Preliminary Design of an Anthropomorphic Dexterous Hand for a 2-Years-Old Humanoid: towards Cognition

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***Abstract* - This paper presents first results in developing an anthropomorphic dextrous hand for a 2-years-old Humanoid. As this robot is aimed to be a physical platform for cognition, the number of degrees of freedom of the upper part of the body has been maximized. The robotic hand has 20 DoFs and 9 motors to accomplish optimal grasping and manipulation. Based on the manipulation tasks required in the project and on the human hand functional anatomy, we decided a mixed implementation of cable directed driven and under-actuated joints, locating most of the motors in the upper limb. The abduction/adduction of the fingers and the hollowing of the palm have been implemented and coupled together, driven by a single actuator. The first prototype has been developed; it includes the hand mechanism, the actuators and a proprioceptive sensory system for the joint positioning and the grasping force control. The sensor for cable tension and the design of the actuation units to be placed in the arm are described in detail.**

***Index Terms* – Cognitive, Manipulation, Hand, Humanoid, Under-actuation.**

I. Introduction

This papers starts from the work done during the first year of the RobotCub EU Integrated Project IST-2004-004370. The main goal of RobotCub are to create a physical platform for research that can be used by researchers involved in embodied cognition, and to advance the understanding of several key issues in the investigation of several cognitive capabilities.

To achieve this goal an embodied system is under construction. This cognitive system (the iCub) will be shaped, physically and mentally, like a human 2 years old child. The iCub will be able to learn how to interact with environment through manipulation and gesture, in a bi-directional way (production/interpretation), and how to develop its perceptual, motor and communication skills to perform goal directed and manipulation tasks.

Drawing on our broad multidisciplinary background in human developmental psychology, physiology, cognitive robotics, mechatronics, and perceptual science, a program of a experimental research have been planned. We defined two main task from which we elicited the requirements to meet in the design: (1) the crawling and (2) the manipulation seem to be the more challenging tasks. Involving and stressing the main articulation, these tasks point out the complexity and the weakness of the mechanics (actuation, transmission and kinematics) and of the sensory system (in terms of range, sensitivity, wiring, load bearing etc.).

According to these tasks, the dimensions of the Cub are the main limitation in the choice of the actuators and sensors. Moreover, the Cub is quite an autonomous mobile robot; only the power supply and the high level control will not be in the body: the wiring, the dimension of the electronic board for the acquisition and processing, robustness and safety are all critical issues.

In this paper we present the first results of our work concerning the design of the hand: the mechanism, the actuation, the transmission, the first attempts to endow the hand with perception.

II. A Critical Analysis of the State of the Art

In the analysis of all Humanoid Robotic Platforms, different characterization of the State of the Art can be argued. It is possible to classify the Humanoid Platforms developed so far in two main groups according to the tasks that are addressed. The first one includes mobile robotic platforms (as Sony QRIO e Honda ASIMO) can be found [1],[2], that are reliable and have a complete body; nevertheless their hands are still in development and have only one or two DoFs. Thus they cannot be considered as effective cognition tools because they are unable to perform exploration tasks. The latter group consists of *incomplete* platforms but provided with dexterous hands, [3],[4],[5]. Manipulation is an addressed feature and although they seem not complete, they are fundamental experimental tools in developing artificial intelligences with cognitive abilities.

The iCub can be therefore considered as an *unicum* among all robotics platforms; it could belong to both the two groups. Nevertheless, meeting the different requirements of the two robot classes is quite complex. Table I gives an overview of the specifics of the main humanoid platforms of the two groups described.

For the actuation system, DC motors are indeed the favorite choice. They have not a high power to weight ratio but they don't need huge power sources as fluidpower actuators do; anyway their efficiency is high (>.9). It has to be pointed out that the mentioned mobile robots use battery packs; this is extremely important for such kind of platforms.

In the whole list the Shadow platform is both the only research tool and pneumatic powered device. The hand has the highest overall number of DoFs and the finger are cable driven with an agonistic/antagonistic muscle strategy. Pneumatic air muscles are indeed the technology closest to real muscles characteristics [6]; thus it is well-known as these artificial muscles have a dynamical behavior (contraction and compliance) much closer to real muscles than DC motors do. From a cognitional point of view, they probably are the best tool available. Anyway, as the iCub is an open platform, we have to consider the platform modularity as mandatory; to this purpose DC motors are more suitable.

