An Embedded Tactile and Force Sensor for Robotic Manipulation and Grasping

Giorgio Cannata, Marco Maggiali
Mechatronics and Automatic Control Laboratory
Department of Communications, Computer and System Science
University of Genoa
Via Opera Pia 13, 16145, Genova, Italy
cannata@dist.unige.it, marco.maggiali@unige.it

Abstract— **A new fully embedded tactile/force sensor system is presented. The sensor has been designed to be installed on a dextrous robot gripper (MAC-HAND). The tactile sensor consists of a matrix of 64 electrodes, etched on a flexible PCB covered by a conductive rubber layer. The force sensor is an off-the-shelf integrated three components micro-joystick. The analog and digital electronics is fully embedded with the sensor that is a self-standing module mounted on each finger phalange.**

I. INTRODUCTION

Manipulation capability is essential for a humanoid robot. Interaction between a humanoid hand and objects can be properly controlled only is suitable sensors are available. In particular, information about the contact location, the forces applied at the contact, other indirect measurements, e.g. estimate of mass object, its inertia ellipsoid, or even non mechanical measurements, e.g. temperature, may play a crucial role to implement secure grasp and safe manipulation tasks.

In the past two decades several robot hands, and dexterous grippers have been developed. The major goals have been on one hand that of studying and implement newer mechanical solutions in order to increase miniaturization and dexterity, and, on the other, to investigate manipulation models and control techniques.

At mechanical level study on dextrous grippers has mainly focused on the actuation and kinematics aspects. With very few exceptions (e.g. [10]-[13]), small or miniature dextrous robot grippers are actuated by tendons. Starting from the actuation models proposed in seminal works of Salisbury [1], and Jacobsen [2], tendon actuated mechanisms, and their numerous variants, still represent an effective way to implement compact manipulators. Actuation of tendon based robot grippers poses various technical problems. Tendons coupling on one hand, friction and elasticity on the other, pose important problems for the control of tendon actuated mechanisms. However, the mechanical accuracy required to design a miniature (e.g. human sized) dextrous gripper, is by far less than an equivalent design based on gears or other stiff transmission mechanism. The recent design proposed in [3], goes into this direction making the mechanical design significantly simpler than current ones. The three-fingered Stanford/JPL Hand [1] and the four-fingered Utah/MIT hand [2] have been both groundbreaking devices. These devices, with complex mechanics, have few electronics and few sensors integrated on the hand. Recently the tendency is to create robot hands more compact and high integrated sensors system, in order to increase the grasping capability and in order to reduce cabling through the finger, the palm and the arm.

The problem of manipulation control involves the availability of information about geometric and mechanical quantities, either from direct measurements or using suitable estimates. To this aim, various tactile and force/torque sensors have been proposed and designed. However, only limited effort has been put to design and implement, integrated tactile and force/torque sensors as embedded systems. As a matter of fact, miniaturization and cabling harness represents a significant limitation to the design of small sized embedded sensors. The four-fingered hand DLR-II, [4], is a significant example of robot gripper integrating on board a complete force/torque sensor system. The hand has 22 degrees of freedom (DOFs) and is a complete self-contained system including motors, electronics and sensors all embedded in the palm and the fingers. In particular, on each fingertip is installed a six components force/torque sensor with embedded electronics, connected with the control modules using 10 wires: 8 wires for high speed data communications, 2 wire power supply). The force/torque transducer features a sophisticated mechanical design specific for the finger tip of the hand. It is worth noting that the DLR-II gripper does not make use of tactile sensors. Another recent interesting example of integrated mechanical and sensing design is the robot hand RTR-II, [5]. RTR-II is a three-fingered underactuated tendon driven hand, actuated by four DC motors. Each fingertip is sensorized with a custom three components force sensor without integrated electronics. All the fingers are sensorized with polyimide custom on-off tactile sensors (44 sensitive areas for each finger), with an activation force of about 1N, [5].

