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Embedded Hardware Architecture Based on Microcontrollers for the Action and Perception of a Transradial Prosthesis

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Abstract—**This paper presents the design of a flexible, embedded control architecture for the action and perception of an anthropomorphic 16 degree of freedom, 4 degree of actuation prosthetic hand for use by transradial amputees. The prosthetic hand is provided with 40 structurally integrated sensors useful both for automatic grasp control and for biofeedback delivery to the user through an appropriate interface (either neural or noninvasive). The paper briefly describes the mechatronic design of the prosthesis, the set of sensors embedded in the hand and finally focuses on the design of the control architecture that allows action and perception for such a sophisticated device.**

I. Introduction

Research in the field of prosthetic hands has been moving in the past years, from the analysis of simple grippers, towards the development of new complex anthropomorphic devices, originated from the fusion of six primary issues such as:

1) Smart mechanisms design (in order to perform prehension patterns, useful in everyday life).
2) Low volume/weight/power actuation units (for energy saving).
3) Sensors development and hand embedding.
4) Intelligent grasping control.
5) High density power sources.
6) User-Prosthesis Interfaces (UPI).

The combination of these topics provides the general scheme of an advanced prosthetic hand system trying to mimic the natural model: on one side there is the subject; on the other side the stand-alone prosthesis responsible for putting in action subject intentions. The interface is placed between man and machine: the UPI is responsible for exchanging signals to decode efferent commands to control the hand *action* (accordingly to subjects intention) and to encode some kind of hand information in order to provide the user of *perception* (either proprioception or exteroception). In current commercial prosthesis the only kind of perception available is in the form of visual feedback. However, conscious grasping decisions that are based solely on visual feedback require the user to continuously monitor the prosthesis, leading to fatigue and handling errors [1]. As a consequence surveys on using such artificial hands reveal that subjects would like to have a sensory feedback in order to be able to grasp independently from visual control [2], [3] and to feel the hand as part of their own body. Based on this point of view, the sensory equipment to be endowed in advanced prosthetic hands, should not be chosen and used just with the aim of closing automatic control loops, but also for delivering biofeedback to the user through the UPI. On this basis several groups working in the prosthetic field are developing advanced artificial hands for use with feedback systems both invasive (neural interfaces) [4], [5] and non-invasive [6]-[9] in order to create an intimate connection between the device and the subject [10].

Achieving the goal – an artificial hand that mimics the human hand – thus requires not only the mechanical design and implementation of an anthropomorphic hand, and the implementation of a sensory system that compares with the human sensory system [11], but also the development of a dedicated hand controller able to put in action user wishes and provide him perception dealing with the UPI. This controller apart from being low power, ensuring proper operation, and avoiding damages, should also be flexible in order to be customized by the prostheticist to meet the user's needs [12].

This paper presents the ongoing work towards the development of a dedicated embedded hardware architecture for the low level control of a novel transradial prosthetic hand in the framework of the SMARTHAND project [13]. The overall scientific objective of the SMARTHAND project is to develop an intelligent artificial hand that looks and feels like a real hand.

The embedded hardware architecture, object of this paper, has been designed in order to allow exchanging information with the subject either employing a non-invasive UPI (classical EMG control, plus tactile display), in the short term, or an invasive neural interface connected to the peripheral nervous system, in the long term. The main idea pursued during the design stage then, has been to develop a simple architecture able to execute primitive actions (basically grasps and gestures) by closing control loops, and

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to digitalize and interconnect all sensor signals from the artificial hand to different kinds of UPI (i.e. control the action and provide perception). For this reason an architecture based on 8-bit microcontrollers has been selected. Simple architecture microcontrollers have proven to be a practical, low-cost solution to the problem of embedded control in upper limb prosthetics [4], [7], [8], [14], [15]. Whereas the use of complex architecture microprocessors or digital signal processors, is more indicated for the bio-signals (EMG, ENG, EEG, etc.) features extraction performed by the UPI [16]. An embedded architecture is by definition strongly customized to the device it is controlling; in prosthetic hand research, architectures are thus strongly related to the development of the whole hand (including sensors, actuators and UPIs). Because of this the state of the art of embedded controllers basically goes along with new developments in prosthetics and is basically limited to the previously cited references.

