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DLR's Multisensory Articulated Hand
Part I: Hard- and Software Architecture

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Abstract

The main features of DLR's dextrous robot hand as a modular component of a complete robotics system are outlined in this paper. The application of robotics systems in unstructured servicing environments requires dextrous manipulation abilities and facilities to perform complex remote operations in a very flexible way. Therefore we have developed a multisensory articulated four finger hand, where all actuators are integrated in the hand's palm or the fingers directly. It is an integrated part of a complex light-weight manipulation system aiming at the development of robonauts for space.

After a brief description of the hand and it's sensorial equipment the hard- and software architecture is outlined with particular emphasis on flexibility and performance issues. The hand is typically controlled through a data glove for telemanipulation and skill-transfer purposes. Autonomous grasping and manipulation capabilities are currently under development.

Motivation

For many space operations, e.g. handling drawers, doors and bayonet closures in an internal lab environment, two finger grippers seem adequate and sufficient; the appropriate mechanical counterparts in the lab equipment are easily designed and realised even in a very late design stage. For more complex tasks however, future space robots need articulated multifingered hands.

In the past, impressive dextrous robot hands have been built [2][3][4][5][6][7][8][9]. However, all of them suffer from one main drawback: if the number of active degrees of freedom exceeds a fairly small number, there is no chance to integrate the actuators in the hand's wrist or palm if one wants to limit the size of the artificial hand to approximately 1.5 times the size of a human hand.

Thus, it was our declared goal to build a multisensory four finger hand with in total twelve degrees of freedom, where all actuators are integrated in the hand's palm or in the fingers directly.

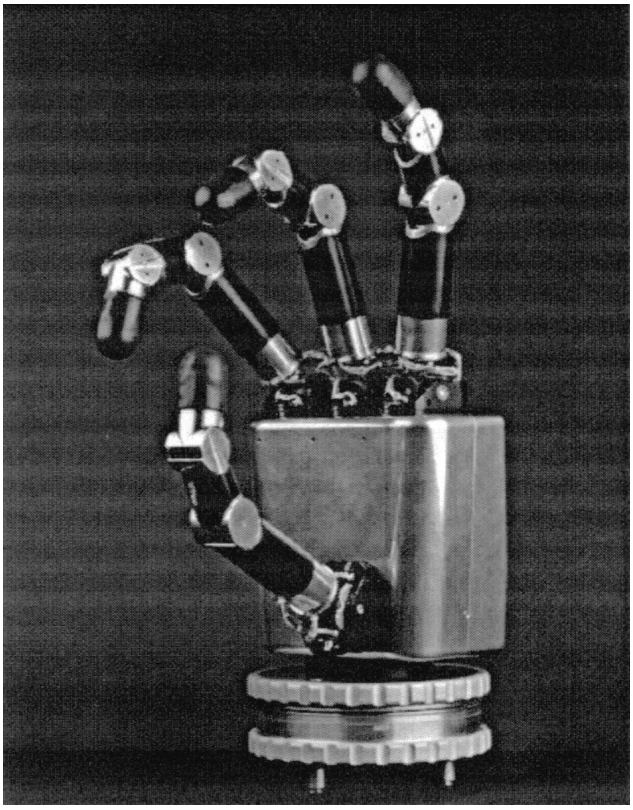

Fig. 1: DLR's Multisensory Articulated Hand mounted on a force torque sensor.

This became only feasible by using our specially designed miniaturised linear actuator.

Overall System Description

The DLR Hand, as shown in *Fig.1*, is a four fingered dextrous robot hand with a semi-anthropromorphic design. To achieve a high degree of modularity the hand consists of four identical fingers. The current arrangement shows three fingers and an opposing thumb (*Fig. 1*). Each finger shows up a two degrees of freedom base joint with

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intersecting axes for curling motion and for abduction/adduction driven by one actuator each. A third actuator is located in the proximal link actuating the medial link actively and, by coupling, the distal link passively.

The finger joints are actuated by specially designed linear actuators. Each linear actuator consists of a combination of a brushless DC motor with hollow shaft and DLR's miniaturised planetary roller spindle drive (*Fig. 2*) [10].