TABLE I
OVERVIEW OF ANTHROPOMORPHIC PLATFORM

DoMs (Hand/Arm/Total)	*Purpose*	*Actuation*	*Hand dexterity*	*Mobility req.ts*
Sony QRIO (1/ 5/ 38)	Entertainment	DC motors	Grasping	Walking; climbing stairs
Honda ASIMO (1/ 5/ 26)	Entertainment	DC motors	Grasping	Walking; dancing; managing uneven surfaces
Robonaut (17 / 7 / n.d.)	Working tool	DC motors; gears, flexible shaft	Manipulation	no
DLR (13 / 7 / -)	Working tool	DC motors; gears	Manipulation	no
Shadow 22 / 7 / -)	Research tool	Pneumatic artificial muscles; direct and cable actuation	Manipulation	no

Moreover, several specs address the design toward different approaches; e.g., manipulation hardly coexists with advanced mobility.

The actuator selection has been made taking in account characteristics as easy adaptation to different conditions, better control response and, last but not least, the advantage of using the same energy type for sensors, control electronics and actuators. DC motors were eventually chosen.

B. *Overview of the whole upper limb System*

In Tab. II the number of DoFs and of DoMs (Degrees of Mobility, to be intended as DoFs directly controlled) are listed.

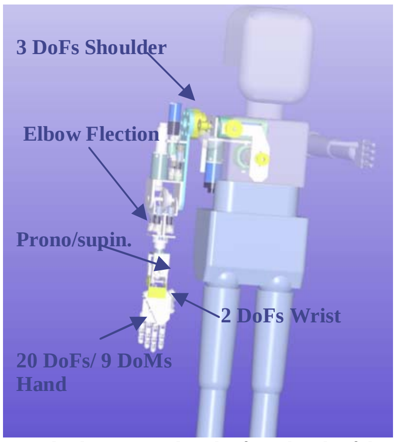

Fig. 1 The upper limb integrated in the first sketch of the Cub.

TABLE II
KINEMATICS OF THE UPPER LIMB

Subsystem	*DoFs*	*DoMs*
Shoulder (abduction/adduction, flexion on the sagittal plan and on the horizontal plan)	3	3
Elbow (flexion)	1	1
Forearm (abduction/adduction)	1	1
Wrist (flexion/extension and abduction/adduction)	2	2
Hand	20	9
Total	27	16

As in the human hand the most of the finger movements are performed by muscles *extrinsic* , the most of the motors (7) have been placed in the forearm and arm [7]. As the humanoid has to be sized and shaped as a 2-years-old child, dimensions are a critical requirement. Thus the other DoFs have to be taken in account to check if there is room enough for the finger actuation units. So the design of the hand and of the arm have been carried on together in order to make each motor and transmission of the elbow, forearm and wrist coexisting with the finger actuation units (see Fig. 2). This problem is amplified by the mobility requirements of the project; both high torques and high velocities are required for the elbow and the shoulder. To enable the investigation of relevant cognitive aspects of manipulation the design has been aimed at maximizing the number of degrees of freedom of the upper part of the body (head, torso, arms, and hands). The lower body and the arms should support crawling "on four legs" and sitting on the ground in a stable position (and smoothly transition from crawling to sitting autonomously). This will allow the robot to explore the environment and to grasp and manipulate objects on the floor.

III. The Design of the Prototype

According to the manipulation tasks and the limit we decided a mixed implementation of directed driven joints and under-actuated joints (hybrid actuated finger).