The following sections briefly introduce the mechanical characteristics of the transradial prosthesis, and the sensory system embedded in its structure, in order to better understand the control architecture design and its rationale, which is the object of this paper. Ongoing results are finally presented.

II. Mechanical Design

In order to design a transradial prosthesis, the hand cannot be conceived by reproducing the biological model where the hand is considered a non-separable part of the arm, deeply integrated with it, but must be considered like an independent and modular device. In such a case, the hand must contain all its functional components (actuators, sensors, electronics, etc.) in order to be fitted at transradial level amputation. The limited energy density of commercially available actuators precluded us to fit more than four motors inside the palm, so, wishing to have a five fingered device, the design is strongly based on differential mechanisms. Underactuated fingers were chosen to obtain compliant grasps [4], [17]; novel non-back-drivable actuation units were designed to reduce power consumption. Finally, the dimensions are based on anthropometric measurements [18]. Figure 1 shows the mechanical design. Sixteen degrees of freedom (three for each finger, plus one for the thumb opposition axis) are operated using nylon coated steel tendons, pulleys and steel Bowden cables by 4 non-back-drivable actuation units based on DC motors located inside the palm. The motors by pulling the tendons which are wrapped along the finger pulleys located in the joints are employed in the flexion of the fingers. Extension is achieved releasing the tendons due to torsion springs placed in the finger joints (as in [4]). Thumb (F_1 in Fig. 1) and index (F_2) are independently actuated (by M_1 and M_2 in Fig. 1), whereas the middle (F_3), the ring (F_4), and the little (F_5) fingers are joined together (actuated by M_3). This is implemented using a differential mechanism placed inside the palm. Another motor (M_4) is used for the thumb opposition axis movement, in order to allow different prehension patterns useful in everyday life (cylindrical, tri-digital, lateral etc. grasps). For a complete description refer to [19].

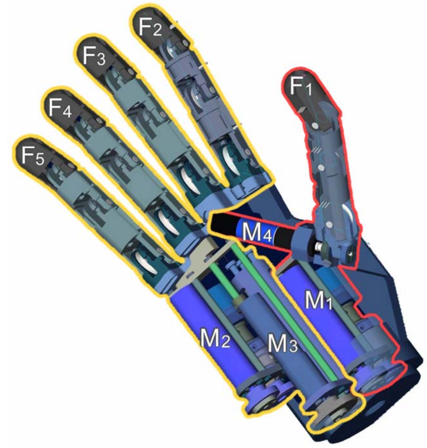

Fig. 1 The transradial prosthesis mechanical design. Motor 1 and 2 (M_1 and M_2) are employed for the flexion/extension of the thumb and index fingers (F_1 and F_2); M_3, due to a differential mechanism actuates the flexion/extension of middle, ring and little fingers ($F_{3\text{-}5}$). M_4 actuates the thumb opposition plane. The dimensions are comparable with the human hand, since they are based on anthropometric information.

III. Embedded Sensory System

The main requirement that led sensor integration and design has been, the necessity of providing a robust system, able to be used in clinical application with good reliability. For this reason sensors requiring complex wiring or signal processing have been avoided. Nevertheless, the sensor set chosen is still redundant and it provides three different types of information such as position, tactile/pressure and force. The hand is equipped with 32 proprioceptive and exteroceptive analogue sensors: 15 joint sensors (integrated in all the joints), 5 cable tension sensors (measuring the grasping force of each finger) [20], 4 current sensors (one for each motor) and 4 optical-based tactile/pressure sensors based on [21] in the intermediate and proximal phalanxes of the thumb and index. All these signals are acquired by the local controller and will be available for feedback delivery to the patient through the UPI. Actuation units are also sensory equipped, since they are provided both with position sensors (either a resistive potentiometer placed on the motor shaft of M_1 and M_2, or an integrated relative encoder on M_3 and M_4) and with digital limit switches (2 for each motor, detecting the mechanical ends).