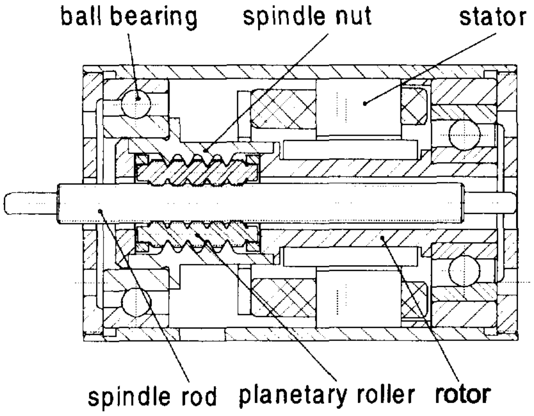

Fig. 2: Principal view of the DLR Linear Actuator.

With a cylindrical size of 21 mm in diameter and 33 mm in length this actuator is capable of applying a force of 150 N (*Table 1*). The 12 power converters needed to drive the 12 actuators are integrated in the hand's palm as well. Force transmission to the joints in the fingers is currently realised by SPECTRA® tendons.

DLR Linear Actuator	
diameter	21 mm
length	33 mm
mass	40 g
max. speed	50 mm/s
max. force	150 N

Table 1: Technical data of the DLR Linear Actuator.

Following our mechatronics design principles, the finger is equipped with various sensors, and literally any space in the finger is occupied by sensor signal processing electronics. Whenever possible the sensors are integrated into the mechanical structure to prevent them from being damaged (*Fig. 4 and 6*). Every finger unit with its 3 active degrees of freedom integrates 28 sensors. A small separate controller box houses the finger controllers coupled by a fiber optic link ring to any external workstation running the hand controller. The system is completed by a data glove with or without (*Fig. 3*) force feed-back and a SPACE MOUSE® as input device.

Fig. 3: Manipulation system consisting of DLR Hand and light weight robot, controlled by data glove and tracker.

Mechanical Structure

Each of the four identical fingers consists of two independent units, the base joint unit (*Fig. 4*) with two degrees of freedom realised in a cardanic manner and the finger unit (*Fig. 6*) with one actuator for two joints.

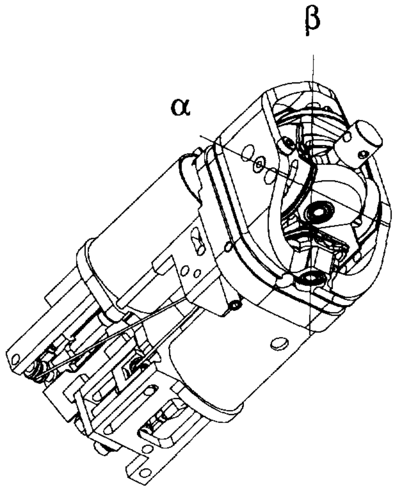

Fig. 4: Base joint unit with two actuators for two degrees of freedom.

Two actuators fixed in the base joint unit result in a slight kinematic coupling of the two axes. Due to mechanical constraints we are not able to measure the actual position of joint 2 (abduction/adduction) but of actuator 2. Thus we have to calculate the actual joint position from the measured position of joint 1 and actuator 2. Devoting the position of axis 1 α (*Fig. 4*) the position of actuator 2 β, the position γ of joint 2 is given as:

$$\gamma = sign(\beta)\arccos\left(\frac{1}{\sqrt{1+\cos^2(\alpha)\tan^2(\beta)}}\right).$$

On the other hand this means to achieve a desired position γ of axis 2, β has to be measured as:

$$\beta = \arctan\left(\frac{1}{\cos(\alpha)}\tan(\gamma)\right).$$

In case of axis 1 in its initial position (α=0), there is no coupling. We observe the highest degree of coupling in the extreme positions of joint 1 and joint 2. In this case β deviates 9.23° from γ. Since the equation is known, the deviation can be compensated.

The range of motion for the joints is given as ±45°for joint 1 (curling motion of base joint), ±30° for joint 2 (abduction/adduction of base joint) and 105° for joint 3 and 110° for joint 4 respectively (both joints: curling motion of finger).