The under-actuation is the exploitation of a number of motors smaller than the number of DoFs involved. The implementation of the under-actuated mechanism, based on the differential connected mechanism, can be found in [8], [9]. When the under-actuation concept is exploited in a gripper device, the latter shows an adaptive behaviour, that is an enveloping grasp: the phalanges automatically wrap the object, according to its shape [10],[11]. As in the Hirose's Softfinger a pulling cable runs along the phalanges and around idle pulley and flexes the finger and torsional spring (when cable is released) extend the finger

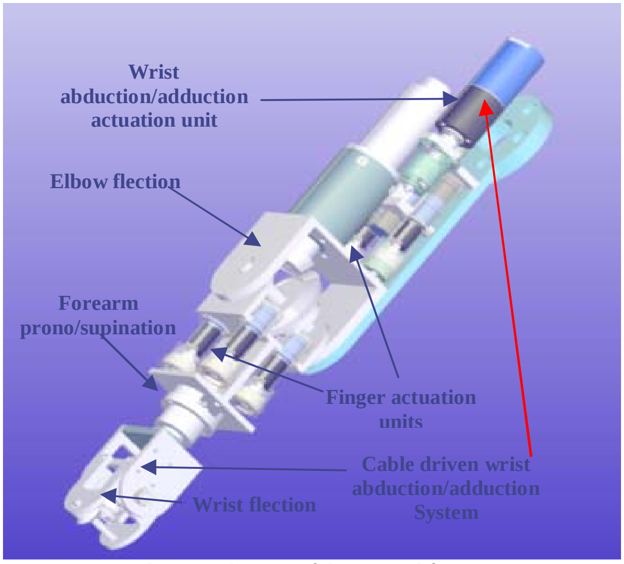

Fig. 2 The CAD drawing of the arm and forearm.

Although, an under-actuated gripper may pretty well accomplish the grasping tasks, such device may not perform manipulation: to meet the manipulation requirements direct driven joints and adequate sensing are mandatory. According to the human hand physiology [12] the PIP joint and the DIP joint are coupled; while the MP joint is direct driven and endowed with ad/abduction; this type of implementation can be found in [13]. Moreover, the little and the ring fingers are designed as fully under-actuated fingers, and coupled together. The latter provide stability during the grasping and the manipulation, and are able to apply force during power grasp, as in the human hand. Two very peculiar DoFs in the human hand are (1) the thumb opposition and (2) the hollowing of the palm. The opposition of the thumb makes the human hand an extraordinary versatile tool, allowing several grasp types and specially the power grasp and the precision grasp. The hollowing of the palm and the abduction of the fingers allows the spherical grasp (for power grasp) or tripod grasp (for precision grasp). The hollowing is also involved in the diagonal palmar grasp (see Fig. 5)

Eventually, as shown in Fig. 3, the number of DoFs for each hand is 20:

- 15 flexions of the phalanges
- 1 thumb opposition
- 3 ad/abduction (for little finger, ring finger and index)
- 1 hollowing of the palm (flexing little and ring finger toward the thumb)

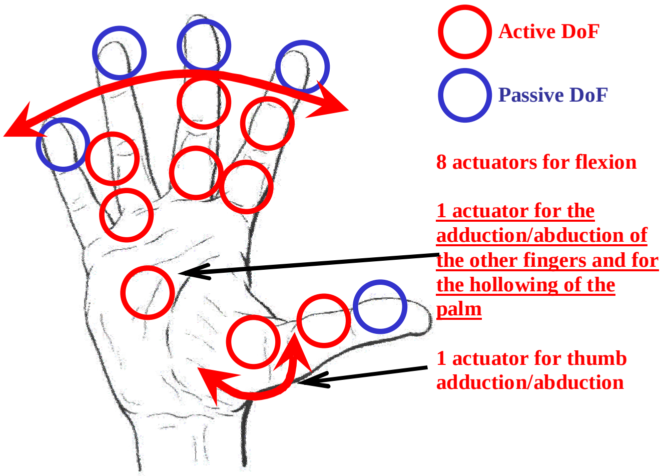

Fig. 3 The selection DoFs/DoMs in the Cub Hand.

According to the exploitation of the under-actuation concept, the number of actuators for each hand is 9, as shown in Fig. 4:

- 3 for MP joints flection of thumb, index and middle finger
- 3 for PIP and DIP (coupled in an unique under-actuated DoM) joints flection of thumb, index and middle finger
- 1 for thumb opposition (the only one located in the palm)
- 1 for flection of fully under-actuated fingers, both the little and the ring finger (3 phalanges each one), with a differential mechanism
- 1 for the hollowing of the palm and the abduction of little finger, ring finger and index. We preferred to couple the hollowing and the abduction, because both are involved usefully in the spherical grasp.

