To enable the investigation of relevant cognitive aspects the robot should be able to explore the environment and to grasp and manipulate objects on the floor. It has to be pointed out that manipulation capabilities (obviously supported with sensors) are not considered only as a tool but also the *main link between action and perception*. Anyway as the room for the motors is a huge problem, a trade-off between the accomplishment of high-level manipulation tasks and the dimensional limitations is mandatory. Eventually a mixed implementation of direct-driven joints and under-actuated joints (hybrid actuated finger) has been chosen.

Under-actuated mechanisms allow to decrease the number of active degrees of freedom by means of connected differential mechanisms in the system [1],[2]. When the under-actuation concept is exploited in a gripper device, it shows an adaptive behaviour and its phalanges automatically wrap the object, according to its shape [3],[4]. This also means that the active coordination of the phalanges is not required, hence both the complexity of control and the overall size are reduced. Although an under-actuated gripper accomplish the grasping tasks in a way closer to humans than independent actuation (Montambault and Gosselin, 2001), such device may not perform manipulation: to meet this further requirement direct driven joints and adequate sensing are mandatory.

The implementation of manipulation requires all the MP joints are directly driven and endowed with ad/abduction to perform more complex tasks[5]. In the *iCub* implementation a different design was developed because the need of optimising the number of motors. The functional division by Kapandji demonstrates how that the index and the middle finger help the thumb to achieve the precision grips and to manipulation objects finely. Hence directly driven MP joint with ab/adduction are mandatory in these three fingers.

Even if the ring and the little fingers are indeed useful for stability while manipulating, the main aim of these fingers is the transmission of a large amount of force on the grasped object during the power grasp. Hence a different design solution is more suitable.

Eventually two typologies of finger have been developed, the *totally under-actuated* and the *hybrid actuated* ones.

Concerning the under-actuated joints, a pulling cable runs along the phalanges and around idle pulley and flexes the finger (as in the Hirose's Softfinger) and torsion spring (when cable is released) extend the finger. According to the human hand physiology [6] the PIP joint and the DIP joint are coupled in all the fingers. The little and the ring fingers are designed as fully under-actuated and coupled together as in the *Robonaut*'s [7] hand. This is implemented using a differential mechanism placed in the palm. A motor pulling two tendons in an agonistic/antagonist way is the solution for controlling independently the MP joint in the *hybrid fingers*. This is a compact solution, even if cable pretension is mandatory. The number of DoMs/DoFs (8/14) of the thumb, index and middle fingers are enough for manipulation (if well controlled).

Concerning the under-actuated phalanges and fingers, their kinematics depend on the length of the links/phalanges, on the radii of the fingers pulleys and on the stiffness of the torsion springs. Nevertheless as Hirose demonstrated an object can be gripped by the entire surface of the gripper with uniform force if the pulley diameters are dimensioned as quadrical series. The diameter of the proximal phalanx is 12 mm, hence the bigger pulley (at MP joint of totally underactuated finger) has been designed on this value and the other ones on quadrical series. The torsion stiffness of each spring has been chosen first on calculations and then adjusted by trials on the final prototype. Further details and the length of the links are exposed in the next paragraph.

During the first year of the project [8] a preliminary version of the thumb opposition and hollowing of the palm were presented. The tests conducted on the previous prototypes showed several changes to be implemented. The ultimate goal is providing the iCub with an effective dextrous hand and achieving a link from action to perception through manipulation. Hence the design has been oriented to perform a wider range of grasp typologies and to handle as many objects as possible without changing the overall dimensions. 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. Anyway, a hand with long fingers and short palm performs a more effective grasp. Furthermore a thinner palm allows the grasping of thicker objects. In the final prototype the thumb opposition mechanism was changed basically. Instead of using a worm screw and a gear the motor has been connected directly to the thumb metacarpus. This solution is not as robust as the previous but surely more compact. Furthermore a DC motor without encoder is used; the output shaft rotation is measured by means of a new optical sensor .