The major contribution of this paper is to present the design of a fully integrated tactile and 3-axis force sensor, with embedded electronics. The approach adopted has been that of using low cost components available off-the-shelf, and to pursue a highly modular sensor design. The proposed system consists of a distributed array (8×8), of analog tactile elements based on conductive rubber, and of a solid state

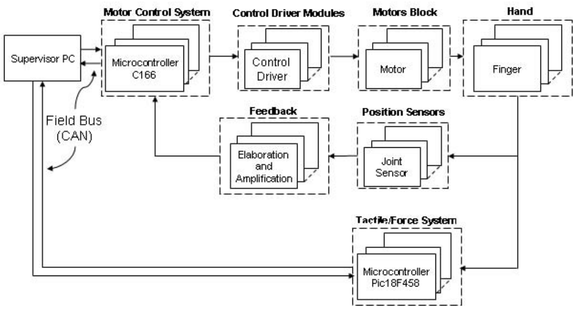

Fig. 1. MAC-HAND system architecture.

Fig. 2. Skeleton of the fingers with joint sensors.

force transducer. All the electronics required (both analog and digital) is embedded on the sensor. The system is scalabe and designed to be integrated on the supporting four-fingered hand (MAC-HAND). In particular, two identical sensors are mounted on each finger, one for phalange. The sensor is connected to the control modules using a CAN bus link, thus requiring only four cables to be routed along the finger.

CAN bandwidth poses important limits to the direct implementation of high rate tactile image feedback from all the sensors. In order to overcome limitations we propose to approximate the tactile image of the contact, as an ellipsoid and to transmit only its geometrical parameters. Computations are all performed onboard and enable high rate tactile and force feedback.

The structure of this paper is as follows. In section II, the robot hand MAC-HAND is shortly described. Then, in section III the basics of the contact-sensing problem are discussed. In section IV the modular structure of the sensor is presented and detailed in sections V, VI and VII. Conclusions are finally discussed in section VIII.

II. THE MAC-HAND ROBOT

MAC-HAND is a four fingered anthropomorphic robot hand. Each finger has three DOFs and is actuated by four independent tendons [6], driven by DC motors. The four fingers are identical, and consist of two phalanges. The principal characteristics of MAC-HAND are summarized in table 1. Fig. 1. shows the modularity of the MAC-HAND system. Each finger is independently actuated by four motors. The control is performed by four Infineon C166 microcontrollers, one for each finger, Finally the coordinated control of the hand is demanded to a supervision computer connected through a CAN bus link.

The hand has been designed as an open skeleton structure made of acetal homopolimer resin in order to reduce its weight. The skeleton structure has been chosen to embed sensors and electronics needed for tactile/force sensor system directly on-board. In the following the design of the embedded tactile and its integration is discussed.

III. TACTILE AND FORCE SENSING

Manipulation control requires in general some sort of feedback which could provide information about the interactions occurring during contact between the gripper and the grasped object. Assumptions must be made about the nature of the contact and, on the base of the selected contact models, it is possible to specify the nature of feedback required to properly control the interaction. Detailed contact mechanics models are in general too complex to be taken into account in real-time control applications. In practice, simplified lumped parameter models are usually considered, [6]. Among these the most relevant are the so called point contact model, and soft finger model. Point contact is used when the area of contact is significantly smaller than the objects involved in contact, and at the contacts are transmitted only forces, compatible with the classic Coulomb models. In the soft finger model it is assumed that also a torque, aligned with the normal to the surfaces in contact, arises. The model equations for these models are:

$$\begin{cases} \mathbf{f} = \mathbf{p} \\ \mathbf{m} = \mathbf{q} + \mathbf{c} \times \mathbf{p} \end{cases} \tag{1}$$

where **p** and **q** are the contact force and torque (for soft finger models only), **c** is the contact location, and **f** and **m** are the measured force and torque.

Bicchi and Salisbury, [6], proposed procedures for computing **p** and **q** on the base of the measurements **f** and **m**. However a precise geometric model of the pressor (the robot finger) is required, and, except the case of simple geometries, the method is computationally intensive and critical for realtime

TABLE I

CHARATERISTICS OF THE MAC-HAND

Number of finger	4 (identical)
Degree of freedom	12 (3 each finger)
Joint position sensor	mini-potentiometers (Murata)
Force sensors	8(2 each finger)
Tactile sensors	8(8×8 array -2 each finger)
Actuators	16(6V, DC motors)
Weight	∼350g(w/o motors) < 1 Kg(including motors and cabling)
Finger length	115 mm (from first axis to finger tip)
Finger width	23 mm
Hand length	180 mm (from first axis to finger tip)
Maximum load	2.5 N (at finger tip)