IV. Control Architecture

A. Overview

The transradial prosthetic hand will be integrated around the flexible electronic control architecture presented in Fig. 2. The architecture has to be flexible enough to support the real time control of four active axes, real time identification of external commands, computation of control loops and delivering of sensory biofeedback. A modular hierarchical architecture (as in [4], [8], [14]) based on an high-level hand controller (HLHC, based on the Microchip microcontroller PIC18F8722) and two low-level motor controllers (LLMCs, based on the PIC18F4431) has been selected. Both LLMCs (LLMC-A and LLMC-B) are associated to two actuators whilst the host HLHC is in charge of the general functionality of the prosthesis. The HLHC, in master configuration, communicates through a fast SPI bus with the slave LLMCs, whereas external world (UPI or a PC) may deal with the HLHC both using a standard RS232 or a fast SPI bus. The functions supported by the HLHC are:

- General status and error management.
- Power management.
- Action sequencer (based on internal finite-state machine and on control strategy).
- Cable tension, tactile and joint sensing.
- Limit switches sensing.
- Providing all sensory information for biofeedback.
- Acting as interface for the external world.

Among the functions supported by the LLMCs are:

- Position (encoder or potentiometer) sensing and control.
- Grasping based on cable tension control.
- Limit switches sensing.
- Torque sensing, over-voltage/current shut-off.

Current is delivered to the DC motors using integrated H-bridges (Q-HBD in the scheme) driven using a pulse-width modulation (PWM) technique.

Two batteries, one for the motors (12V) and one for the controller (6V) supply the hand. Since power budget is a key issue in prosthetics, particular attention has been paid to design a flexible architecture able to manage low power modes; three different voltage regulators are used. The first one, named in the schematic of Fig. 2, *PIC* V_{REG}, supplies the main components of the circuit, i.e. the three microcontrollers; its regulated output, is shut down by an external-world digital line (EN P). A second and a third regulator, named *FINGER* V_{REG} and *ACTUATORS SENSORS* V_{REG}, are employed to supply the sensors embedded in the fingers and the sensory equipped actuators, respectively. These supplies, directly controlled by the HLHC (using EN F and EN A), will be used in switching modality when possible, in order to reduce power consumption. Moreover, the selected microcontrollers can operate in power-managed modes, thus saving energy.

The following sections will describe the design of the main controller components: the two LLMCs and the HLHC, as well as the implementation on a printed circuit board to be embedded in the transradial prosthesis.

B. LLMCs Rationale

Each LLMC is in charge of controlling two actuators; M_1 and M_4 (F_1 motors) are driven by LLMC-A, while M_2 and M_3 ($F_{2\text{-}5}$ motors) are driven by LLMC-B. LLMCs are composed of a microcontroller, an integrated Quad-half bridge driver and some extra circuitry for sensors conditioning. The core of the LLMC subsystem is the PIC18F4431 microcontroller (Microchip Technology Inc.). This is a 44 pin integrated circuit (IC), low power, with high performance PWM and A/D converters, in a small surface mounting package, purposely designed for motion control applications. The microcontroller based on the artificial sensors embedded in the hand generates two independent PWM duty cycle signals in order to correctly drive two motors by means of an integrated quad-half bridge (TLE 4208, Infineon Tecnologies AG) able to continuously deliver up to 0.8 A to both actuators.