One of the main characteristic of the iCub hand is the implementation of the palm hollowing. This movement together with the abduction of the fingers is involved in tripod, spherical and diagonal grasps [9]; thus the iCub, endowed with thumb opposition movement, will be able to handle properly a wider range of objects.

The dedicated motor moves 4 pulleys together and a Bowden cable connects each of them to a DoF. Torsion springs are used in the joints as antagonistic elements; the diameters of each pulleys has been fixed to replicate the original human movement. This DoM together with a pre-shaping control strategy will be helpful to increase the contact area and so the grasp stability. The same sensor solution used in the thumb mechanism has been adopted. This design solution could be improved using one more motor.

Eventually, as shown in Fig. 1 and 2, the number of DoFs for each hand is 20. The number of DoMs is 9.

*Extrinsic actuation:*

- 15 flexions of the phalanges (3 DoMs for MP joints flection of thumb, index and middle finger; 3 DoMs for PIP and DIP coupled in an unique under-actuated joints flection of thumb, index and middle finger; 1 DoM for the totally under-actuated flection of ring and little finger, coupled with a differential mechanism)

*Intrinsic actuation:*

- 1 thumb opposition (1 DoM)
- 3 ad/abduction (for little finger, ring finger and index) + 1 hollowing of the palm (flexing little and ring finger toward the thumb) with 1 only DoM.

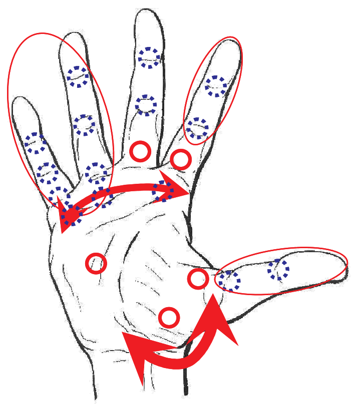

Fig. 1 The selection DoFs/DoMs in the *iCub*

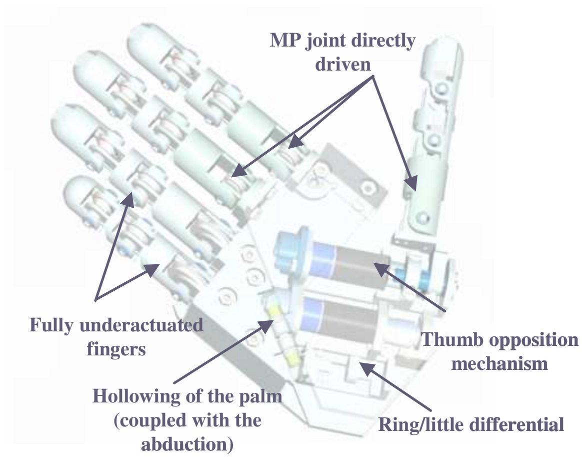


Fig. 2 The CAD drawing of the iCub Hand.

## I. Prototype

At the end of the second year of the RobotCub Project an advanced hand prototype has been produced (see Fig.3). Several test showed the design of fingers is ready; anyway something in the palm could be debugged further. However the range of movements and all the dimensions (exposed in Tab I) will not be modified.

Fig. 3 The *iCub* hand.

| Finger | Length (mm) | Diameter (mm) | Range flection PIP,DIP, MP (°) | Range ab/adduction (°) |
|---|---|---|---|---|
| Index/Middle/Thumb | 57 | 12 | 90 | 30 (only index) |
| Ring | 57 | 12 | 90 | 30 |
| Little | 44 | 11 | 90 | 45 |