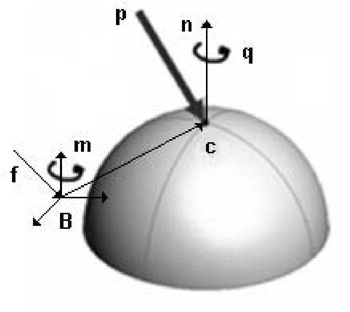

Fig. 3. Point of contact (**q**=0) and soft finger contact model. The torque **q** is parallel to **n**, the normal to the surface at point **c**

implementation. A direct solution to the contact problem would be obviously possible if the contact location c would be directly measured. Therefore the availability of a direct force measurement and of the contact location allows directly to solve the point contact problem. We have pursued this solution due to the availability of commercial solid state miniature three components force sensors, and focused on the design of a simple custom made matrix tactile sensor for contact location measurement.

IV. FORCE/TACTILE SENSOR DESIGN

At system level the goal is to develop to an integrated tactile/force sensors with embedded electronics to be placed on the falanges of MAC-HAND. The relevant problems considered have been: choice of appropriate force transducers, pressure transducers for contact measurements, integrated electronic design. Fig. 4 shows the modules featuring each sensor.

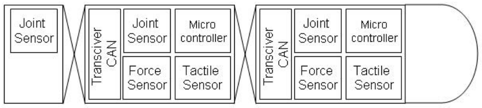

Fig. 4. Sensing, electronic and communication modules installed on each finger

V. FORCE SENSOR

As a force sensor, we have used the integrated micro joystick, CTS Series 109 manufactured by CTS Corporation. This device has good sensitivity and linearity, furthermore its SMD packaging makes its embedding and integration with other electronics very simple, see table 2 for detailed specifications.

Fig. 5. Pointing device series 109

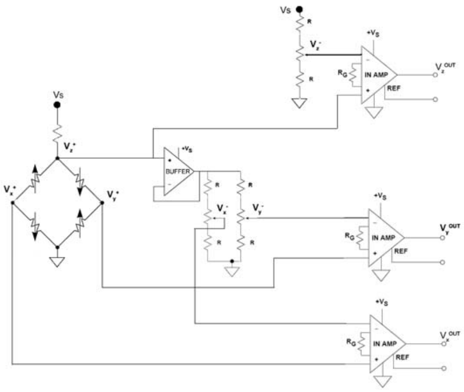

Fig. 6. Circuit diagram of force sensor and amplification circuit

The device consists of four strain sensitive thick-film resistors. A force applied to the interface stick produces a change of resistivity. Proper arrangement of the resistors in three Wheatstone bridges, and a simple decoupling amplifier, allow to obtain three voltages proportional to the applied force components. Digital potentiometers are used for self-calibration of the bridges and three instrument amplifier provide appropriate signal conditioning before sampling.

VI. TACTILE SENSOR

A. *Tactile Sensor Transducer*

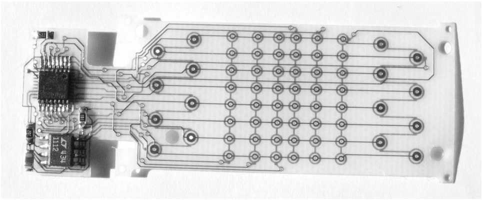

Fig. 7. The electrodes are etched on a flexible printed circuit board, are configured as a variable resolution 8×8 matrix (back side shown).

The tactile transducer is a matrix of 64 electrodes covered by a layer of pressure sensitive conductive rubber (PCR Co. Ltd.). The electrodes are etched on a flexible PCB substrate, fig. 7, in order to conform to a cylindrical surface. A thin elastic sheet covers the whole sensor and provide a mild preload usefull to reduce noise. Pressure due to contacts produces changes of resistance among the electrodes. The geometry of the electrodes, fig. 9 and fig. 10, has been defined

TABLE II

SPECIFICATIONS OF CTS SERIES 109 FORCE TRANSDUCER

Output Linearity	1.0 %
X, Y Axis Output Characteristics	0.85 $\mu V/V/g$
Z Axis Output Characteristics	0.125 $\mu V/V/g$
Maximum Overload Force	40N
Dimensions	10×7.5×5.5 mm