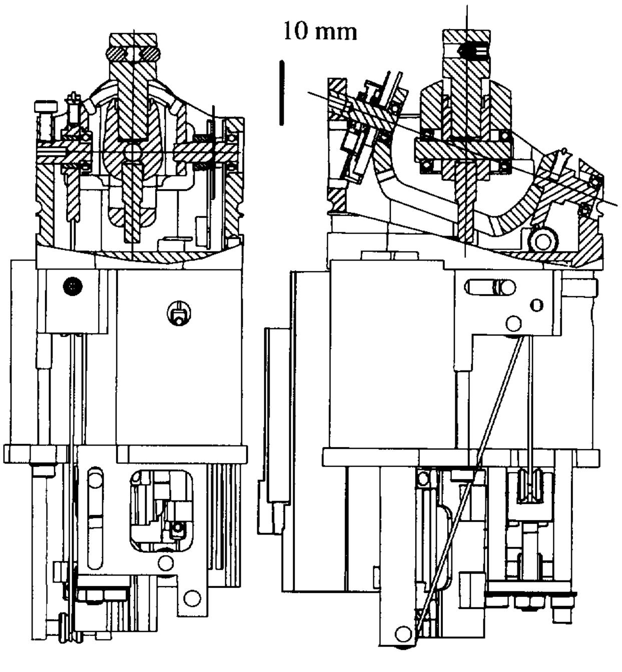

Fig. 5: Sectional view of base joint unit with two actuators and two joints from front (left) and side (right).

Sensorial Structure

A dextrous robot hand needs as a minimum a set of force and position sensors to enable control schemes like position control, force control and stiffness control. Special types of sensors add to this basic sensor equipment (*Table 2*).

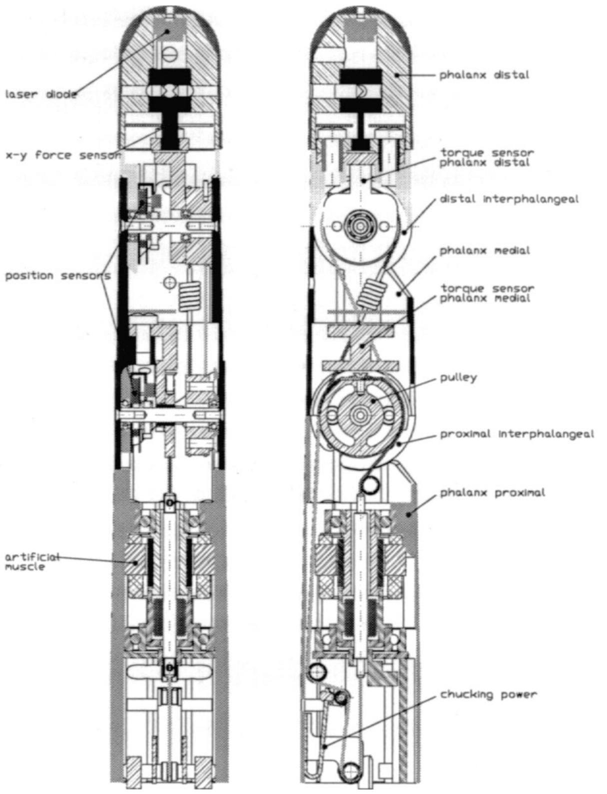

Fig. 6: Design of the finger unit with one integrated actuator and two coupled joints.

Beside conventional strain gauge based joint torque sensors in each joint a newly developed optical position sensor is integrated in every joint of the DLR Hand in order to meet the requirements. A separate joint angle sensor is necessary due to the presence of slippage in the planetary roller spindle drive and hysteresis of tendon transmission.

This optical joint position sensor (*Fig. 7*) fits in an almost human sized finger (*Fig. 6*).

The sensor is based on a one-dimensional PSD (Position Sensitive Device). This PSD is illuminated by an infrared LED via an etched measurement slot. Using an optimized PCB design exclusively equipped with tiny SMD items and the development of a circuit with a minimized number of items used it was possible to create an optical position sensor with excellent 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 analogue conditioning circuit is included in the sensor itself. 10 Bit angular solution are achieved with a linearity error of less than 1 % using a supply voltage of 14 V.

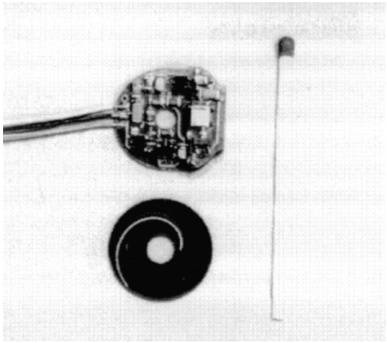

Fig. 7: Joint position sensor

By replacing the slice with the measurement slot the measurement range can easily be adapted to various requirements.