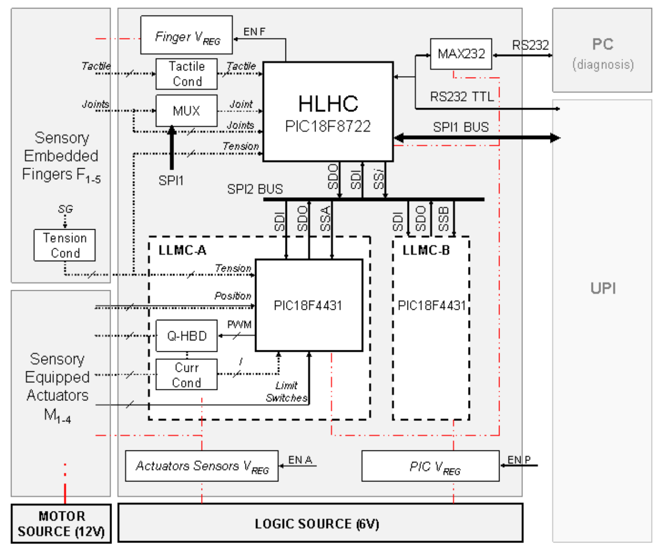

Fig. 2 The four axis control architecture based on microcontrollers. Straight lines are logic lines; dotted lines are analogue lines; dot-dot-dashed lines are power supply lines. The high-level hand controller (HLHC) is directly connected to the external world both with a RS232 and SPI bus. The HLHC deals with the low-level motor controllers via a further SPI bus. The LLMCs are directly connected to Quad-Half Bridge Drivers (Q-HBD) providing current to the DC motors.

With the aim of achieving their main functions (position and force control), the microcontroller resources have been mapped as presented in Table I. For position control, each LLMC reads the encoder from one motor, the potentiometer from the other motor, and finally, their relative limit switches (2 per motor). The relative encoder is continuously acquired by the microcontroller through its quadrature encoder interface (QEI), which is also able to measure motor speed. The potentiometer analogue signal instead, is acquired by the microcontroller by means of the 200Ksps, 10 bit A/D converter. This signal is previously filtered using a passive low-pass RC circuit (pole at 150Hz) and properly amplified by a low-power, rail to rail op-amp (LMV344, Texas Instruments Inc.) in non-inverting configuration.

Cable tension sensors, based on strain gauges (SG in the scheme of Fig. 2) glued on a micro-fabricated cantilever, are placed in series with the tendon, and housed in the fingertips; they result in being fundamental to execute force control [20], and for this reason their conditioned signals are acquired by the microcontroller. The conditioning circuit is a Wheatstone quarter bridge with temperature compensation, whereby output is amplified by an instrumentation amplifier (INA156, Texas Instruments Inc.) with fixed gain; the output offset is tuneable by means of a trimmer. This conditioning circuit is mounted on a small printed circuit board (5.5 x 14 mm^2) housed in the proximal phalanx, in order to reduce wiring and noise contamination. F_4 cable tension sensor couldn't be acquired by LLMC-B, due to the limited number of A/D channels, and for this reason has been left out (giving in fact, higher priority to the other signals). However, since F_3, F_4 and F_5 are joined together by means of a differential mechanism based on compression springs [19], and F_4 is physically between F_3 and F_5, it is reasonable to think that its cable tension sensor will give an output value, similar to the one provided by the ones placed on the closest fingers. Anyway, this sensor is acquired by the HLHC.

TABLE I
LLMCS RESOURCES MAPPING

	Purpose	Resource	Q.ty
LLMC-A	Internal communication bus	SPI slave	1
	Sensing: M_1 potentiometer, F_1 tensiometer, M_1 and M_4 current	AI	4
	Sensing M_4 encoder	QEI	1
	Sensing limit switches	DI	4
	Motor driving	PWM	2
		DO	6
	Over-voltage/current sensing	DI	2
	Interrupt from HLHC	DI	1
	Interrupt to HLHC	DO	1
LLMC-B	Internal communication bus	SPI slave	1
	Sensing: M_2 potentiometer, F_2, F_3 and F_5 tensiometer, M_2 and M_3 current.	AI	6
	Sensing M_3 encoder	QEI	1
	Sensing limit switches	DI	4
	Motor driving	PWM	2
		DO	6
	Over-voltage/current sensing	DI	2
	Interrupt from HLHC	DI	1
	Interrupt to HLHC	DO	1

LLMC-A controls finger F_1 by actuating motors M_1 and M_4; LLMC-B controls fingers $F_{2\text{-}5}$ by actuating motors M_2 and M_3. SPI is for Serial Peripheral Interface, AI is Analogue Input, QEI is Quadrature Encoder Interface, DI is Digital Input, DO is Digital Output.

