

Objectives, criteria and methods for the design of the SmartHand transradial prosthesis

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SUMMARY

This paper presents the requirements, design criteria and methodology used to develop the design of a new self-contained prosthetic hand to be used by transradial amputees. The design is based on users' needs, on authors background and knowledge of the state of the art, and feasible fabrication technology with the aim of replicating as much as possible the functionality of the human hand. The paper focuses on the design approach and methodology which is divided into three steps: (i) the mechanical actuation units, design and actuation distribution; (ii) the mechatronic development and finally (iii) the controller architecture design. The design is presented here and compared with significant commercial devices and research prototypes.

KEYWORDS: Biorobotics; Prosthetics; Robotic hand; Mechatronics.

1. Introduction

Two of the challenges in upper limb prosthetics are: the use of neural control signals for extracting user intention, and the mechatronic implementation to provide good functionality.¹ The most natural/intuitive control is that driven by neural signals tapped from the human central nervous system (CNS) or peripheral nervous system (PNS). In particular with the use of a neural interface intimately connected to the PNS or CNS, able to replace the sophisticated bidirectional communication link between the brain and the hand actuators and sensors, an advanced mechatronic limb might be able to put in action user intent, and provide the user with perception of the hand itself by delivering sensory proprioceptive and exteroceptive information.² Currently, bidirectional interfaces with the above properties will allow only a limited number of channels for exchanging efferent and afferent signals between the prosthesis and the nervous system of a human being,² and they are likely to remain the bottleneck for the foreseeable future. So the communication between the biological and the artificial systems is the weakest part of the system.³

The mechatronic limb features are tightly connected to the first challenge – the control interface development – since this will outline the requirements of the prosthesis. An interface with a large bandwidth (i.e. the number of selective, independent efferent and afferent channels) will push the roboticists to find new solutions to overcome actual technological limitations, and to design more and more

dexterous and sensorized artificial hands to fulfil the futuristic goal of developing advanced prostheses.

One of the most challenging tasks in this field is certainly that of building a dexterous *intrinsic* prosthetic hand, i.e. a hand that contains all its functional components (actuators, sensors, electronics, etc.), that can be used for patients after a distal transradial amputation.

In the past decades (due to lack of suitable high power density actuators) the aim was to develop prosthetic hands capable of a determined number of prehensile patterns, therefore prostheses developers have basically focused on the design of adaptable underactuated mechanisms, i.e. systems which have fewer inputs (degrees of actuation, DoAs) than outputs (degrees of freedom, DoFs). Underactuation can be easily achieved by linking the motion of the joints of a finger or linking the motions of one finger to another. If the design of the hand only allows fixed coupling among joint or fingers the resulting mechanism has effectively the same number of DoFs as the number of actuators,⁵ the geometry of the enveloping surface of the hand is fixed and thus no adaptation to object geometry is possible. Outstanding results have been achieved as proven by the number of concepts developed and endowed in intrinsic prosthetic hands such as: the Southampton,⁶ the MARCUS,⁷ the RTR II,⁸ the MANUS⁹ and the Karlsruhe¹⁰ hands. From a commercial standpoint, where Otto Bock¹¹ is the leading company, only one new company has entered the market in the past 30 years with a new design: the i-Limb hand.¹² Nevertheless, all these hands have been designed with the aim of being controlled by electromyographic (EMG) surface electrodes or other intelligent control schemes,¹³ so that in most of them the sensorization is limited and mainly employed for the low-level control of the grasp. Even if some attempts to connect these hands to non-invasive feedback systems have been done,^{9,14,15} most of these prototypes (with the exception of the Southampton-REMEDI hand, which contains sufficient active DoFs for different prehensile patterns, and an extended sensory system) would not be suitable if neurally interfaced with a large bandwidth link due to either their limited (or inexistent) sensorization or limited dexterity. Table I presents and compare commercial prostheses and research (intrinsic) prototypes highlighting (grey cells) those features that would be inadequate for such purpose.

2. Objectives

The overall scientific objective of the EU funded SMARTHAND project¹⁶ is to develop an intelligent

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Table I. Comparison between commercial prostheses, research (intrinsic) prototypes and the SmartHand.

	Southampton REMEDI ⁶	MARCUS ⁷	RTR II ⁸	MANUS ⁹	Karlsruhe ¹⁰	Otto Bock SensorHand ¹¹	Touch Bionics i-Limb ¹²	SmartHand
DoA ^a	6	2	2	3	8	1 (or 2 ^c)	5	4
DoF	6	4	9	4	8	1 (or 2 ^c)	6	16
Weight	400 g	N.A.	350 g	1.2 Kg	891 g ^b	500 g (700 g ^c)	518 g	520 g
Finger sensors	J, To	J	J, To	J	–	J (1), To (1)	To (5)	J (19), F (5), Ta (4), To (4)
Fingertip sensors	Te, S, F	F, S	F	F	–	3AF (1)	–	–
Palm Sensors	F	F	–	–	–	–	–	Ta ^f
Power grip	Yes	Yes	Yes	Yes	Yes	Yes ^d	Yes	Yes
Precision grip	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Lateral grip	Yes	No	Yes	Yes	Yes	No	Yes ^e	Yes
Index pointing	Yes	No	No	No	Yes	No	Yes	Yes
Counting	Yes	No	No	No	Yes	No	Yes	Yes