To increase the controllability of the actuators, speed sensors are important. Therefore we developed a so-called Tracking Converter providing us with a high resolution (3072 steps per motor revolution) position information of the motor's rotor. The sensor is based on linear Hall effect sensors as commutation sensors in the motors. The Tracking Converter is a small hardware circuit which converts the three sinusoidal commutation signals to a high resolution position information.

Sensor Type	count	Range/resolution
joint position	4	110° (8 bit), 90° (10 bit)
joint torque	5	1.8 Nm (9 bit)
Tactile sensors	4	0.5-10 N, 35 mN res.
rotor position	3	3072 steps per revolution
Temperature	5	0-100 °C, 0.5 °C res.
light barriers	6	
proj. laser diode	1	0.5 m

Table 2: Sensors of one finger

These three sensor types are essential for low level joint control. The hand is equipped with various other sensors as well.

- Tactile sensors cover each finger link. They consist of tactile foils detecting center and size of external forces applied to the fingers. The sensors are based on FSR (force sensing resistor) technology and arranged as XYZ pads [11]. With a cycle time of 2 ms they are also suitable for low level joint control.
- The finger tips provide a light projection laser diode to simplify image processing for a tiny stereo camera system integrated in the hand's palm. Due to the already mentioned modularity the finger tips might be easily exchanged with a version containing e.g. fiber optics. The two-axis torque sensor hereby serves as fast exchange adapter.
- Several temperature sensors and light barriers are present for security purposes.
- Additionally the hand is equipped with a six dimensional force torque sensor in the wrist.

Signal conditioning for the sensors in the finger is completely integrated in the finger unit.

Hand Controller Hardware Design

DLR's Dextrous Hand is controlled by a multiprocessor system.

The controller hardware design shows up a fully modular concept (*Fig. 8*). The control architecture is split into two levels, the global hand control level and the local finger control level. The global hand controller is externally located in a PC running a real time operating system.

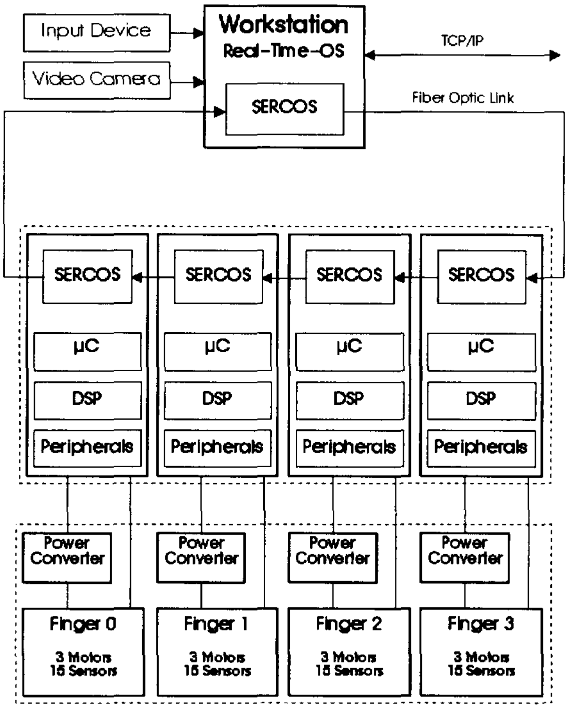

Fig. 8: Hand control system

Thus maximum flexibility is provided for implementing various hand control strategies.

In contrast to the widely used controller hardware designs the modular local finger controllers are located near the hand (*Fig. 9*) attached to the manipulator carrying the hand. This design became feasible due to the high degree of integration and miniaturisation of the finger controller hardware.

Global hand controllers and local finger controllers communicate via SERCOS (SErial Real Time COmmunication System) by fiber optic link. SERCOS is powerful enough to exchange all sensor information and control signal within 1 ms for all four fingers.

The main goals taken into consideration for this design are high flexibility, easy expandability and maximum computational performance.

The current finger controller solution is about 1.8 kg in weight and 12 x 11 x 22 cm^3 in size for the whole hand with four fingers (*Fig. 9*). Thus it can easily be carried by common robots used with our dextrous hand. For the future additional miniaturisation is envisaged.

