containing e.g. fiber optics. The two-axis torque sensor hereby serves as fast exchange adapter. Signal processing for the tip is integrated in phalanx distal for assuring optimal signal quality.

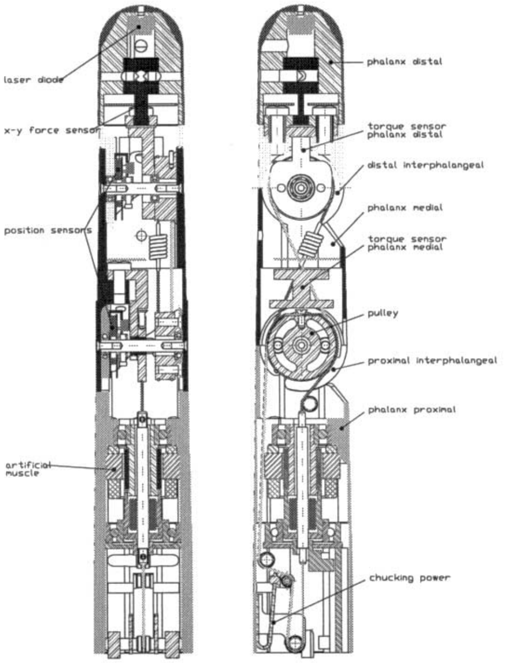


Fig. 11. The finger's construction with integrated artificial muscle (two orthogonal views without 2 dof base joint)

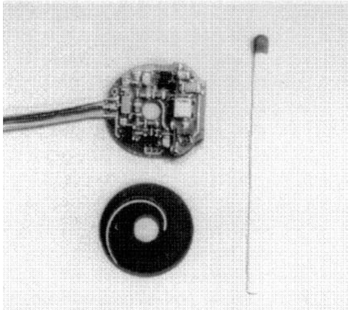


Fig. 12. Angular position sensor

Distal interphalangeal (the upper joint) is equipped with a torque sensor and a specially developed, optically and absolutely measuring angular position sensor. This sensor (Fig. 12) is based on a one-dimensional PSD (Position Sensitive Device), which is illuminated by an infrared LED via an etched spiral-type measurement slot. This measurement principle goes back to the Space-Mouse-development. Using an optimized PCB design exclusively equipped with tiny SMD items and a circuit board with a minimized number *of items used* it was possible to create an optical position sensor with remarkable performance with respect to its size. The sensor measures only 4.8 mm in thickness and 17 mm in diameter. Nevertheless, a voltage regulator and the complete analogous signal conditioning circuit is integrated. The angular resolution is 9 Bit with a linearity error of less than 1 %. The torque sensor transforms forces at the fingertips into pure torques around the joint axis measured via strain gauges on tiny flexible beams. Miniaturized electronic boards in the finger care for preprocessing of the forces and torques as well.

Proximal interphalangeal (the lower joint) shows up sensor technology nearly identical to that of distal interphalangeal. The base joint (MetaCarpoPhalangeal MCP) as in the human hand shows up two rotary joints with a common center of rotation; other than that, the technology is very similar to that inside the finger (2 artificial muscles, similar position and torque sensors).
Summary of the technical characteristics of finger and MCP joint in hand I:

max. joint angle finger	105° proximal interphalangeal 110° distal interphalangeal
max. joint angle MCP joint	90° palmar flexion 30° abduction 30° abduction
max. force	10 N at the fingertip
closing time finger	< 0,5 sec
max. frequency	25 Hz
mass of each finger	135 g (without 2 dof base joint)

Table 1:Technical data for finger / MCP joint

For details of control see e.g. [11].

With 112 sensors, around 1000 mechanical and around 1500 electrical components the DLR hand I is one of the most complex robot hands ever built. The fingers are position-force-controlled (impedance control), they are gravity compensated and they are prevented from colliding by appropriate collision avoidance algorithms. In addition recently a cartesian stiffness control scheme on hand level was implemented which turned out to be of crucial importance for all kinds of manipulation tasks. For more details see [10].