J is for Joint, F is for force, To is for torque, Te is for temperature, S is for slippage, 3AF is for tri-axial force, Ta is for tactile sensors. Number in brackets refer to the number when known. Additional notes: ^aDegrees of actuation (DoA), i.e. the number of actuators. ^bWeight includes batteries, socket and glove. ^cAdding an Otto Bock wrist rotator. ^dLow-number contact points grasp (therefore low stability grip). ^eThumb manually moved (with healthy controlateral hand). ^fTactile sensors on the palm under development.

transradial prosthesis with all the basic features displayed by the human hand: i.e. aesthetically, controlled and felt like a real hand. The first goal of the project, to be addressed in the short term, is to develop a sophisticated system using non-invasive control mechanisms and sensory substitution systems: i.e. an EMG pattern recognition classifier and a tactile display providing biofeedback from artificial sensors embedded in the hand. The second goal, to be achieved in the long term, is to connect the hand directly to the PNS by means of neural electrodes^{17,18} in order to investigate the effectiveness of more natural and intuitive control and feedback strategies.

From the mechatronic standpoint, the objective represents a real challenging task for engineers: to design and develop a transradial prosthesis both capable of allowing the amputee to complete a list of functionalities useful for activities of daily living (ADLs), as well as to embed in such a hand an extended sensory system not just limited to implement automatic control, but also able to provide some kind of biofeedback to the user by means of different interfaces. Moreover, since this hand should be comparable in terms of weight, volume and cosmetics to the natural counterpart, it must be intrinsic. A prosthesis conceived in this way is meant to be used in real clinical trials by amputees, and therefore it should also be robust and reliable. This paper presents the methods, the technological approach and the engineering trade-offs found, that led to the design of such a sophisticated hand.

3. Design Criteria

In order to succeed in such a difficult task, a strong methodological approach has to be pursued. Firstly, based on the objectives, the desired requirements of the final device must be identified; secondly, such requirements should be screened based on their priority and on what is actually feasible with available technology (and budget).

Inputs for such a procedure (the biomechatronic design procedure) have their roots in different fields like biology

and engineering; feasibility and social aspects are other essential parts of a prosthesis design. First of all, since this hand is expected to be used in the future as a prosthesis, it should take inspiration from its natural biological model in terms of *anatomy*, *sensorization* and *performance*.² As an engineering device it should consume *low power* in order to guarantee a full-day autonomy without recharge, should be *modular*, i.e. it should contain all its functional components, *flexible* in terms of control, and of course *robust*, to allow real clinical experimentation. From the social point of view, i.e. the final users' standpoint, other constraints enter into the design process: the hand should satisfy amputee's wishes in terms of *cosmetics* and *functionalities*, and of course should allow *grips useful in ADLs*. Finally, this list of candidate requirements should be compared with what is actually feasible with today's *technology* (off the shelf components), with available construction *facilities*, knowledge of the *state of the art* and, of course, the authors' *background*. Moreover, a *low price* is a hugely important consideration; the numbers who need or would use such a device are sufficiently small that the economies of scale are not generally in their favour, resulting in a limited input of resources for industrial innovation.¹⁹

By looking at all constraints that enter into the design process it soon becomes clear that trade-offs based on a priority list, must be found in order to achieve the objectives.

The limitations on the application of technology to prosthetics is very much based on the overwhelming need for the devices to be *practical*. Users need the device to work all of the time; no matter how elegant and advanced a solution might be, if it fails to meet this expectation it will be a greater hindrance than the absence of the device in the first place.¹⁹ Based on this assumption, the highest priority has been given on the social aspects of the device, i.e. what amputees wish to do with their prosthetic hand. According to interview results among the amputee community,²⁰ and to the approximate percentage of utilization of the main grips in ADLs, a set of basic functionalities (grasps and gestures)

that lack in traditional commercial prostheses^{11,31} and should be considered for new prosthetic hands to provide, has been traced as follows:

- (1) Power grasps (used in 35% ADLs);
- (2) Precision grasps (30% ADLs);
- (3) Lateral grasps (20% ADLs);
- (4) Extension grasps (10% ADLs);
- (5) Index pointing (useful for typing on a keyboard, ATM, press lift buttons, etc.);
- (6) Basic gestures (counting).