Tab II Dimensions and range of movement of the fingers

The fingers are made of 5 main parts and micro-machined with the Kern Evo (Kern GmbH, Germany) ; an Electro Discharge Machine by Sodik, Japan, has been used to cut the hollows for cable routing and the housing for the wires. The cables (diameter 0.7 mm and nylon coated) run in steal sheaths working as Bowden cable (spiral flat wire coil, inner diameter 0.8mm, outer diameter 1.1mm, provided by Asahi Inc, Japan) similar to the synovial sheaths. The phalanges are mounted on ball bearing (model UL 204X) provided by RBM GmbH, Swiss. In fig 4 and fig 5 a *hybrid actuated* and a *fully underactuated* ring finger are shown. The distal and intermediate phalanges are the same in both the typologies; the proximal ones are different in pulleys, cables and sensor system. It has to be noticed the dimensional ratio between consecutives pulleys in underactuated coupled joints (see II). Nevertheless the little finger is *fully underactuated* as the ring, there are basic differences. As already exposed in Tab I, in the little finger all the phalanges are shorter and thinner; hence the radii of the pulleys are different ( anyway still dimensioned as a quadratical series).

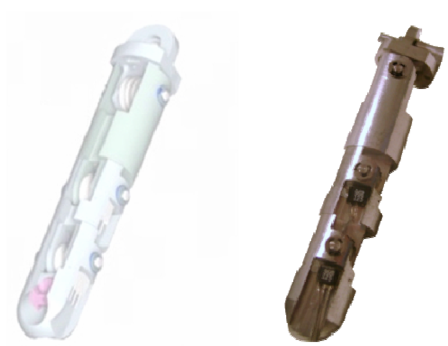

Fig. 4 CAD drawing and prototype of the *hybrid actuated* finger (index).

Fig. 5 CAD drawing and prototype of the *fully underactuated* finger (ring).

Concerning the thumb opposition and the hollowing of the palm (coupled with ab/adduction of the index, ring and little), their actuation is *intrinsic* (see Fig.6) in the palm. The range of movement is 120° for the T.M rotation and 30° for the hollowing of the palm.

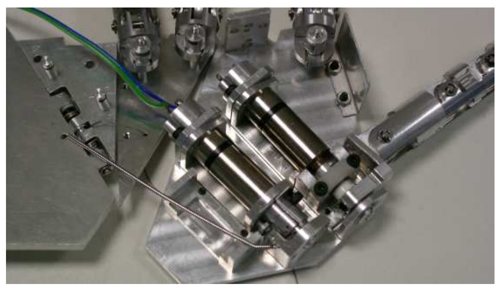

Fig. 6 The *intrinsic* mechanisms

In the implementation of both the DoMs a DC motor without encoder (Faulhaber 1016 006, gearhead 10/1 64:1) is used. Nevertheless the thumb mechanism is direct driven and the hollowing of the palm is cable driven, the angular position is detected using the same kind of sensor. An optical proximity sensor works as angular sensor; a reflecting surface has been designed as a snail and placed in front of it. The snail rotates together with the motor shaft; its geometry imposes a linear relation between the angular position and the distance between the sensor and the reflecting surface.

The sensory system adds useful information for hand operation, but requires complex design, fabrication and dedicated technology, therefore it is necessary to determine the minimum set of sensors that is necessary to control expected hand functionality and performance.

In order to develop a sensorial proprioceptive system for the fingers, Hall effect sensors have been exploited for the joint positioning. In the ring and little finger three sensors have been integrated; 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.

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 .

## II. PROPRIOCEPTIVE SENSORS

The *iCub* hand is equipped with several sensors essentially for control feedback and proprioceptive information. In particular it has:

- 12 hall effect angular sensors. There is one for each flection joint, except for the MP joint of index, thumb and middle.
- 2 optical proximity sensors. One for thumb opposition plane positioning, one for hollowing positioning.
- 5 cable tension sensors based on strain gages, one for each finger.
- 3 Torque sensory systems, based on hall effect linear current sensors. One for each MP joint motor of thumb, index and little.

All the motors dedicated to flection of fingers have their own encoder for position control of the movement of the hand. As a consequence, position information may be obtained by means of different sensors, i.e. motor encoders and hall effect sensors. Currently this redundancy permits to develop different control architectures and control strategies, in order to choose the most performing for the final implementation. The description of the sensors is presented in the following sub-sections.