A number of telepresence demonstrations have meanwhile been performed using a dataglove, a polhemus tracker and on the „remote“ site a robonaut consisting of a 7-dof light-weight robot on a 3-axis rail system, and the four-fingerhand (Fig. 13).

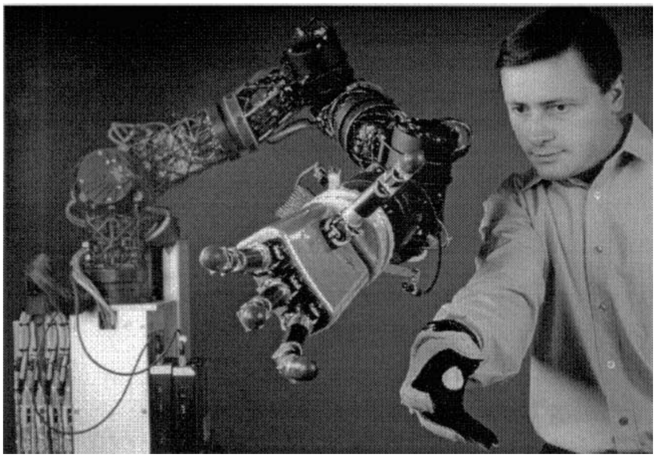


Fig. 13. Controlling 22 dof with Polhemas tracher and dataglove

Mapping the data glove signals into glove finger positions via neural nets (Fig. 14) as well as high and low level grasp planning modules for the position-force controlled fingers are available for our hand (Fig. 15).

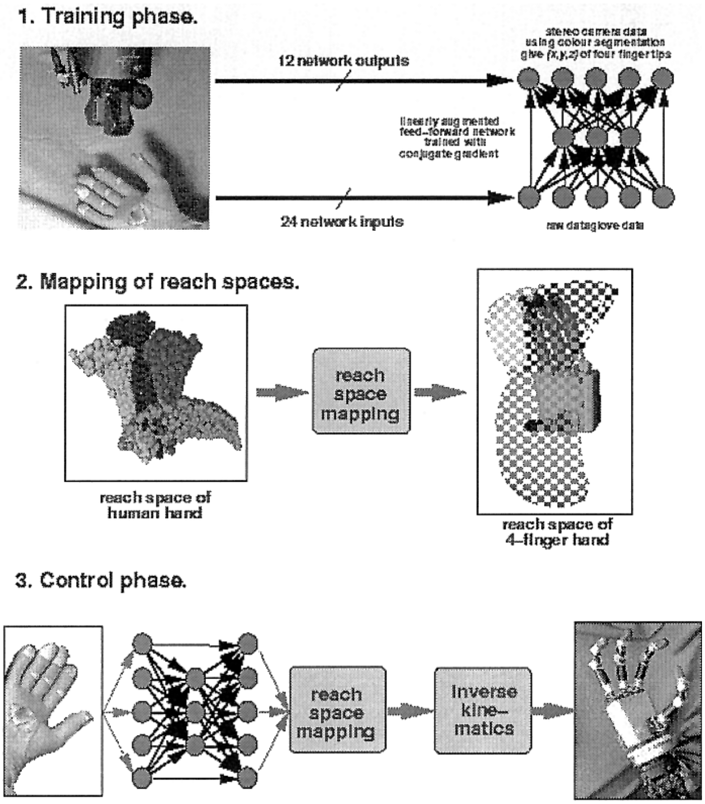


Fig. 14. **Data glove control issues for 4 finger hand control**

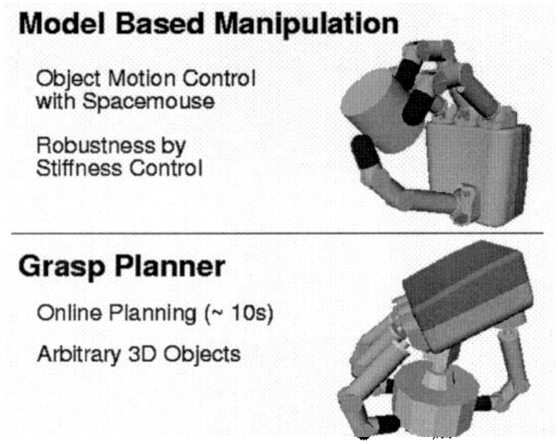


Fig. 15. High level manipulation and grasp planning skills are essential for efficient control of DLR's articulated hand

We have now nearly finished the development of DLR hand II, which will show up an even higher degree of integration. As an example presently around 400 cables are coming out of the hand, they will be reduced down to less than 10 cables in DLR hand II.