This list must then be evaluated together with what is actually feasible in terms of available commercial actuators (to reduce costs), as well as with accessible machining facilities (again, at a reasonable price), and for practical reasons, starting from already assessed solutions, be able to satisfy the previous requirements (i.e. user's wishes). Regarding the last point, the transradial prosthesis digits have been designed based on the underactuated mechanism of the soft finger proposed by Hirose,²² actuated by tendon transmission as in the CyberHand² and RTR II⁸ prototypes. The reasons for the employment of such a mechanism are: the need for just a single actuator to allow simultaneous flexion (or extension, thanks to torsional springs placed in the joints) of three phalanxes (thus reducing weight and volume of the prosthesis), the simplicity of the control to be implemented²³ and the compliance of the mechanism (related to the capability of automatically wrap-around objects, allowing multi-contact and therefore stable grasps).²⁴ Moreover, a finger designed in such a way, allows for the integration of different kinds of sensors in the mechanical structure, like hall effect based joint sensors as in ref. [2], and cable tension sensors in the fingertips as in ref. [25]. Finally, this mechanism has proven to be a robust solution, and has been employed in robotic hands and continuously improved by the authors for the past seven years. The main drawback, considering the list of grips useful for ADLs, is that it cannot allow extension grasps (as reported in ref. [23]); generally speaking, to perform an extension grasp, i.e. that used when gripping a book (where only the metacarpophalangeal, MCP, joints of long fingers are flexed, and the thumb is in opposition), the prosthesis requires to bend the MCP joints independently from the more distal ones. This is possible with two different active joints (as in the human hand), or, employing the Hirose's soft finger mechanism, by dimensioning pulley radius and the stiffness of the torsional springs specifically for this prehensile pattern; in this case, however, the finger would no longer be optimized for power and precision grasps. Since the latter represent in total the 65% of grips used in ADLs, it becomes clear that designing a finger for extension grasps cannot be given priority.

Starting from user's wishes and from our experience (the underactuated finger), and using commercial actuators, the idea has been that of designing a prosthetic hand that mostly replicates the biological model, in both cosmetics: i.e. volume/size and anthropomorphism (DoFs and DoAs), and performance: i.e. speed, torque, embedded mechanoreceptors and fingers functional division. With the latter is meant how fingers are used in a general grasp: Kapandji²⁶ divides the human hand into three components:

- (1) The thumb, which by itself fulfils most of the functions of the hand because of its movement of opposition;
- (2) The index and the middle finger, which help the thumb to achieve precision grips;
- (3) The ring and the little finger, which along with the rest of the hand, are essential for solidly grasping tool-handles on the ulnar side of the hand and thus are vital in strengthening the grip.

The knowledge of this biological functional division, could be of fundamental importance for underactuated prostheses designers, since it gives indications for finding trade-offs. Since decreasing the number of DoAs (and increasing the level of underactuation) means that the final user will have to renounce some tasks useful in everyday life, it is important to know how to reduce dexterity while still maintaining functionalities.

4. Methods

Based on previously described criteria, the biomechatronic design procedure has consisted of 3 steps: actuation units design and distribution of actuation (joining tendons), sensors embedding in the mechatronic design, control architecture selection and design. This sequence is mandatory; the actuation units design is the most critical since it affects overall volume, weight and hand performances. Once the actuation units have been designed, and the distribution of actuation has been selected, it is possible to correctly choose the number of sensors and therefore design the mechatronic parts (parts that include mechanisms, sensors, and necessary electronics). From an engineering point of view, the sensor placement should be primarily based on control issues (the system should be observable and controllable), and so it must follow the actuation distribution. Moreover from a biological standpoint, density of mechanoreceptors is roughly proportional to the contact probability;²⁷ again, this is related to the independently actuated fingers. Finally, an appropriate control architecture, able to drive motors and acquire all sensory signals can be designed; this is the last part to be developed since it is the least critical in terms of weight and volume.

4.1. Actuation units design and actuation distribution

The distribution of actuation and the actuation units design has been based on the upper part of the flow chart presented in Fig. 1; in such graph, M is the number of actively actuated fingers (i.e. the number of motors, or DoAs) and D the number of fingers linked to an active one; V^* is the volume of the 50 percentile male hand based on ref. [28]. The overall requirement has been that of designing fingers capable of torque-speed performances, not that far from the biological model. A good compromise has been found in fingers able to completely close (or open) in about one second, actuated by tendons providing a cable tension up to about 80 N. Such value combined with the adaptability of the underactuated fingers and differential mechanism (also with an appropriate cosmetic covering) permits, e.g. to stably handle bottles weighting up to 4 kg in a power grasp prehensile form. Speed is both important for the social aspect (cosmetics) and