### *Hall Effect Angular Sensors*

Angular sensors are essential, providing proprioceptive information. This is central in robotic artefacts aiming to imitate human hand functionalities, manipulation capabilities and gesture. Joints angle information is necessary to *pre-shape* the hand either before the *enclose* phase [10] of a grasping task, either for gesture. Moreover, hand joint angles knowledge, while grasping objects, gives some information regarding the external world.

The angular sensors developed are structurally integrated in the finger joints: the MP phalanx acts as a support for two magnets generating a magnetic field parallel to the joint axle; this field is detected by the hall sensor SS495A (Honeywell Inc., Freeport, USA) attached on the PIP phalanx. The same structure is repeated (with scaled dimensions) on the PIP and DIP joints.

Hall sensors were chosen due to their durability (no sliding parts are present such as resistive potentiometers), their small dimensions, easily embeddable in the finger structure, and because they do not require particular hardware conditioning systems for their output signals.

The main disadvantage of hall effect sensors is their sensitivity to an almost everywhere present phenomenon such as the magnetic field. Presence of other magnetic fields, apart from the interested one (e.g. proximity of ferromagnetic objects) could disturb the measurement, and lead the system controller to a mismatching with the environment. Fig 7 and 8 show the output voltage of the sensors.

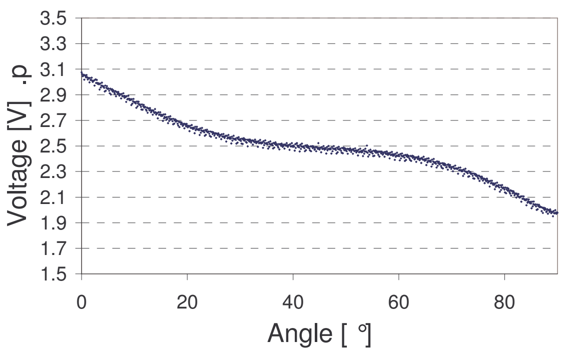


Fig. 7. DIP angular sensor measured characteristic.

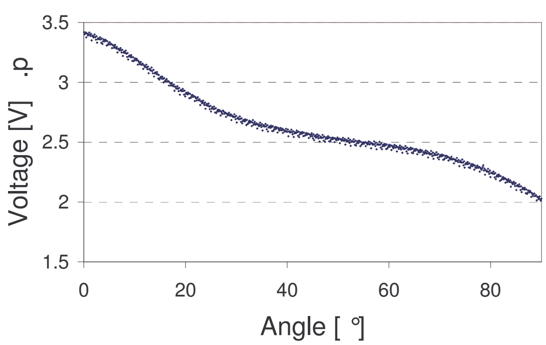


Fig. 8. PIP angular sensor measured characteristic.

### . *Reflective optical angular sensors*

In order to save some room inside the palm, the use of encoders has been avoided. Moreover, because of the magnetic disturbance beside the DC motor, the Hall effect sensors are also been avoided. So a new prototype of angular sensor, based on optical principles has been developed. The sensor is composed of a white painted aluminium snail, mounted on the motor shaft, facing a reflective optical sensor (TCRT1000 Vishay Semiconductors) as shown in Fig. 9.

Fig. 9. The proximity sensor for detecting angular position

The semiconductor device has a compact construction where the emitting-light source and the detector are arranged in the same direction to sense the presence of an object by using the reflective infrared-beam from the object. The operating wavelength is 950 nm. The detector consists of a phototransistor, whose output current linearly depends on the reflected IR-beam, in other words on the proximity of the facing object, i.e. the spiral. This was micro machined in order to transform motor rotation in distance variation between the sensor and the spiral itself. The spiral was also white painted, so as to increase reflection. Sensor characterization is shown in Fig. 10.

