Design of an Anthropomorphic Dexterous Hand for a 2-Years-Old Humanoid: Ongoing Work

Giovanni Stellin[1], Christian Cipriani[1, 2], Franco Zaccone[1], M. C. Carrozza[1], Cecilia Laschi[1] and Paolo Dario[1, 3]

[1] ARTS Lab, Scuola Superiore Sant'Anna, Pisa, Italy
[2] IMT School of Advanced Studies, Lucca, Italy
[3] CRIM Lab, Scuola Superiore Sant'Anna, Pisa, Italy

Abstract. This paper presents the latest 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, a mixed implementation of cable directly driven and under-actuated joints has been designed, developed, tested and debugged. The abduction/adduction of the fingers and the hollowing of the palm have been implemented and coupled together, driven by a single actuator. The latest prototype has been developed; it includes the hand mechanism, the actuators, the control electronics, and a proprioceptive sensory system for position and grasping force control.

1 Introduction

The RobotCub project is a research initiative dedicated to the realization of embodied cognitive systems. It has the twin goals of 1) creating an open humanoid robotic platform for research in embodied cognition – the *iCub* – and 2) advancing our understanding of cognitive systems by exploiting this platform in the study of the development of cognitive capabilities in humanoid robots (www.robotcub.org). This cognitive system (the *iCub*) will be shaped, physically and mentally, like a 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.

Starting from the broad multidisciplinary background of the Consortium in human developmental psychology, physiology, cognitive robotics, mechatronics, and perceptual science, a program of a experimental research has been planned. Concerning the design of the robot, several requirements must be accomplished; particularly (1) the crawling and (2) the manipulation seem to be the most challenging. 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.). Moreover, the *iCub* is quite an autonomous mobile robot; only the power supply and the high level control will not be in the body; thus the wiring, the dimension of the electronic board for the acquisition and processing, the size of the *iCub* itself, robustness and safety are all critical issues. The first complete *iCub* was officially shown in October 2007 (see Fig.1).

Figure 1. Left: The iCub (October ’07). Right: The *hand-forearm* subsystem.

This paper presents the hand subsystem; the implementation of a bio-inspired cable-driven design was chosen. As in the human hand most of the actuators lie in the forearm (as the *flexor digitorum profundus muscles*), the 7 actuation units are *estrinsic* and located in the forearm; thus the motion is transmitted by the means of cables, acting like tendons. Moreover the humanoid has to be sized and shaped as a 2-years-old child; so not only the arm kinematics but also dimensions have to be taken in account to check if there is room enough for the actuation units. In Table I the number of DoFs and of DoMs of the *hand-forearm* subsystem (see Fig.1) are listed.

Table 1. List of DoFs and DoMs of the *hand-forearm* subsystem.

Hand-forearm subsystem	DoFs	DoMs
Forearm (abduction/adduction)	1	1
Wrist (flexion/extension and abduction/adduction)	2	2
Hand	20	9

2 Design Approach

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.

The under-actuation is the exploitation of a number of motors smaller than the number of Degrees of Freedom (DoFs) involved. Under-actuated mechanisms allow to decrease the number of active degrees of freedom by means of connected differential mechanisms in the system (see Hirose, 1985 and Lalibertè and Gosselin, 1998). 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 (Massa et al, 2002). 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. Hence a mixed implementation of direct-driven joints and under-actuated joints (hybrid actuated finger) was chosen.

The implementation of manipulation requires that the metacarpophalangeal (MP) joints are directly driven and endowed with ad/abduction to perform more complex tasks (Mason and Salisbury, 1985). However, the functional division by Kapandji (1982) demonstrates the index and the middle fingers help the thumb in achieving precision grips and in manipulating objects. It has also to be pointed out that one of the main requirements in designing the *iCub* was the optimization of the number of motors. Hence directly driven MP joint with ab/adduction were implemented only in the thumb, index and little. Moreover, even if the ring and the little fingers are indeed useful while manipulating, their main aim is increasing the stability during power grasps. To this purpose a fully underactuated design solution is more suitable.

Eventually two typologies of finger have been developed, the *fully under-actuated* and the *hybrid actuated*. Concerning the under-actuated joints, a pulling cable runs along the phalanges and around idle pulleys and flexes the finger (as in the Hirose’s Softfinger, 1977) and torsion springs (when the cable is released) extend the finger. According to the human hand physiology (Tubiana, 1979) the proximal (PIP) and the distal interphalangeal (DIP) joints 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 (Lovchik et al., 1999) hand. This is implemented using a differential mechanism placed in the forearm. A motor pulling two tendons in an agonistic/antagonist way is the solution for controlling independently the MP joint in *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) (Mason and Salisbury, 1985).

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. 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 section 3.