The diameter of the pulleys and the stiffness of the springs determine the kinematics of the fingers.

The CAD drawing shows the layout of the robotic hand: the DC motor coupled with a worm and a worm gear to change the opposition plane of the thumb; the axle in the palm around which the little and the ring finger flex toward the thumb; the hub around which little, ring and index finger are ad/abducted (notice the middle finger is fixed), the fully under-actuated finger and the hybrid-actuated finger, quite similar (in order to obtain modularity), but differently driven.

As in the human hand most of the actuators lie in the forearm (as the flexor digitorum profundus muscles): the actuation (see III.B) units are located in the forearm; the motion is transmitted by the means of cables, acting like tendons.

The implementation of the hollowing of the palm and of the abduction of the fingers are an important issue to be stretched further. First of all, these movements are all involved in tripod, spherical and diagonal grasps [14] (see Fig. 5); thus the iCub, endowed with thumb opposition movement, will be able to handle a wider range of objects.

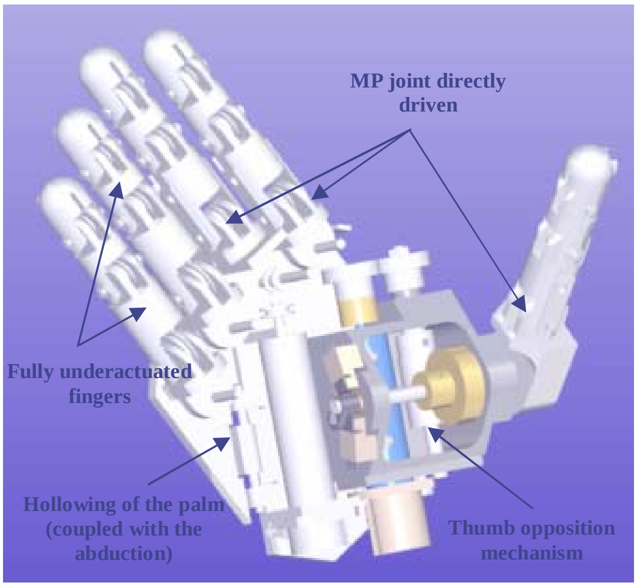

Fig. 4 The CAD drawing of the Cub Hand.

Moreover the fingers and the palm will adapt to shape of the object in a better way by the means of a pre-shaping control strategy. The contact area will be increased and so the grasp stability.

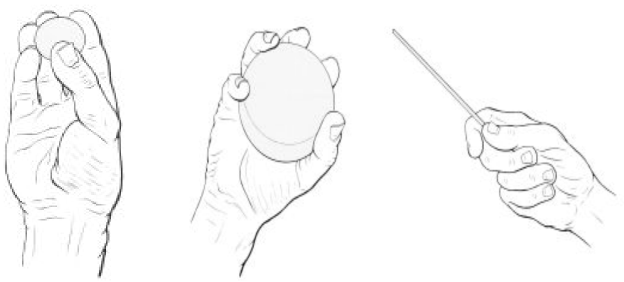

Fig. 5 Three kinds of grasp in which the ab/adduction of the fingers and the hollowing of the palm are involved.

The coupling of the finger abduction and of the hollowing of the palm is obtained by the means of a cable and pulley system in an under-actuated approach. This will permit to control 4 DoFs with only one motor. The implementation of a differential connected mechanism will further increase the self-adaptation of the grasp to the object and thus the number of contact points. Torsion springs, the diameter of the pulleys and mechanical stops will set the right kinematics and impose the desired timing between abduction of the fingers and hollowing of the palm.

III. First Results

A. The ultimate design of the finger

Once the design of the fingers had been fixed, we began to develop the first prototypes. Given the kinematics and the cable transmission system, the sensory system was implemented and integrated in the phalanges. Thus each part allows the wiring for sensor data and supply.