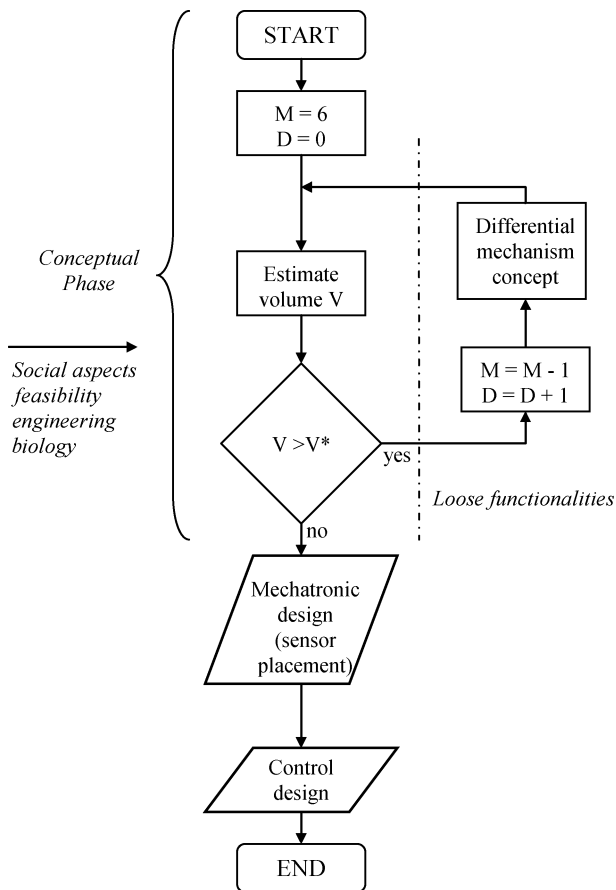


Fig. 1. Bio-mechatronic hand prosthesis design flow chart. M is the number of motors (DoAs) and D the number of fingers joined with a differential mechanism. V^* is the volume of the human hand. In the initial phase, actuation has to be distributed among digits; to this aim several differential mechanism have to be identified until all the components fit in the volume V^* . After this conceptual phase, the mechatronic design and assembling (combined with the sensor placement), and the control architecture design follows.

for functionality (frequency of operation): a hand moving at a natural speed, as long as the control is fast enough to match it, will be more accepted by the amputee community.²⁰ Transmitted torque is very important with the aim of grasping objects tightly. Finally, it is important to point out that in prosthetic hands, actuation units should be non-back-drivable in order to save energy when the motor is braked.² For this reason an innovative high efficiency, miniaturized clutching mechanism based on an eccentric non-eccentric cam-coupling has been developed (scheme in Fig. 2); its volume is about 5900 mm³ (similar to a plastic bottle cap) and weights 35 g. This mechanism allows the transmission of the rotational motion, when it is originated by the motor shaft, blocking instead motions originated from the output shaft (connected to a capstan driving the finger tendon). The clutch is composed of a fixed ring (3 in Fig. 2), an input shaft with two teeth (1), an eccentric cam (5) fixed to the output shaft (2) and finally four spheres (4) that under the action of two elastic elements, tend to wedge between the fixed ring and the cam. The principle of operation is the following: when the input shaft (i.e. the motor shaft) is rotated, the teeth (1) unblock the spheres (4) and the two appendixes of the teeth

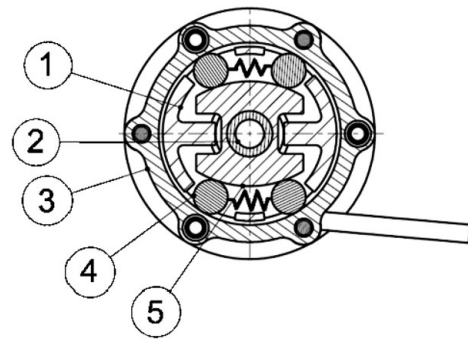


Fig. 2. Clutch mechanism core section.

drag the cam (2), therefore the output shaft. The transmission from the output shaft to the motor shaft is not allowed, since the spheres (4) block the cam (2) rotation before teeth are contacted (and so dragged). High mechanical efficiency is guaranteed by the low rolling friction factor between spheres and the fixed ring; moreover with an appropriate lubrication usury is further reduced and efficiency increased.

The loop in Fig. 1 started as in the CyberHand² (equal to the Southampton-REMEDI⁶) configuration, i.e. $M = 6$ and $D = 0$; in that case all motors could not be fitted in the palm of the hand. This time, employing the newly developed non-back-drivable mechanism, commercial actuators, our underactuated finger and lab machining facilities, and still guaranteeing desired performance requirements the loop has ended with $M = 4$ and $D = 2$, i.e. an intrinsic hand having 4 motors, with two fingers not directly actuated.

Based on Kapandji's functional division (and on many research prototypes^{2,6,8,10,30}) the thumb has been provided with two motors: one for the flexo/extension, the other for the abduction/adduction. The same functional division would lead to couple index-middle and ring-little; even though, this configuration would impede to independently point with the index finger (for typing, pressing buttons, etc.), and for this reason has not been selected. Our selection instead has been based on the statistical investigation of natural hand movement.²⁹ In this the thumb was found to be the most independent of the digits and the index finger was the most independent of the fingers; for this reason we chose to join the middle, the ring and the little fingers and to independently actuate the index (as in one version of the Southampton hand).³⁰