Motor current, useful for executing torque control loops is delivered to the microcontroller after being measured by a fully integrated, Hall effect-based linear current sensor (ACS713) provided by Allegro Microsystems Inc. Its output signal, that is proportional to the current flowing into the motor, is amplified (with the aim of increasing sensitivity) and filtered by an active first-order low-pass filter made with an op-amp in inverting configuration (LMV344).

The function of the firmware implemented in the PIC18F4431 is twofold: firstly, to provide all the necessary motor control functions which make the hand useful, and secondly, to ensure that the hand does not enter unspecified and thus dangerous states. For this purpose, the microcontroller acts as a double finite-state machine (one for each motor) where the transitions between the different states (Table II) are triggered by HLHC commands coming from the SPI2 bus (Fig. 2).

TABLE II
LLMC FINITE-STATE MACHINE DESCRIPTION

State	Name	Description
S_0	STOP	Stop. Motor is in brake condition.
S_1	EXT	Motors are driven by a PWM duty cycle directly controlled by the HLHC.
S_2	POS	The motor is in position control drove by proportional integral derivative (PID) algorithms.
S_3	TENS	Motors devoted to flex fingers are actuated based on cable tension sensors placed on the actuated fingertips. This state is valid for motors M_1, M_2 and M_3; for M_3, cable tension sensors placed on F_3 and F_5 are used.
S_4	STDBY	The microcontroller is in standby condition (all its peripherals are shut off), and motors are still.

In each state (apart from S_4) if a limit switch is detected as active (i.e. the tendon has reached one mechanical end), the corresponding motor is stopped and only opposite direction of movement is allowed.

C. HLHC and Support Circuitry Rationale

A basic schematic of the HLHC is presented in the upper part of Fig. 2. The core of the HLHC is the Microchip microcontroller PIC18F8722, an 80 pin IC, low-power, with 10 bit, up to 16 channels for A/D conversion (with internal multiplexer). Since 16 channels were not sufficient to digitalize sensory signals not yet acquired by LLMCs, a serial-controlled (SPI bus) analogue multiplexer (ADG738, Analog Devices Inc.) adding 8 channels to the system, has been included (MUX in Fig. 2), in a manner that all signals are finally acquired and digitalized by the HLHC A/D converter. While primitive functions are handled by LLMCs, the HLHC is basically in charge of sequencing those functions to obtain meaningful operations (i.e. grasps and gestures) after an external command, to provide artificial sensory information to the UPI, to manage power modes and handle errors. To this aim its resources have been employed as described in Table III.

TABLE III
HLHC RESOURCES MAPPING

Purpose	Resource	Quantity
Internal communication bus	SPI master	1
External communication bus (fast)	SPI slave	1
External communication bus (slow)	USART	1
Sensing limit switches ($M_{1\text{-}4}$)	DI	8
Sensing $F_{1\text{-}5}$ tensiometers	AI	5
Sensing tactile sensors	AI	4
Sensing joints	AI	6+1 of 8 (MUX)
Interrupt to LLMCs	DO	2
Interrupt from UPI	DI	2-3?

The microcontroller is endowed with one RS232 serial interface and two independent SPI bus (SPI1 and SPI2): SPI2 (where the HLHC is in master configuration) is employed for internal communication with the LLMCs, and

SPI1, shared with the MUX and the UPI, may be used by the HLHC *either in master configuration* for controlling the MUX, to connect and acquire its signals, *or in slave configuration* to provide perception and action dealing with the UPI (i.e. the master). This configuration, which strongly depends on the external UPI typology, may be physically selected by soldering two pads in the circuit.

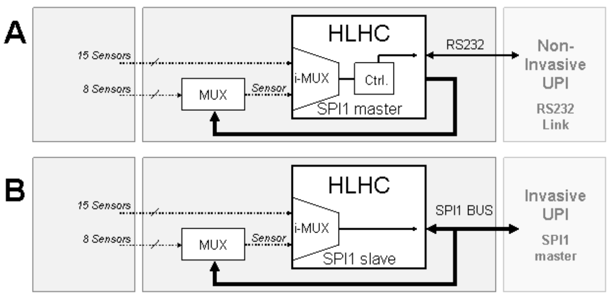

Fig. 3 External bus configurations. A) In the case of a non-invasive UPI a standard RS232 bus is used, and sensors attached to the MUX can purposely be acquired by the HLHC through the SPI1 bus. B) If an invasive interface is used that requires a fast link with the hand, the UPI becomes the master device of the SPI1 bus, and the MUX signals are no longer purposely readable by the HLHC.