DLR's hand II

The development of DLR's hand II is of course based on the experiences made during the usage of hand I in different grasping situations and the results gained from simulation and the development of grasping strategies.

The main design targets for hand II were particularly major improvements in the manipulation and power-grasp performance. Further on we wanted to increase finger velocities and manipulation-forces and last but not least improve the manufacturing, assembly and maintenance of the hand.

The results gained in simulation and practical usage showed that the position of the 4 fingers of hand I are not yet optimal for doing fine manipulation nor for doing power-grasps. Therefore we developed a completely re-designed palm which allows to position the 4 fingers in optimal configuration, as extracted from simulation results, for both power-grasp and fine manipulation with an easy to realize mechanism. Nevertheless all actuators in hand II are placed in the palm and the fingers further on, in order to allow assembling it on the wrist of various robots without modifying the robot.

DLR's hand II is now equipped with more powerful motors in combination with tiny harmonic-drive gears and a new differential bevel gear wheel mechanism in the base joint and another harmonic-drive actuation unit in the finger joint to improve velocity and grasping power. Three main changes in the mechanical structure were realized:

a) Merging the actuators in the basejoint

In the design of DLR's hand I there has been one actuator for curling motion and one for abduction/adduction. Therefore most of the manipulations have been carried out by just one single actuator. But due to the 2 dimensional joint in the base, which is for sure necessary for most kinds of manipulation, two actuators are necessary.
The new concept of DLR´s hand II realizes a mechanism where the torque and power of both actuators is used for manipulation without respect of the desired direction of actuation. This is possible due to the realized differential bevel gear mechanism as seen in picture (Fig. 16). For curling motion the motors apply a synchronous motion to the bevel gears using the torque of both motors. For abduction/adduction the motors turn in contrary directions. This causes a curling motion on the fingertip again using the torque of both motors. In respect of this asset of the differential mechanism the maximum force on the fingertip was doubled, (i.e. now ≈30N) while using identical motors.

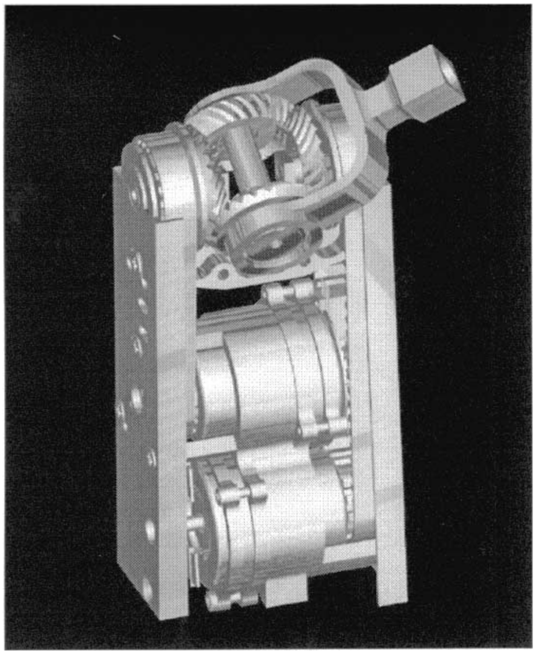


Fig. 16. Design of the new basejoint of DRL's hand II

b) Open Structure

To reduce the necessary time to maintain the hand and in especial to enable the use of flexible PCB instead of single wires as in hand I the former closed cylindrical structure of the fingers was replaced by an open skeleton- structure of only 27.7g (Fig. 17).