A differential mechanism that allows the simultaneous flexion/extension of middle, ring and little fingers, as well as their adaptation on the object, allowing a multiple contact grasp, has been then designed (cf. scheme in Fig. 3) improving an already assessed solution proposed by Massa *et al.*, in the RTR II hand.⁸ The working principle is simple: three tendons (F_3 , F_4 , F_5 in Fig. 3) are connected to a linear slider by means of three compression springs; the input torque generated by the motor moves the slider along the screw by means of a screw/lead screw pair and pulls (or releases) the tendons. When the first finger (e.g. middle finger) comes in contact with the object, the relative spring starts to compress; the slider is free to continue its motion and the second (e.g. ring finger) can flex reaching the object. The

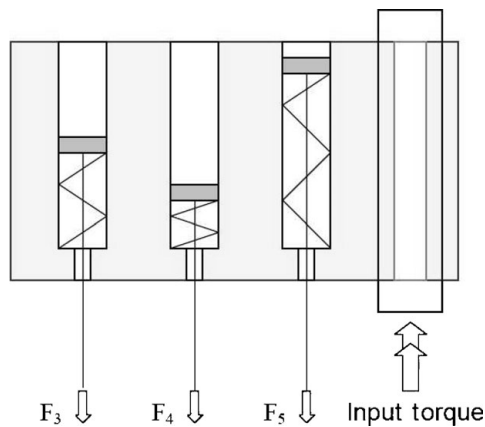


Fig. 3. Adaptive grasp mechanism scheme.

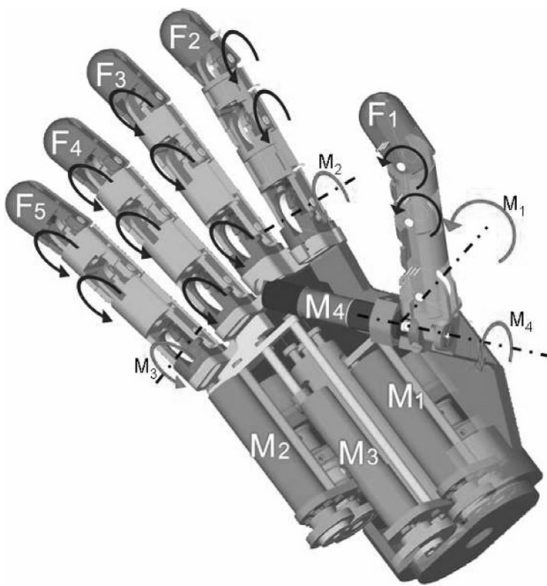


Fig. 4. The intrinsic transradial prosthesis design. Five fingers F_{1-5} are actuated by means of four DC brushed motors M_{1-4} all located inside the palm structure. Each *light grey arrow* corresponds to the proximal joint acted on by an individual actuator. *Dark grey arrows* represent rotations carried out by actuators also acting on more joints. The distribution of tendons allows for most of the grips useful in ADLs and for basic gesture (pointing and counting, see Fig. 7).

same happens with the last finger (e.g. little finger). Since the screw/lead screw is a non-back-drivable pair, when a desired position has been reached, the power can be switched off, thereby saving energy.

While developing the MANUS-HAND, Pons *et al.* have considered brushless motors to be the most indicated in hand prostheses development.⁹ Even though, his treatment on types of actuators in artificial hands, did not consider price and commercial availability. In our power range of interest, commercial brushed DC motors (combined with precision integrated reduction gears) come with a wider offer, and their stall torque is even higher than that of brushless ones. These are the reasons why DC brushed motors have been chosen. Finally, all the designed mechanical components have been assembled in an anthropometric size²⁸ of the 50 percentile male hand as presented in Fig. 4.

4.2. Sensors distribution

After the mechanical concept had been developed, the sensory system distribution followed (cf. Fig. 1). This is a crucial part in prosthetics willing to restore the sensory function of the hand.⁴ In commercial myoelectric prosthesis, basically Otto Bock,¹¹ Motion Control³¹ and since 2007, Touch Bionics ones,¹² no biofeedback is purposely delivered to the amputee, so that the prosthesis is felt as an external device, and worn as a pair of shoes would be worn. There is the need to reduce the cognitive effort required for interacting with the prosthesis, in order to increase its acceptance. Even if myoelectric prosthesis users often employ the sound and vibration of the motor(s) to control their artificial limb, they would like to get enhanced feedback from it.^{20,32} It must be noted though, that there is no reported evidence that this is actually useful for grasping on a day to day basis (using past prostheses), but to fulfil users wishes researchers are investigating the effectiveness of innovative methods. Recent studies have preliminarily shown the possibility to deliver force and position afferent information directly to the PNS, by means of an implanted neural interface,³³ or touch, pressure and temperature even employing a non-invasive sensory feedback system to redirected parts of the body after targeted reinnervation procedure.³⁴ More recently, it has been shown how amputees can be made to experience a rubber hand as part of their own body³⁵ by simply tricking their brain using the so-called *rubber hand illusion*³⁷ (and the same could happen with a robot-like hand);³⁶ a simple method based on a prosthesis equipped with tactile sensors for transferring sensations from the stump to the prosthesis has been then outlined.³⁵