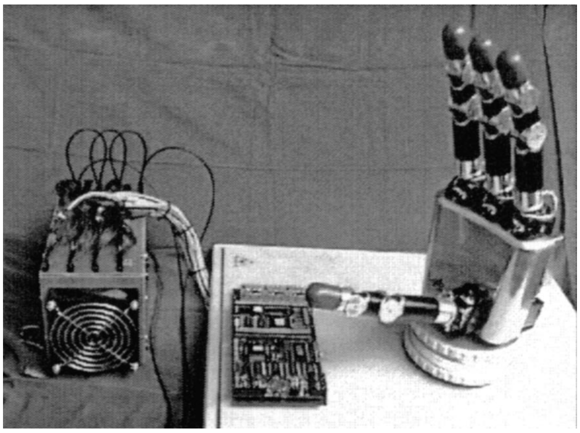

Fig. 9: Finger controller (left) and DLR Hand. In the middle one finger controller module is shown.

Due to the integration of the local finger controllers as well as the complete drive system including the power converters into the hand-arm system the cabling carried by the manipulator arm reduces to a fiber optic link ring and a four line power supply interface.

Finger Controller Hardware Architecture

For the control of each finger one finger controller module is necessary. The controller module (*Fig. 10*) is an independent subsystem of the hand system and receives commands from the global control level by SERCOS via fiber optic link.

One μ-controller per finger is responsible for the information management inside the controller module. An additional 60 MFLOPS floating-point DSP provides a control hardware with sufficient computational power to realise future control algorithms for the three motors of each finger. These finger controllers integrate all the peripherals shown in *Fig. 10* necessary to drive a complete finger.

Identical finger control modules are put together by a common power supply to form the complete control system for the local finger level. The modular design allows the use of up to four finger control modules with the current power supply design. In order to obtain a certain number of fingers for a fixed design a redesign of the power supply is sufficient to get the optimal solution in respect of size and weight.

Joint control strategies are presented in a complementary paper at this conference.

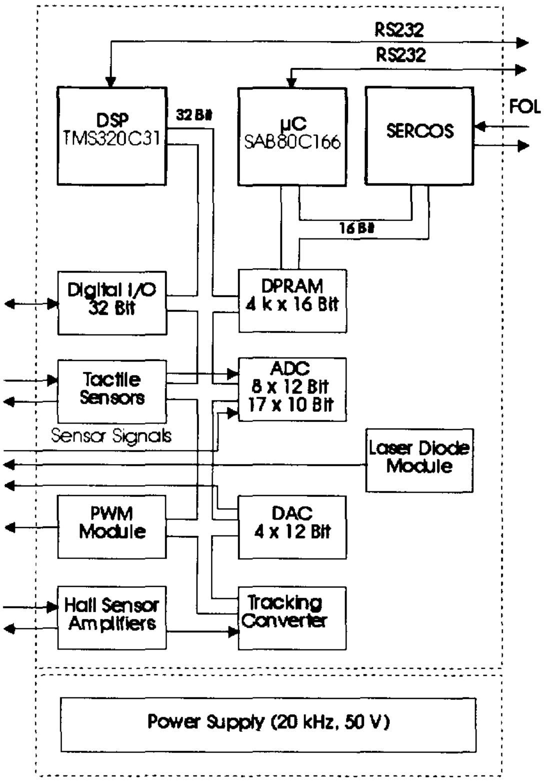

Fig. 10: Finger controller hardware

Software Structure

In terms of flexibility a modular software structure is essential for a research system like the hand system presented here.

Software is separated in the task level programming environment and the real time control environment (*Fig. 11*). The real time control environment contains the joint controllers running on the finger DSPs and the hand controller running a real time operating system.

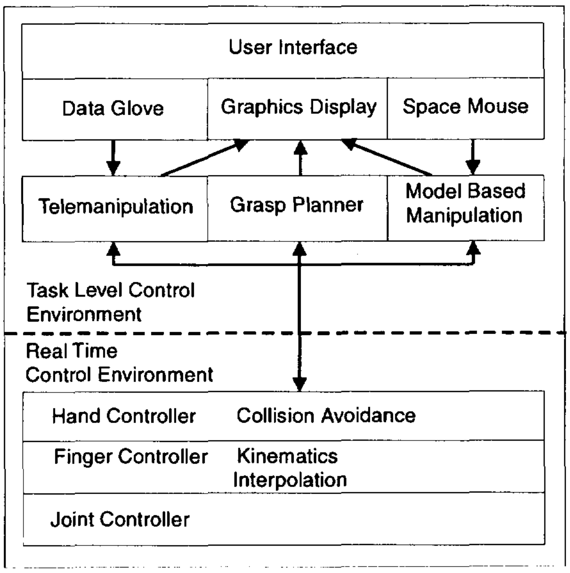

Fig. 11: Software structure

This hand controller is located between the finger controllers and the external task level programming environment and is responsible for kinematics calculation, cartesian stiffness calculation and trajectory interpolation.