In a previous work (Stellin et al., 2006) a preliminary version of the thumb opposition and hollowing of the palm mechanisms was presented. The tests conducted on the previous prototype suggested several changes. 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. A hand with long fingers and thin palm works better. Thus the finger length has been increased. The opposition of the thumb is extremely important as it makes the human hand an extraordinary versatile tool, allowing several grasp types, specially the power and the precision grasp. 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.

Another relevant 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 (Cutkosky, 1989); 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 diameter of each pulley 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.

Eventually, as shown in Table.1, the number of DoFs for the hand is 20 with 9 DoMs.

Extrinsic actuation:

- 3 DoMs / 3 DoFs for MP joint flection (thumb, index, middle);
- 3 DoMs / 6 DoFs for coupled PIP-DIP joints (thumb, index, middle);
- 1 DoM / 6 DoFs for coupled *fully underactuated fingers* (little, ring).

Intrinsic actuation:

- 1 DoM / 1 DoF for thumb opposition axis movement;
- 1 DoM / 4 DoFs for coupled ad/abduction (index, ring, little) and palm hollowing.

3 Mechanical Prototype

At the end of the third year of the project an advanced hand prototype has been developed (see Fig. 2) and connected to the forearm (see Fig.1). The range of movements and all the dimensions are exposed in Table 2.

Table 2. Dimensions and range of movement of the fingers.

Finger	Length (mm)	Diameter (mm)	Range flection PIP, DIP, MP (°)	Range ad/abduction (°)
Index/Middle/ Thumb	68	12	95	30 (only index)
Ring	68	12	95	30
Little	57	11	95	45

The fingers were micro-machined with the Kern Evo (Kern GmbH, Germany); an Electro Discharge Machine by Sodik, Japan, was used to cut the hollows for cable routing and the housing for the wires. The cables (diameter 0.4 mm and nylon coated) run in steal sheaths working as Bowden cables (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 bearings (model UL 204X) provided by RBM GmbH, Swiss. The distal and intermediate phalanges are the same in both the *hybrid actuated* and the *fully underactuated* finger typology; the proximal ones are different in pulleys, cables and sensors. Even if the little finger is *fully underactuated* as the ring, its phalanges are shorter and thinner; hence the kynematics are different.

Concerning the thumb opposition and the hollowing of the palm (coupled with ab/adduction of the index, ring and little), their actuation is *intrinsic* (inside the palm). The range of movement is 120° for the thumb opposition axis rotation and 30° for the hollowing of the palm. In the implementation of both these movements a DC motor with encoder (Faulhaber 1016 006, 256:1) is used. Anyway the thumb mechanism is direct driven and the hollowing of the palm is cable driven.

Hall effect sensors for detecting the angular displacement during the flection of the fingers have been embedded in all joints but the MP of the *hybrid fingers*. So for both the ring and little three angular sensors were employed; for the thumb, index and middle, just two.

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 (see section 6).

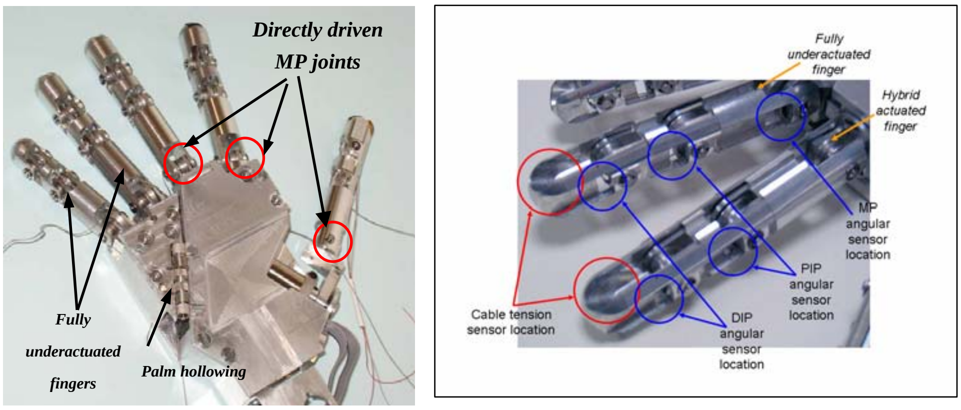

Figure 2. The developed iCub hand and the proprioceptive sensory system location.

4 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: one per flexion joint, except for the MP joint of thumb, index and middle.
- 5 cable tension sensors based on strain gages (one per motor).
- 9 Torque sensory systems (one per motor), based on hall effect linear current sensors: one for each motor.

All motors have their own embedded encoder for position control of the movement of the hand. As a consequence, position information may be obtained by means of multiple 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.