Indeed, the circuit has been designed to be flexible enough to be customized to different levels of connection and hybridness (i.e. different interfaces) for different devices and applications [10]. A functional (i.e. portable) non-invasive feedback system, due to its relatively rough nature (e.g. vibrotactile, electrotactile, acoustic, or tactile feedback system), cannot effectively provide the subject in the afferent path, full and detailed sensory feedback; whereas it may successfully provide some general information regarding the whole hand. A neural interface instead, due to its intimate connection with the subject's nervous system, is the natural candidate to provide complete and comprehensive perception [10]. In the first case (non-invasive interface) since all sensor information is actually redundant for feedback, there is no need to (rapidly) transfer it to the UPI, but it can mainly be used for executing automatic control. In this case then, the capability of reading the 8 MUX channels, is given to the HLHC (which becomes the master device in SPI1 communication bus) as shown in Fig. 3A. Moreover, since the bandwidth of the communication link between UPI and HLHC is relatively low, the standard RS232 is used. In other words, when a non-invasive interface is connected to this controller, all sensory signals can directly be linked to the HLHC, i.e. priority is given to the low-level control capabilities of the hand rather on having a large bandwidth link with the external world. In the other case instead (invasive UPI), all kinds of sensory information could be crucial for feedback delivering, and a fast communication link between UPI and HLHC is required. In this instance then, the circuit is soldered in a manner that the UPI becomes the master device of SPI1 bus, being able to rapidly and purposely request all kinds of signals through the MUX and the HLHC (Fig. 3B). The choice of connecting the MUX to the external SPI1 bus, rather on the SPI2 internal bus, has been purposely made in order to reduce delays in serving neural-UPI requests; if it's placed on the external bus, signals can be immediately available to the external world.

Previous exposition can be resumed in a few words: if an intimate interface is used, a large bandwidth bidirectional link between the HLHC and the UPI, could allow the subject to directly interact with the device, feeling it, and deliberately close some high level control loops. Instead, if a non-invasive interface is used, not able to replace the sophisticated link between user and device, more intelligence should be provided to the hand itself to execute automatic loops, by allowing the HLHC to have a complete sensory description of what's going on. This description is illustrated by the following matrix.

$$S_{ii} = \left| \begin{array}{cccccccccc} I_1 & LS_{1A} & LS_{1B} & Pot_1 & MCP_1 & TaP_1 & PIP_1 & TaI_1 & DIP_1 & Te_1 \\ I_2 & LS_{2A} & LS_{2B} & Pot_2 & MCP_2 & TaP_2 & PIP_2 & TaI_2 & DIP_2 & Te_2 \\ I_3 & LS_{3A} & LS_{3B} & Enc_3 & MCP_3 & & PIP_3 & & DIP_3 & Te_3 \\ & & & & MCP_4 & & PIP_4 & & DIP_4 & Te_4 \\ & & & & MCP_5 & & PIP_5 & & DIP_5 & Te_5 \\ I_4 & LS_{4A} & LS_{4B} & Enc_4 & & & & & & \end{array} \right|$$

The first 4 columns refer to actuators sensors; the last 6 columns refer to the embedded sensors in the fingers. Indexes (rows) refer either on motor numbers, or on finger numbers. *I* is for current, *LS* is for limit switch, *Pot* is for absolute potentiometer, *Enc* is for relative encoder, *MCP* is the metacarpophalangeal joint, *PIP* is for proximal interphalangeal joint, *DIP* is for distal interphalangeal joint, *TaP* is for tactile proximal, *TaI* is for tactile intermediate, *Te* is for cable tension.