The sensory equipment to be endowed in advanced prosthetic hands then, should not be chosen and used just for closing control loops (position control, force control etc.) as in automatic systems, but also with the aim of delivering afferent information to the user through an adequate user-prosthesis interface (UPI).⁴ Based on the mentioned researches three different types of information have been considered for integration: joint position, tactile/pressure and force. As for the mechanical design, they have been selected based on: cheapness, low power, robustness, availability and simplicity to use; sensors requiring complex wiring or signal processing have been avoided. Sensors have been placed similarly to the density of natural model:²⁷ higher on the independently actuated thumb and index fingers. The hand has been designed with 32 proprioceptive and exteroceptive analogue sensors: 15 joint sensors (integrated in all the joints),² 5 cable tension sensors (measuring the grasping force of each finger),² 4 current sensors (one for each motor) and 4 optical-based tactile/pressure sensors in the intermediate and proximal phalanxes of the thumb and index (based on ref. [38]). Actuation units are also sensory-equipped, since they have been endowed 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). All these signals (for details see Table II) will be employed in the local controller and will be available for feedback delivery to the patient through the UPI.

Table II. SmartHand sensory system features.

Sensor	Working principle	Dynamic range	Resolution	Linearity	Frequency bandwidth	Power consumption
Joint ²	Hall effect	0–90 deg	0.4 deg	± 5%	10 KHz ^a	35 mW
Cable tension ²	Strain gauge	0–180 N	0.18 N	± 2%	50 Hz ^b	30 mW
Tactile ³⁸	Optoelectronics and silicone	0–100 N	0.10 N	± 5%	< 50 Hz ^b	15 mW
Motor current	Hall effect	0–1 A	1 mA	± 4.7% ^c	50 KHz ^c	40 mW ^c
Motor potentiometer	Resistive potentiometer	200 deg	0.2 deg	± 2%	50 Hz ^b	2 mW
Opposition encoder	Digital quadrature encoder	90 deg	10 lpr ^d	± 0.005%	7.2 KHz ^d	25 mW ^d
MRL encoder	Digital quadrature encoder	200 deg	100 lpr ^e	± 0.03%	40 KHz ^e	30 mW ^e
Limit switches ²	Hall effect (digital)	N/a	N/a	N/a	N/a	25 mW ^f

MRL stands for middle-ring-little. Additional notes: ^aDerived from the SS495 (Honeywell Inc., IL) hall effect sensor data-sheet. ^bBandwidth limited by an active filter on the SmartHand control board. ^cDerived from the ACS706 (Allegro microsystems Inc., MA) hall effect based linear current sensor data sheet. ^dDerived from the 30B19 (Faulhaber Minimotor SA, CH) magnetic encoder data sheet; lpr stands for: lines per revolution. ^eDerived from the IE2–100 (Faulhaber Minimotor SA, CH) magnetic encoder data sheet. ^fDerived from the 3213 (Allegro microsystems Inc., MA) micropower hall effect switch data sheet.

4.3. Control architecture

Achieving the goal – an artificial hand that mimics the human hand – 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,³⁹ but also the development of a dedicated low-level hand controller able to deal in real-time with the UPI. This controller apart from being low power and ensuring proper operation, should also be flexible in order to be customized by the prosthetist to meet the user's needs.⁴⁰

The embedded hardware architecture has been designed in order to allow exchanging information with the amputee employing different levels of connection and hybridness interfaces (as defined in ref. [41]), ranging from lowly (e.g. superficial) to highly invasive (e.g. surgically implanted) ones, responsible for performing active motor control (based on user's intention) and for delivering sensory feedback to the user itself. Therefore the main idea pursued during the design stage then, has been to develop a simple architecture able to execute primitive actions by closing low-level control loops (force, position, etc.), and to digitalize and interconnect all sensor signals from the artificial hand to the external world. For this purpose a modular hierarchical architecture (as in refs. [2, 7, 42]) based on 8-bit microcontrollers has been selected⁴⁴; 8 bit micros have shown to be a practical, low-cost solution to the problem of embedded control,^{2,7,10,42} whereas the employing of complex architecture microprocessors or digital signal processors, could be more suitable in the UPI for extracting the bio-signals (EMG, ENG, EEG, etc.) features.⁴³ Power budget is a key issue; particular attention has been paid to design a flexible architecture able to manage low power modes and different voltage regulators are used to selectively switch on/off different parts of the controller.