Angular sensors are essential, providing proprioceptive information. This is central in robotic artefacts aiming to imitate human hand functionalities, manipulation capabilities and gesture. Joint angle information is necessary both to *pre-shape* the hand before the *enclose* phase (Otzop and Arbib, 2002) of a grasping task, and for gesture. Moreover, hand joint angles knowledge, while grasping an object, provides information regarding the object itself permitting the automatic recognition through neural networks (as in Asuni et al.,2006). 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 (see Fig. 2).

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 tendon tensiometer is based on strain gauges sensors. The micromechanical structure has been fabricated to obtain a cantilever 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 Cipriani et al. (2006).

The tendon tensiometers are located on all the fingertips as shown in Fig. 2; 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 ring-little couple. There are no tensiometers on the MP tendons 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 employed.

5 Control Architecture

The *iCub* hand is controlled by a hierarchical architecture consisting of nine Low Level Motion Controllers (LLMCs) and one High Level Hand Controller (HLHC). Each motor is directly actuated and controlled by means of a LLMC that achieves position control and monitors motor current consumption. The open architecture distributed-control approach followed in designing this system is widely accepted in motion control. Unlikely from a centralized system in which all control loops are executed on a single processor, in a distributed system, the trajectory generation and logic control are executed on the central controller, whereas the PID motor control loop is executed by intelligent drivers. A distributed approach reduces overall wiring, cost and system complexity. In particular, in this system with a master/slave architecture, the HLHC directly controls each LLMC, achieves force closed-loop control during grasps, regulates overall hand operation and acts as interface with the central *iCub* controller. Hand operation is thus obtained thanks to the shared control between LLMCs and HLHC. Fig. 3 describes the control architecture.

The developed architecture has been designed in order to be functional to grasping and manipulation tasks: as these require continuous monitoring of the applied force (for control), cable tension and torque sensors are directly connected to the HLHC (acting as central unit of the hand) after being properly conditioned. Torque sensors are conditioned on the LLMC boards whereas cable tension sensors are conditioned by a separate board. Moreover, hall effect angular sensors are multiplexed on a further board. Encoders are directly connected only to the LLMCs, even though, information is available to the HLHC by means of a developed communication protocol between the two systems.

Three control bus are employed in this first architecture implementation: the first, named Bus 1, permits the communication between the stand-alone *iCub* hand and the central robot controller. A second Bus (Bus 2) is employed as interface between the HLHC and the nine LLMCs, permitting both to drive hand actuation, and to exchange information about the encoders. Finally Bus 3 is devoted to exchange angular sensory information between the HLHC and the multiplexing board. Even if this architecture reduces control sampling rate, it has been chosen in order to minimize wiring problems. In this first implementation, both Bus 1 and Bus 2 consist of standard two wires serial asynchronous bus (Bus 1 is based on RS232 logic levels, whereas Bus 2 on TTL levels); Bus 3 is instead an SPI able to connect the HLHC to the multiplexing board. Future work plans to merge Bus 2 and Bus 3 in an unique SPI interface, and transform Bus 3 from RS232 to CAN bus.

Currently both the HLHC and the LLMC are based on Microchip microcontrollers (Microchip Technology Inc.). Printed circuit boards have been developed, in order to be mounted one above the other in a modular way.

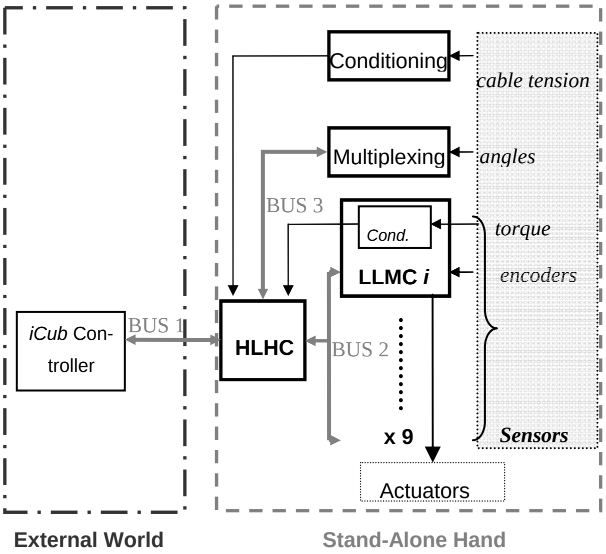

Fig. 3. The *iCub* control architecture scheme.

6 Conclusions

In this paper the design, the prototype and the control architecture 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 *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. The original design has been debugged and endowed with a proprioceptive sensory system for the joint positioning and the control of the grasping force. The implemented abduction/adduction of the fingers and the hollowing increase the grasping and manipulation capabilities. A hierarchical control architecture functional to grasping and manipulation tasks and based on three different control buses has been developed, built on dedicated printed circuit boards and tested. Further work is being focused on the design of an exteroceptive sensory system, on the development of different solutions for controlling a *shoulder-arm-hand* subsystem and on their related functional tests.

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