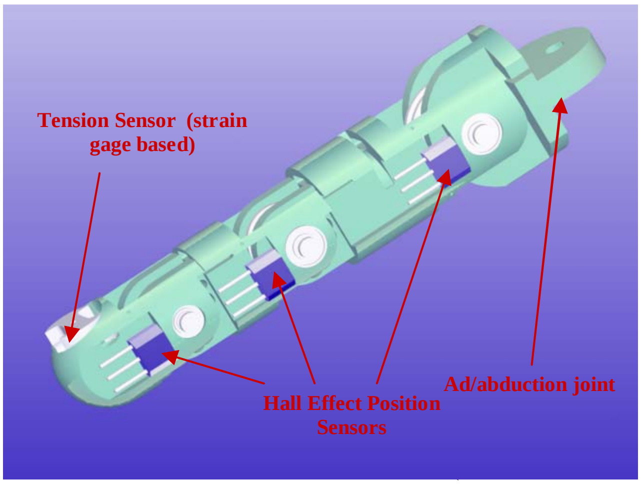

Fig. 6 The CAD drawing of Cub Finger (fully under-actuated finger).

In Fig. 6 the ultimate design of the fully under-actuated finger is shown (ring and little fingers). In order to develop a sensorial proprioceptive system, Hall effect sensors have been exploited for the joint positioning. In the ring and little finger three sensors have been integrated; in addiction to this configuration, another Hall effect sensor has been placed in the related actuation unit (see Fig. 11). In the three *hybrid-actuated* fingers, the flexion is controlled by two Hall effect sensors in the DIP and PIP joints (coupled in an under-actuated approach); for each MP joint, an encoder in the motor unit is used (see next paragraph Fig. 10).

Moreover, a cable tension tensor has been developed and integrated in the nail of the each fingertip. By the means of these devices it is possible to control the grasping force. This tendon tensiometer is based on strain gauges sensors (model ESU-025-1000, Entran Device Inc, Fairfield, NJ, USA). The micromechanical structure has been fabricated to obtain a cantilever (Fig. 7) elastically strained by the cable, in order to continuously monitor the cable tension applied by the motors, similarly as the Golgi tendon organ in series with a muscle [10].

In order to obtain both high sensitivity and mechanical strength, a FEM analysis has been performed, using width, thickness, radii of the cantilever as parameters (material is defined by the tension and the overall dimension: C40 steel).

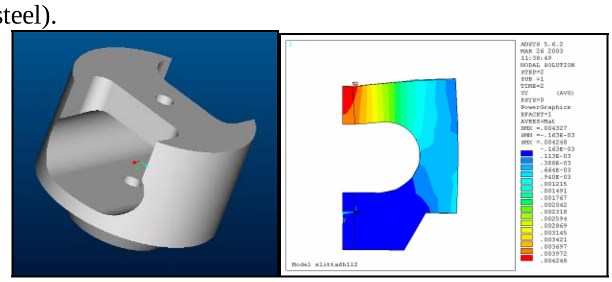

Fig. 7 Mechanical structure of the cable tension sensor and FEM analysis.

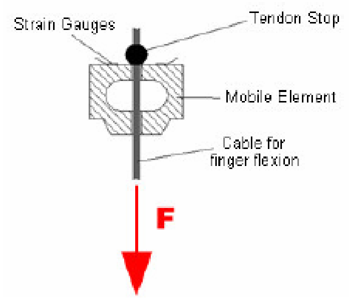

Fig. 8 Cable tension sensor: working principle.

The characterization of the sensors was performed with the INSTRON 4461 equipment. The system exploited a load cell of 100 N in order to allow the analysis of materials through extension and compression tests. Glued on the sensor cantilever there are two strain gauges (Entran ESU-025-1000): one is the varying resistor; the other is a dummy resistor used for temperature compensation. The acquisition circuit was a standard Wheatstone bridge whose signal was amplified by an AD524 (Analog Devices); the amplifier gain was fixed by a trimmer. The strain gage amplified signal and the INSTRON load cell output were acquired with a National Instruments (NI) DAQ (Data Acquisition) Card . Compression tests were performed by using a conic tip fixed onto the load cell. The sensor was radially constrained by a special support on which it was fixed during the tests. The graphs in Fig. 9 shows the results of a loading (blue curve) and unloading (red curve) cycle obtained with an amplification of 30. The experimental results show a good repeatability and linearity, and a maximum hysteresis error of about 8% of full scale.