5. Results

The previously presented criteria and methods have led to the design of a five-finger anthropomorphic prosthetic hand with 40 embedded sensors both in the mechanical structure and in the electronic control board (cf. Fig. 5). The size of the SmartHand is slightly bigger than the 50 percentile male hand

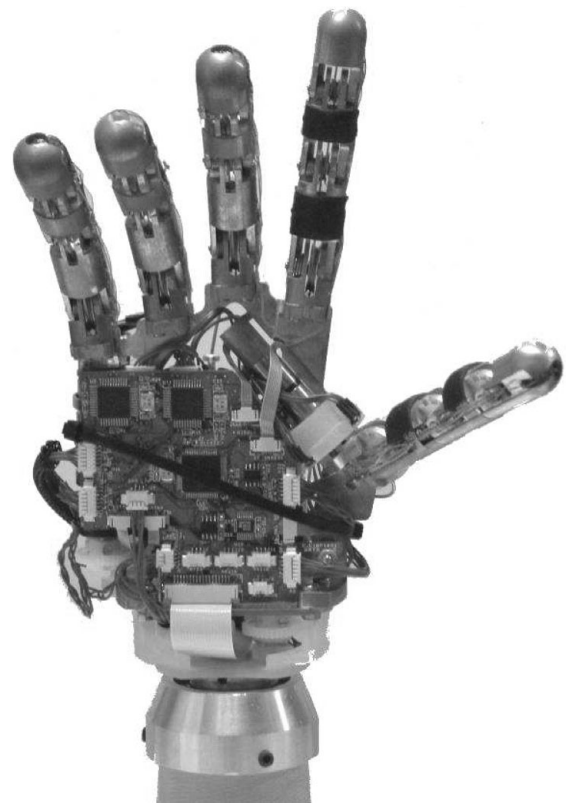


Fig. 5. The SmartHand mounted onto a prosthetic socket. The control architecture has been built on a PCB embeddable in the palm of the hand.

size: it is 12 mm longer (122 mm instead of 110 mm from the middle fingertip to the wrist attachment) and the palm is 8 mm thicker (39 mm instead of 31 mm).²⁸ The overall volume indeed is about 1,3 times the natural hand. The weight, including sensors and electronics (excluding the cosmetic glove that should cover the hand, and the batteries that could be placed in the prosthetic socket) is 520 g, i.e. again 1,3 the natural hand weight (about 400 g). A comparison between the developed SmartHand and a male hand is showed in Fig. 6, whereas features comparison with most significant commercial and research prostheses is shown in Table I. Four

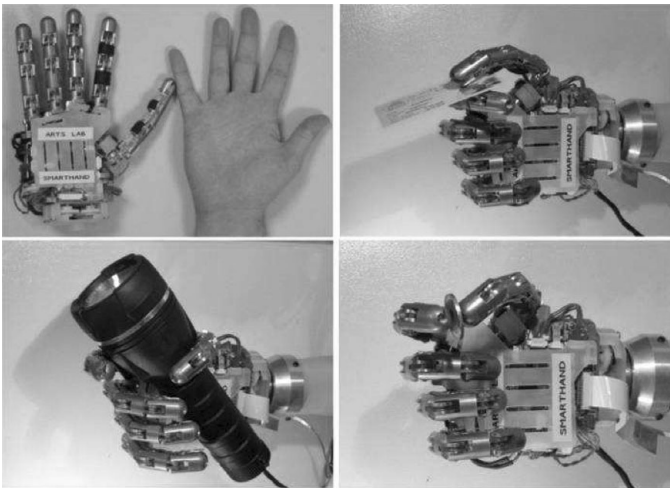


Fig. 6. Top left: comparison between the natural hand and the SmartHand. Grasps used in ADLs performed by the SmartHand: top right – lateral grasp, bottom left – power grasp, bottom right – precision grasp.

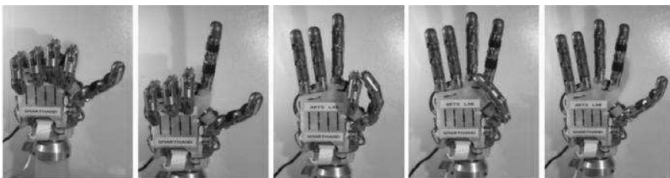


Fig. 7. The distribution of actuation from the four motors allows the SmartHand for a minimum gesture (i.e. counting).

degrees of actuation will allow users to execute most of the grips useful in ADLs through an adequate control interface, and minimal gesture as counting and index pointing is also permitted (cf. Fig. 7). It has been calculated that a full day operation (estimated in 4000 grasps) would be guaranteed with a 12 V, 1.5 Ah battery for supplying the motors and a 6 V 1.5 Ah battery for the sensors and embedded controller (two batteries are required).

Such prosthesis, by means of a control architecture conceived in a flexible way, may be connected to different kinds of interfaces and employed for clinical trials. Moreover thanks to the extensive sensory system, based on the biological one and on actual trends of research on interfaces, the device will be ready to provide proprioceptive and exteroceptive feedback information.

6. Discussion

The objective of the designed transradial prosthesis, is to provide amputees with a new dexterous and sensorized biomechatronic hand easily connectable to different kinds of interfaces. Restoring the natural hand functionalities, is an extremely challenging task with today's commercially available components, therefore many trade-offs based on requirements that come from different fields, must be found and applied in order to achieve such a goal. The proposed biomechatronic design, that has taken account of users wishes and has made the range of ADLs grips its highest priority, represents a competing design, compared to actual state of

the art in prosthetics. Nevertheless some design criteria and outputs present some issues that should be discussed.