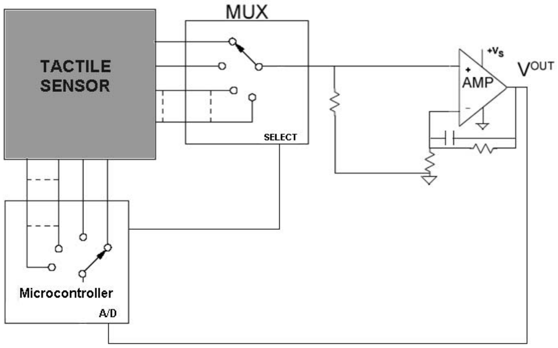

Fig. 8. Functional scheme of the tactile sensor.

with the goal of limiting the spurious currents that may occur across the various electrodes, and interfere with measurement, as discussed in [7]. The principle of operation of the transducer is the well known rows-columns scanning. In order to limit the number of components the column selection is made by direct polarization of each line by the local microcontroller (MCU). An analog multiplexer selects the row signal lines and finally an amplification and filtering stage condition the signal before sampling, fig. 8. All the components needed for the signal conditioning have been placed on the flexible PCB, in order limit cabling. A miniature connector interfaces the transducer with the local microcontroller (MCU) board.

B. Tactile Data Processing

Tactile data are sampled by the on-board MCU, with 10 bit resolution. Preliminary tests show an actual sensor resolution of 8 bit/taxel. Each tactile image consists of 64 taxels. Communications of the tactile/force sensor with the remote hand controller are based on a CAN bus. A reasonably conservative transmission rate for CAN messages (with full payload) is about 200÷250 μsec. Therefore, complete transmission of the eight tactile images for the whole hand would take 12.8 ÷16.0 msec. These figures do not account for latency times due to actual data acquisition and data processing (both at control level and data acquisition level). In order to make the delay due to transmission less critical, accordingly with the contact model analysis discussed in section III, we propose to perform locally at sensor level a preprocessing of the tactile images and transmitting over CAN only relevant information about the sensed contact and force. During contact, a number of adjacent taxels are subject to pressure. The analog output of the tactile sensor allows to measure the distribution of pressure over all the transducer. Therefore, we propose to compute the contact centroid [6], as

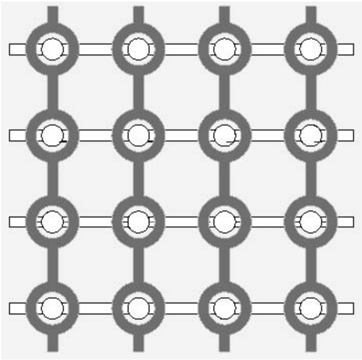

Fig. 9. Shape of the electrodes

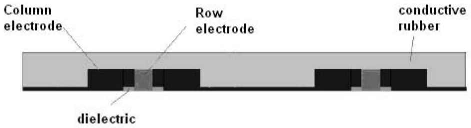

Fig. 10. Section of a column of the matrix. Row electrode is surrounded by column electrode

$$\hat{\mathbf{C}} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} \mathbf{x}_{ij} \cdot p(\mathbf{x}_{ij})}{\sum_{i=1}^{N}\sum_{j=1}^{N} p(\mathbf{x}_{ij})} \tag{2}$$

where $\hat{\mathbf{C}}$ is the computed contact centroid, $\mathbf{x}_{ij}$ is the coordinate of the taxel and $p(\mathbf{x}_{ij})$ the weight of this. As a matter of fact further geometric information about the distribution of the pressure during contact could be usefull, although not directly relevant to point contact model solution. To this aim the pressure distribution is approximated as an ellipsoid, fig. 11, as follows:

$$\mathbf{E} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} (\mathbf{x}_{ij} - \hat{\mathbf{C}})(\mathbf{x}_{ij} - \hat{\mathbf{C}})^T \cdot p(\mathbf{x}_{ij})}{\sum_{i=1}^{N}\sum_{j=1}^{N} p(\mathbf{x}_{ij})} \tag{3}$$

Where $\mathbf{E}$ is a symmetric matrix who represent the ellipsoid. The approach used to compute and the associated approximate ellipsoid, is strongly based on the availability of an analog tactile sensor.