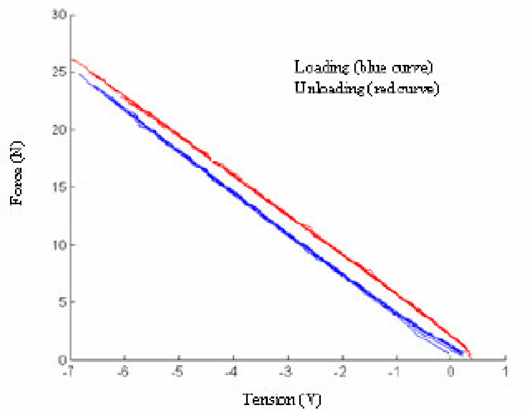

Fig. 9 Test results for loading and unloading phase.

B. *The actuation units*

The actuation allows the cable to be winded around a capstan. The capstan is directly coupled on the motor shaft. When the motor turns, the cable is pulled, acting as a tendon and flexes (or extends) the phalanges. The cables (diameter 0.7 mm and nylon coated) run in steal sheaths similarly to the synovial sheaths (spiral flat wire coil, inner diameter 0.8mm, outer diameter 1.1mm, provided by Asahi Inc, Japan), working as Bowden Cable.

The actuation units have been designed as modular elements: a DC motor-reduction units (provided by Faulhaber GmbH, Swiss), is assembled in a main frame with a flange allowing the assembling on the arm structure. A rear cap and the capstan, with spiral groove holding the cable in, complete the units.

Two different types of actuation units have been built: (1) the units for MP joint and (2) the unit for under-actuated joints. The unit for Mp joint has two capstans with two antagonistic tendons. The pre-tension is allowed by the relative rotation of the capstans around the shaft, finally compressed (and so stuck together by the friction) by the means of a bolt. The motor is provided with an encoder.

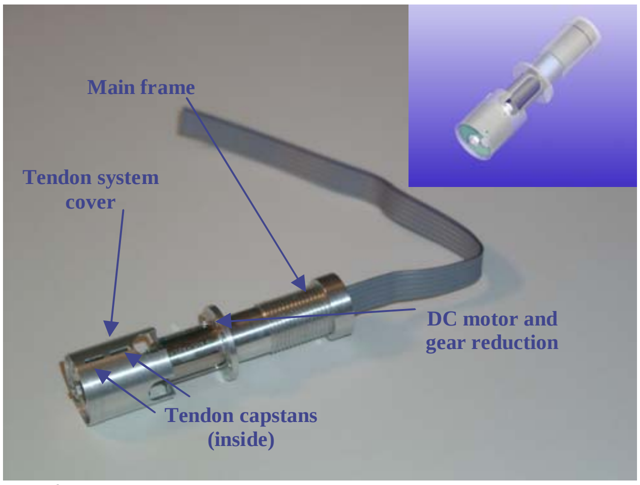

Fig. 10 Actuation Units for MP joint (hybrid actuated finger).

The actuation units for the under-actuated joints has only one capstan. The cable acts as *flexor digitorum profundus* tendon and torsion springs in the joints extend the fingers. On the top of the capstan, 2 permanent magnets (diameter 2mm, provided by MPI s.r.l., Italy) are mounted, generating a magnetic field. A front cap screwed on the main frame bears a Hall effect sensor detecting the joint angle position.