The HLHC has knowledge of the matrix elements either requesting them to the LLMC through the SPI2 bus (2 motor currents, 2 potentiometers and 2 encoders), or directly by polling its internal multiplexer (5 cable tensions, 6 joints and 4 tactile sensors), or through its digital inputs (8 limit switches). In the case of neural UPI, as mentioned before, the 8 signals connected to the MUX are not purposely readable by the HLHC due to the SPI1 bus configuration (Fig. 3B). These signals have been selected to be 8 joints ($MP_{1\text{-}2}$, $PIP_{1\text{-}2}$ and $DIP_{1\text{-}4}$), due to their low-priority needing in low-level control. In the case of non-invasive UPI instead, these 8 joints are directly requested by the HLHC by means of the SPI1-controlled MUX. The only signal that is not acquired by this architecture resources is the DIP_5 joint; in author's opinion the knowledge of this signal did not justify the addition of another MUX. However, the raw signal can still be used for biofeedback delivery, since it is routed to an external connector.

V. Boards Prototyping

Electronic boards have been embedded both in the hand carpus (Fig. 4A) and in the hand digits (Fig. 4B). The former contains the controller board, whereas all proximal phalanxes embed one cable tensiometer conditioning board as previously mentioned. Both kind of boards are populated with surface mount device components. The controller board which has been shaped based on the carpus dimensions is fabricated using a 4 layer technology, in order to fit in such small space; the cable tension conditioning board instead, measure 5.5mm x 14mm and it is a single sided PCB (Fig. 4B). Flexible PCBs serves as the interconnect between nano-connectors placed at the bases of the fingers (Fig. 4B), and the control board itself (Fig. 4C).

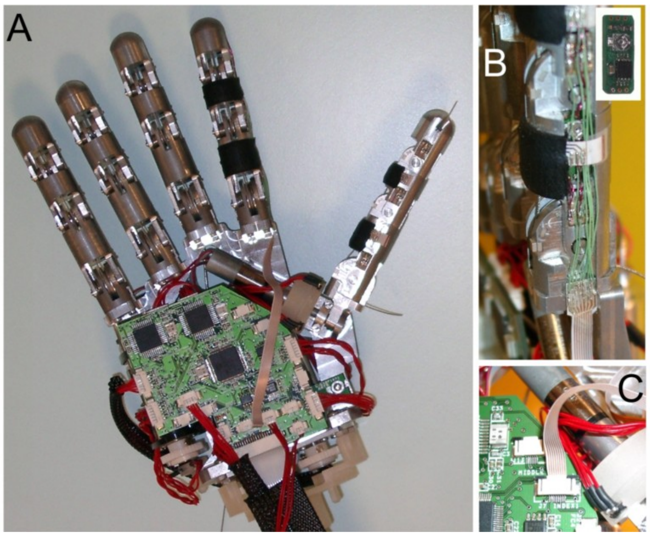

Fig. 4 Developed PCBs. A) Hand controller embedded in the SMARTHAND prototype. B) Cable tension conditioning board embedded in the proximal phalanx. C) Flexible cable interconnection.

VI. Conclusion and Future Work

A control architecture design for a novel transradial prosthetic hand has been presented. This has been designed with the aim to connect it to different levels of hybridness interfaces, both lowly and highly invasive, in order to perform active motor control (based on user's intention) and to provide feedback information to the user itself. The control, is arranged in a hierarchical manner, and it consists of an HLHC and two LLMCs based on 8 bit architecture microcontrollers. It acquires and processes 39 sensory signals from the hand, both analogue and digital, and it controls the four motors embedded in the hand in order to perform gestures and grasps useful in everyday life. Based on our previous experience [4], [9] and on the modular design, the proposed embedded architecture, even if based on simple 8 bits microcontrollers, is expected to be efficient enough to allow a fast bidirectional link between the motors/sensors and the external UPI. Moreover, an accurate separation of power supplies will allow a long life of the batteries. The main advancement of the present system compared to our previous controllers, is basically related to its customization to the new hand characteristics, both in terms of hardware and integration in the mechanism. This mechatronic design will allow to use the hand in clinical trials with transradial amputees in the near future.

Acknowledgment

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