Currently the task programming environment comprises collision avoidance, a grasp planner and the man machine interface.

The interface between the data glove and the artificial hand is a separate software module due to the fact, that the data glove measurements are non-linear with respect to the finger positions and highly coupled. We solved this problem by using a feed-forward neural network which learns the non-linear relationship between the fingertip positions and the data glove measurements. This will be outlined in a different publication at this conference.

Conclusion

The main features of a modular manipulation system with integrated actuators for dextrous manipulation in unstructured servicing environment has been presented. The presentation focused on the efficient control architecture.

It shows flexibility and computational power to meet even future requirements for autonomous manipulation.

Future activities will focus on the implementation of powerful grasping strategies, further miniaturisation and further improvement of mechanical and electrical reliability. The hand is supposed to become a central component for the development of future robonauts in space, but also aims at being used as a prosthesis at least long-term.

References

[1] G. Hirzinger, J. Butterfass, S. Knoch, H. Liu, *DLR'S Multisensory Articulated Hand,* Preprints Fifth Int. Symposium on Experimental Robotics, Barcelona, Spain, June 1997, pp. 28-34.

[2] S.C. Jacobsen, I.K. Iversen, D. Knutti, R.T. Johnson, K.B. Biggers, *Design of the Utah/MIT Dextrous Hand,* Proceedings IEEE Int. Conf. on Robotics and Automation, USA, 1986, pp. 1520-1532.

[3] C. Melchiorri, G. Vassura, *Mechanical and Control Features of the University of Bologna Hand Version 2,* Proc. IEEE Int. Conf. on Intelligent Robots and Systems, Raleigh, 1992, pp. 187-193.

[4] J.K. Salisbury, *Design and Control of an Articulated Hand,* Int. Symposium on Design and Synthesis, Tokio, 1984.

[5] B.M. Jau, *Man-Equivalent Telepresence Through Four Fingered Human-Like Hand System,* Proc. IEEE Conf. on Robotics and Automation, France, 1992, pp. 843-848.

[6] Y. Maeda, S. Tachi, A. Fujikawa, *Development of an Anthropomorphic Hand (Mark-1),* Proc. Int. Symp. on Industrial Robots, Tokyo, 1989, pp. 537-544.

[7] S. Sugano, I. Kato, *Wabot-2: Autonomous Robot with Dextrous Finger-Arm Coordination in Keyboard Performance,* Proc. IEEE Conf. on Robotics and Automation, Raleigh, 1987.

[8] H. Hashimoto, H. Ogawa, M. Obamam, T.Umeda, K. Tatuno, T. Kurukawa, *Development of a Multi-Fingered Robot Hand with Fingertip Tactile Sensors,* Proc. IEEE Conf. on Intelligent Robots and Systems, Yokohama, 1993, pp. 875-882.

[9] M. S. Ali, K.J. Kyriakopoulos, H.E. Stephanou, *The Kinematics of the Anthrobot-2 Dextrous Hand,* Proc. IEEE Conf. on Robotics and Automation, Atlanta, 1993, pp. 705-710.

[10]J. Dietrich, G. Hirzinger, B. Gombert, J. Schott, *On a Unified Concept for a New Generation of Light-Weight-Robots,* Proc. Int. Symp. on Experimental Robotics, Montreal, Canada, 1989.

[11]H. Liu, P. Meusel, G. Hirzinger, *Tactile Sensing System for the DLR Three-Finger Robot Hand,* IMEKO Technical Committee on Robotics, 1995, pp. 91-96.

[12]M.T. Mason, J.K. Salisbury, *Robot Hands and the Mechanics of Manipulation,* MIT Press, Cambridge, USA, 1985.

[13]S.T. Venkatamaran, T. Iberall, *Dextrous Robot Hands,* 1st ed., NY, Springer Verlag, 1990.

[14]T. Matsui, T. Omata, Y. Kuniyoshi, *Multi-Agent Architecture for Controlling a Multi-Fingered Robot,* Proc. IEEE Conf. on Intelligent Robots and Systems, Raleigh, 1992, pp. 182-186.