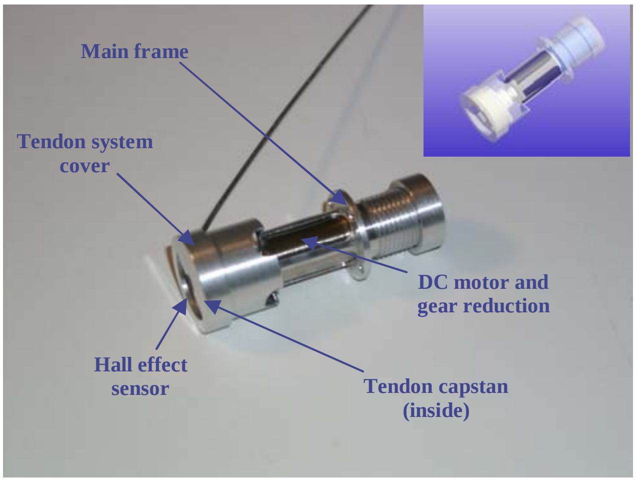

Fig. 11 Actuation Units for under-actuated joint (PIP and DIP in hybrid actuated finger or the 3 joints of fully under-actuated finger).

In order to decrease the number of wires, we preferred to not use encoder on motor shaft, using the absolute sensors, such as Hall effect. This choice also reduces the dimension of the actuation units.

IV. MANUFACTURING

As shown in Fig. 12, the fingers have been manufactured. The phalanges made of aluminium in 5 main parts, have been micro-machined with the Kern Evo (Kern GmbH, Germany)

- a metacarpus (diameter 13mm, length 11mm)
- a proximal phalange (diameter 11mm, length 29.5mm)
- an intermediate phalange (diameter 10mm, length 20.5mm)
- a distal phalange(diameter 10mm, length 15.5mm)
- a tension sensor (diameter 6mm, length 5mm)

The overall length is 53mm. An Electro Discharge Machine by Sodik, Japan, has been used to cut the hollowings for cable routing and the housing for the wires

The phalanges are mounted on ball bearing provided by RBM GmbH, Swiss.

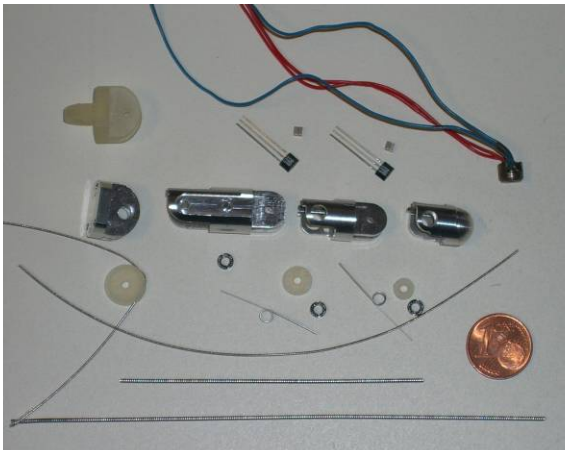

Fig. 12 Parts of the finger units.

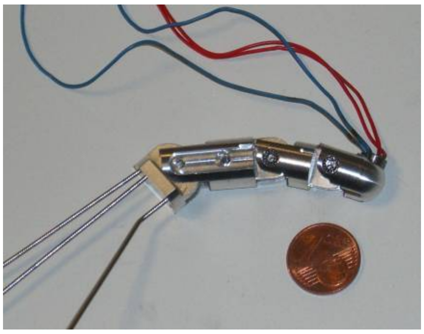

Fig. 13 Assembled finger units.

V. FUTURE WORK AND CONCLUSIONS

In this paper the concept and a preliminary design of a new anthropomorphic dextrous hand for a 2-years-old humanoid are presented. As this robotic platform is aimed to work as a cognition tool, the number of DoFs of the upper part of the body were maximized. Thus the iCub hand has 20 DoFs and 9 motors to accomplish optimal grasping and manipulation. According to these tasks and to the human hand physiology, a mixed design of cable directed driven and under-actuated joints has been implemented, locating the most of the motors in the upper limb. A first finger prototype has been developed and endowed with a proprioceptive sensory system for the joint positioning and the control of the grasping force. The abduction/adduction of the fingers and the hollowing of the palm have been implemented and coupled together driven by a single motor. Future works will be focused on the palm; then the design will be set and the whole hand prototype (fingers, palm and actuation units) will be tested. At the same time the design of the arm and of the shoulder will be carried on.

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