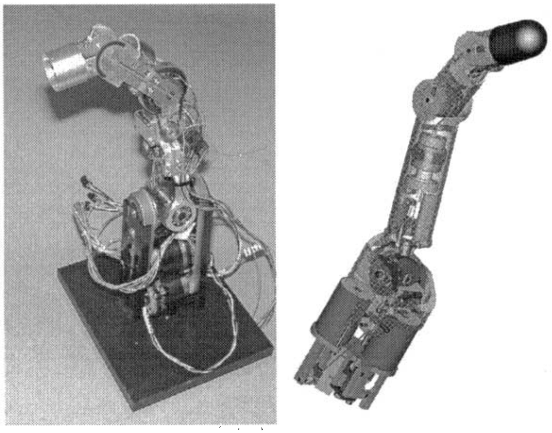


Fig. 17. Comparison of the open skeleton- structure of hand II (left) and the closed structure of hand I (right)

This also enables to change between various housings of the fingers. Due to this fact the influence of parameters like the consistency and form of the surfaces on manipulation can be tested.

c) Fully integrated optimized sensors

To reduce the size of the fingers and the hand the former optical angular positionsensors were replaced by special tiny potentiometers which could be integrated with only 0.2 mm additional space requirement in axial direction (Fig. 18). The torque sensor located in finger-joint 1 is integrated into the pulley for the coupling wires and can measure the fully decoupled torque of the gear (Fig. 19). In all fingertips we have integrated now tiny 6 dof strain gauge-based force-torque sensors (20mm in diameter and 16mm in height) with full digital output (Fig. 20). It needs only 6 wires including power supply for the high speed data transmission(15.625 kHz sampling frequency). The sensor is composed of two sensitive parts, one is a round plate with three symmetrical sensitive beams, another is a square hollow beam with a very thin wall. The signal processing circuit and high speed serial A/D converter(12 bit) are also integrated in the sensor. The force and torque measure ranges are 10N for Fx and Fy, 40N for Fz, 150Nmm for Mx, My and Mz respectively. Also a 200% mechanical overload protection is provided in the structure.

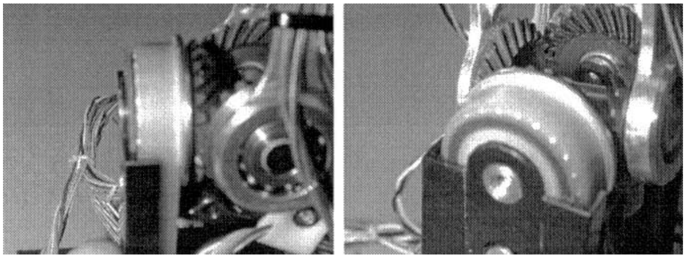


Fig. 18. The angular position-sensor in the basejoint

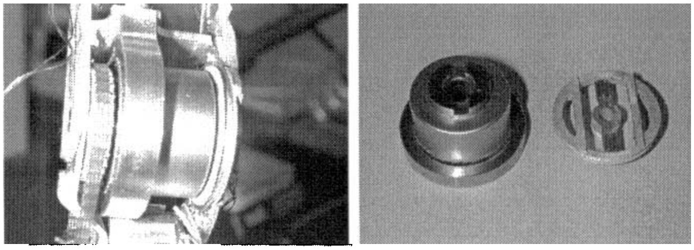


Fig. 19. The integrated torque sensor in finger joint1

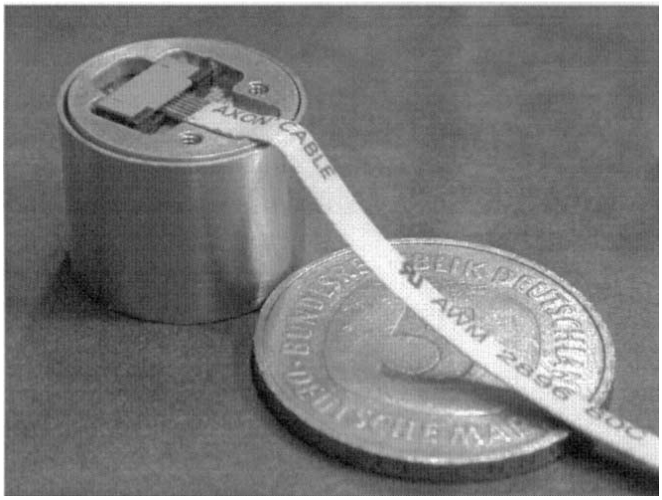


Fig. 20. Tiny 6 dof force torque sensors are integrated into all fingertips of hand II