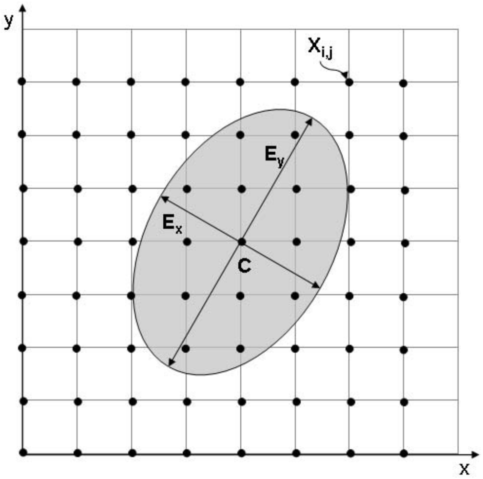

Fig. 11. Ellipsoid of contact

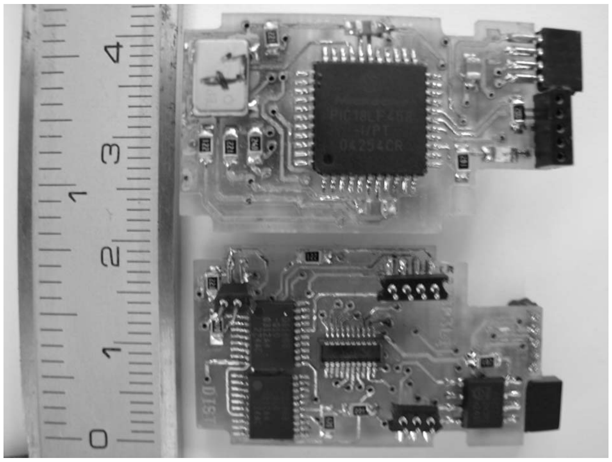

Fig. 12. Microcontroller module

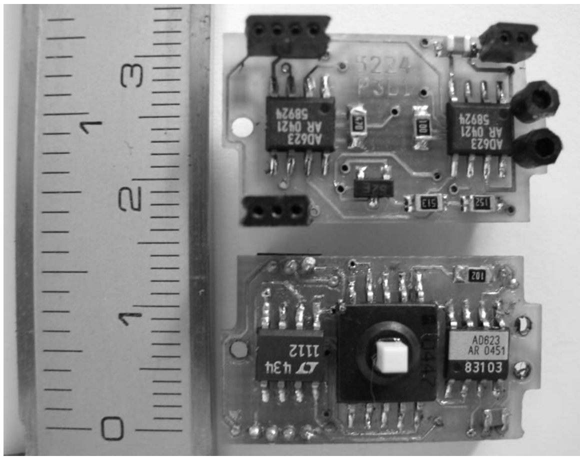

Fig. 14. Force sensor module

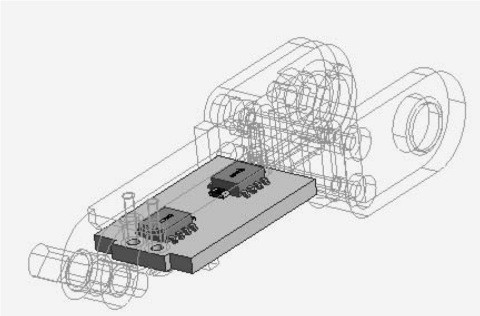

Fig. 15. Positions of the force board on the phalange

Assuming computed and measured data resolution of 1 byte, only one CAN message per sensor is required to transmit force/tactile feedback to the hand controller.

VII. INTEGRATION

In order to simplify the design a common mechanical interface has been designed for all the sensors. Each sensor consists of three modules. The first module contains: the MCU (currently a Microchip PIC18F458 with 40MHz clock); the digital potentiometers (needed for the calibration of the force sensors); the transceiver CAN needed for the communication with the hand controller. The module is shown in fig. 12, at is fixed on the upper part of the corresponding link, fig. 13.

The second module contains the force sensor (fig. 14), and the associated analog electronics, consisting of three instrument amplifiers and an analog low noise operational amplifier.

In fig 15, you can note that this board is fixed on the skeleton of the phalange, and through three comb connectors is connected with the microcontroller board.

The third module is the tactile sensors. It consists of a flexible PCB shaped to conform to the phalange cover, (fig. 16), and etched to form the array of electrodes. The flex PCB, supports the signal amplifier, the row scanning multiplexer and the interface connector to the microcontroller module. A pressure conductive rubber sheet covers the flexible circuit, and an external thin elastic cover provides the required preload on each contact.

Fig. 17 shows the entire phalange assembly procedure. It is important to note that the sensor is entirely supported by the force sensor. Therefore, force measurement can be obtained around the whole falange, although tactile information is available only for contacts generated lower half of the finger.