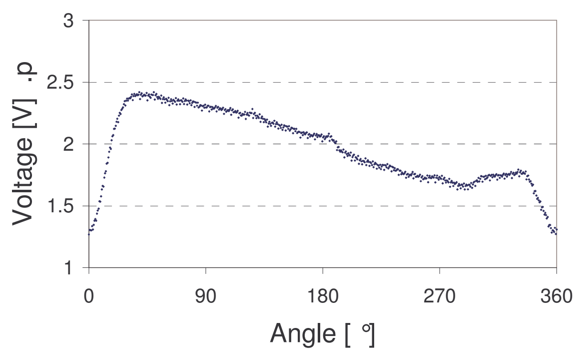


Fig. 10. Proximity sensor characterization.

The developed sensory structure shows good linearity. The small flex present in the middle of the characteristic is due to a spiral micro fabrication imperfection.

## . *Cable Tension Sensors*

This tendon tensiometer is based on strain gauges sensors. The micromechanical structure has been fabricated to obtain a cantilever (Fig. 11) 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 . Glued on the sensor cantilever there are two strain gauges (model ESU-025-1000, Entran Device Inc, Fairfield, NJ, USA): one is the varying resistor; the other is a dummy resistor used for temperature compensation. An exhaustive description of this sensor may be found in [10].

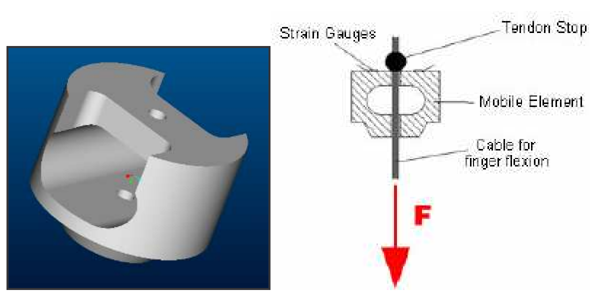


Fig. 11. Cable tension sensor: working principle.

The tendon tensiometers developed are based on strain gauges sensors (model ESU-025-1000, Entran The conditioning circuit is a standard Wheatstone bridge whose signal is amplified by a single supply rail to rail instrumentation amplifier INA155 (Texas Instruments); the amplifier gain is fixed in order to obtain maximum output voltage at the nominal maximum strain (40 N), whereas offset voltage is adjustable by means of a trimmer.

Fig. 12 shows the developed board, to be attached on the palm (and, in future works, to be embedded inside the hand), able to acquire up to five tendons tensiometers signals.

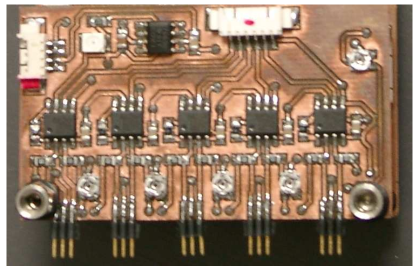

Fig. 12 The developed board.

The tendon tensiometers are located on all the fingertips as shown in Fig.4 and Fig.5; the monitored tensions regard the PIP-DIP joint tendon of thumb, index and middle fingers and the only tendon of the ring and the little. For this reason, output signals refer to the grasping force applied by the last two phalanx of thumb, index and middle, and to the grasping force applied by the whole couple ring-little. No space was available for placing tensiometers for the MP joint tendon of thumb, index and middle finger. In order to measure the force impressed by these proximal phalanges, torque sensory systems for the related motors have been exploited.

### *TORQUE SENSORY SYSTEMS*

Motor torque is proportional to current absorption. The torque sensory system, is based on a 1.5 mΩ hall effect based linear current sensor ACS704 (Allegro Microsystems, Inc.), measuring motor current. The sensor output voltage is then properly translated, amplified and filtered by a 50 Hz third order low pass filter, in order to cut out current noise. The developed system was designed in order to meet microcontrollers voltage acquisition range (from 0 to 5V), with a maximum input current range of 1A.

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