Resume

We presume that there is a huge market in the near future for light weight arms with articulated hands as the wide field of personal and service robots is still in a premature state. We found that even with classical principles as are electromagnetic motor concepts there are still considerable potentials for approaching the human arm and finger performance more and more. DLR's work on one side aims at the development of robonaut systems for space applications [1, 12] and on the other side at the terrestrial use of ultralight weight arms and multifinger hands on mobile platforms. Robots as the ones presented in this paper are completely different from industrial robots not only by their relatively low weight, but also by special features as is joint torque control, thus allowing to realize a fully programmable impedance behaviour of the arm. In a similar way we hope that the next generation of our 4-fingered hand in addition to full actuator integration will be a version with minimal signal, power and control lines to the outer world, thus emphasizing its modular character and reproducibility. Thus although the steps towards human arm and hand performance are small and slow, they are nevertheless obvious.

References

[1] G. Hirzinger, B. Brunner, J. Dietrich, J. Heindl, „ROTEX - The First Remotely Controlled Robot in Space", IEEE Int. Conference on Robotics and Automation, San Diego, California, May 8-13, 1994

[2] G. Hirzinger, J. Butterfass, S. Knoch, H. Liu, DLR's multisensory articulated hand, ISER'95 Fifth International Symposium on Experimental Robotics, Barcelona, Catalonia, June 15-18, 1997

[3] B. Gombert, G. Hirzinger, G. Plank, M. Schedl, „Modular concepts for a new generation of light weight robots", Prod. IEEE Int. Conf. on Industrial Elektronics, Instrumentation and Control (IECON), Bologna, Italy, 1994

[4] V. Senft, G. Hirzinger, „Redundant Motions of Non Redundant Robots - A New Approach to Singularity Treatment", 1995 IEEE Int. Conf. on Robotics and Automation ICRA'95, Nagoya, Japan, vol 2, pp. 1553-1558, 1995

[5] J. Shi, Y. Lu, „Chatter Free Variable Structure Perturbarion Estimator on the Torque Control of Flexible Robot Joints with Disturbance and Parametric Uncertainties", Proc. IEEE Conf. on Industrial Electronics, Control and Instrumentation, IECON'96, Taipei, 1996

[6] O. Khatib, „A Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation", IEEE J. Robotics and Automation, vol. 3, pp.43-53, 1987.

[7] F. Arai, L. Rong, and T. Fukuda. Asymptotic convergence of feedback error learning method and improvement of learning speed. In IEEE Int. Conf. on Intelligent Robots and Systems (IROS) , Yokohama, Japan, July 26-30 1993

[8] F. Lange and G. Hirzinger, "Application of multilayer perceptrons to decouple the dynamical behaviour of robot links," presented at Proc. International Conference on Artificial Neural Networks, ICANN'95, Paris, France, 1995.

[9] C.Natale, R.Koeppe, G.Hirzinger, An Automatic Procedure for Force Controller Design accepted for publication at the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM 99, Sep 19-22 Atlanta, GA, USA.

[10] M. Fischer, P. van der Smagt, G. Hirzinger, Learning techniques in a dataglove based telemanipulation system for the DLR hand. IEEE International Conference on Robotics and Automation (ICRA), 1998

[11] H. Liu, J. Butterfaß, S. Knoch, P. Meusel, G. Hirzinger; „A New Control Strategy for DLR's Multisensory Articulated Hand", IEEE Control Systems, Vol. 19, No. 2, pp. 47-54, April 1999

[12] G. Hirzinger, B. Brunner, R. Lampariello, K. Landzettel, J. Schott, B.-M. Steinmetz "Advances in orbital robotics", IEEE Int. Conference on Robotics and Automation, San Francisco, April 2000