Fig. 18 shows the two phalanges of the finger. The same modules are mounted in both phalanges. In this first prototype, the tactile sensor does not cover the tip.

VIII. CONCLUSIONS AND FUTURE WORK

An integrated force/tactile sensor with embedded electronics has been presented. The sensor consists of a three components

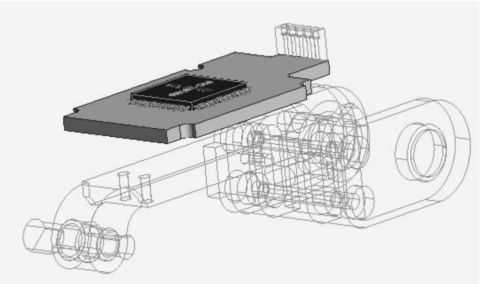

Fig. 13. Position of the microcontroller board on the phalange

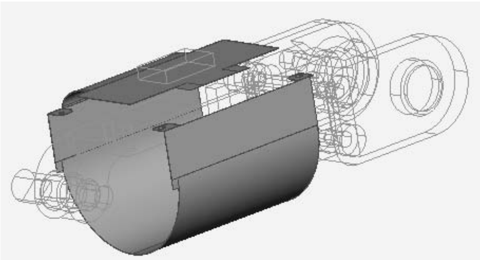

Fig. 16. The flexible circuit covers shell of the phalanges

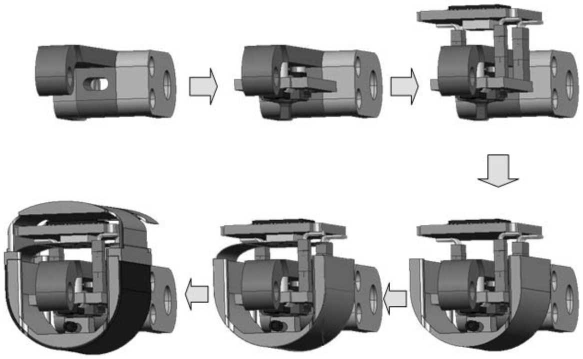

Fig. 17. Phalange assembly

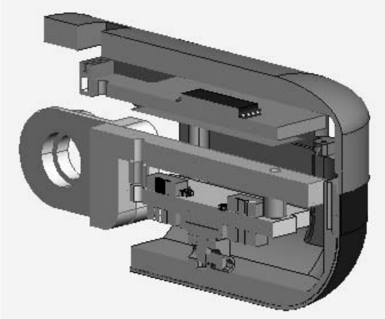

Fig. 18. A longitudinal section of the finger

commercial force sensor and of a custom matrix tactile sensor based pressure sensitive conductive rubber. The sensor is modular and mounted in eight identical replicas on the phalanges of the humanoid gripper MAC-HAND. The joint use of both tactile and force information allows the direct solution of the point contact problem. A technique to compute the contact centroid and a quadratic approximation of the pressure distribution during contact has been proposed. This technique allows to reduce the delay due to the limited bandwidth of the CAN bus data link implemented. The tactile/force sensor system has been so far integrated an functional tests have been performed on the various modules separately. Ongoing work is focusing on detailed aspects of calibration and detailed performance analysis. Future work will involve the redesign of the palm of the DIST-HAND to host a tactile sensor based on the same principle of the sensor described here.

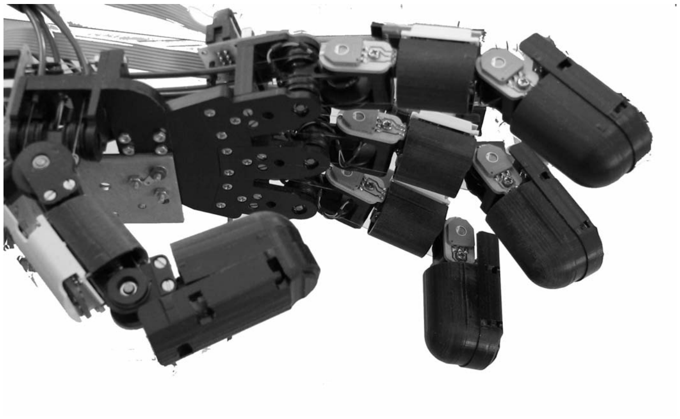

Fig. 19. The MAC-HAND

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