The design sequence, as previously presented, starts from the mechanical part, then considers the sensors placement and finally the control architecture selection. Even though, the design of such components is not straightly sequential. The mechanical design is based on the assessed Hirose's finger also because it can include sensors,^{2,25} and it is simple to drive using 8 bit microcontrollers. Moreover, the number of sensors has been based mainly on the distribution of actuation, but still considering available microcontrollers peripherals (i.e. the number of analog and digital ports, etc.). These are just two examples that show that the design flow is mostly directed from the mechanical to the electronic part, but still could be defined as concurrent.

Although Hirose's soft finger presents all of the advantages mentioned in Section 3, and has been shown to successfully grasp objects,²³ it is a low efficiency mechanism: the transmitted torque on the grasped object is a minimal fraction of the input tendon tension.²² By this means, in order to obtain an output torque able to correctly support objects, actuators result in their being bulkier and heavier than what they would be if employing a different mechanism, e.g. a fixed kinematics finger (with no adaptation capabilities) as in the Southampton-REMEDI⁶ or in the i-Limb hand.¹¹ In other words, the advantage of having an adaptable finger is paid for in terms of volume of its actuation unit, and for this reason the SmartHand has less DoAs than the i-Limb or the Southampton-REMEDI hands.

Hand performances have been set to be 80 N of maximum tendon tension and minimum 1 second of closing (or opening) speed. Torque values are based on data derived in ref. [2], whereas maximum speed, comparable to commercial devices^{11,30} is found to be acceptable. Four motors fulfilling such requirements could be fitted in the intrinsic hand. Trying to achieve better performances while still using commercial actuators, will inevitably lead to further reduce the DoAs, thus losing dexterity and hand functionalities.

From a sensory system standpoint the hand design includes 32 embedded proprioceptive and exteroceptive sensors in the fingers. Among the sensory sensations that may be transferred to the amputee by means of an adequate interface,^{33–35} joint position, touch and force sensors are included whereas only the temperature is not. Slippage and palm sensors are not included either but could be embedded in future versions of the hand, thanks to the flexible electronic boards that allow extending the sensory system as desired (by means of additional analog to digital converters). The palm, for example, could be provided with some tactile sensitive areas, and arrays of temperature sensors could be spread all over the hand in order to measure the mean temperature value of the prosthesis.

The main issue related to the control architecture and the sensory system is power budget; the electronic part should not consume more energy than that required by actuators to execute grasps and gestures. To this aim, sensors could be powered in switching modality and peripherals should be shut-off soon after use. With all the peripherals and sensors switched-on power consumption is less than 1.5 W (6 V, 240 mA), but such value could fall down to some

(<100) mW with the hand in sleep operation mode. It becomes clear that after the hardware design, high effort should be placed in firmware writing, in order to minimize power consumption.

The last issue not yet fully addressed by this work is the cosmetic covering. The glove is of primary importance both from an engineering perspective (it protects mechanisms from dust, water, etc.) and from a social point of view since it should give an acceptable cosmetic appearance to the robot-like device. In the proposed design scheme the glove development and fitting follows the hardware development, nevertheless it has been considered from the start. The idea, to be achieved in future work is to develop a low-cost, easily cleanable (and changeable) glove composed of a lycra (or other tissue) inner glove, covered by a thin, flexible silicone rubber layer (similarly to i-Limb¹² cosmetic cover). To this aim the most critical components for the fitting of the glove (i.e. multi-DoF fingers) have been purposely shaped: no sharp edges are present in the SmartHand fingers, an adequate distance (8 mm) between adjacent fingers has been left, and all sensors have been embedded in the mechanisms. The torque-speed performances of the hand will inevitably be worsened in an uncertain, non-linear manner; nevertheless the elastic behaviour of the silicone could be positively exploited (if correctly modelled or characterised) for extending the fingers in place of the torsional springs (that could be removed, leaving space for an extra tendon). In this way some of the dispelled torque could be recovered. Preliminary tests have been conducted on the CyberHand prototype (unpublished data) showing that a regular layer of silicone rubber does not significantly change the designed closure dynamics of Hirose's mechanism. Moreover the glove will improve friction, therefore grip stability and won't significantly affect sensors outputs since these are intrinsic.

7. Conclusion

The SMARTHAND project aims to develop an intelligent prosthetic hand, able to be naturally controlled by amputees through different levels of invasiveness interfaces (ranging from superficial to implanted ones). The design of a transradial stand-alone prosthesis is a challenging task for engineers, since it must deal with a multitude of constraints coming from different fields like biology, engineering and social aspects, never forgetting practical issues. The criteria and methods towards the development of this intrinsic transradial prosthesis have been presented, as well as the result of such procedure, i.e. the biomechatronic prosthesis design. This consists of a five finger, 4 DoAs, intrinsic hand, with 40 embedded sensors to be used for automatic control and feedback delivery thanks to the intrinsic control board. The overall weight, including electronics, is similar to the natural hand weight and it is also comparable to actual commercial prostheses. Future work will be focused on the embedding of sensors in the palm, the fitting of the hand in a cosmetic glove and for developing controller firmware aiming to minimize power consumption.

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