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Objectives and technological approach to the development of the multifunctional MANUS upper limb prosthesis

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SUMMARY

The design of multifunctional upper limb prosthetics has been investigated in recent years. In 1998, the MANUS consortium was set up on the basis of multidisciplinary skills of the partners in order to provide a global approach to the problem of upper limb prosthetics. In the framework of this approach, the consortium addressed the development of appropriate hand mechanics, the analysis and implementation of control electronics, the development of advanced control strategies and the implementation of broad band command interfaces based on EMG.

As a result, the prototype of a multifunctional prosthesis was developed, integrated and clinically evaluated. This paper describes the objectives, technological approach and results of the MANUS prosthesis prototype.

KEYWORDS: MANUS; Multifunctional; Prosthesis.

I. INTRODUCTION

Mechatronic dextrous artificial hands have evolved into an established field of research since the 1950's,[1] some examples are even earlier first described in the second decade of the 20th Century.[2] Since then, a number of research groups have addressed different aspects of the problem, from hand design to control issues (See Pons et al.[3] for a thorough review of the state of the art).

In the context of robotics as it was in April, 1982, at a workshop held at the MIT,[4] it was pointed out that "*the current actuation technology provides perhaps the most serious, long term impediment to artificial hand design*". The same statement holds 20 years after this meeting. In fact, current actuation technologies fail to provide efficient, high power density actuators suitable for artificial hand design. The lack of adequate actuation technologies directly affects the design of dextrous hands. If dexterity is to be increased, a larger number of active joints is needed, as a consequence bulky solutions are the result. Depending upon the application this may or may not be acceptable. In fact, as pointed out by Pfeiffer,[5] one of the most interesting and practical background for the development of dextrous hands are prosthetic applications. The need in this application field of aesthetic, light solutions is obvious. Within the MANUS approach, this has been addressed by providing new driving strategies that allow additional grasping modes whilst keeping the number of actuators. In addition, new actuator technologies were evaluated and designed.

Moreover, when prosthetic applications are considered, the problem of the man-machine interface always appears, i.e. the more dextrous the prosthetic hand, the higher the number of command channels required to the man-machine interface. In addition, the amputation of upper extremities is much more problematic than the loss of the lower extremities since the manipulative function is performed according to complex motion carried out with full sensorial feedback.

Elliot et al.[6] proposed a distinction between grasping and manipulation as a classification of manipulative hand movements in terms of extrinsic and intrinsic movements of the hand. Extrinsic movements, i.e. grasping, define movements of a prehended object by displacement of the hand as a whole, while intrinsic movements, i.e. manipulation, define motion of the prehended object within the hand. Current existing commercial prosthesis provide a reduced set of manipulative capabilities as compared to human hand extrinsic movements, and all of them fail to provide the user with a feel of grasping force. As a consequence the adaptation to degree of amputation is not optimally solved, control on the environment is difficult and the capability of manipulation is limited.

With this background the MANUS project was set up on June 1998. The overall objective of MANUS was the development of modular hand prosthesis with enhanced mobility so that the basic grasping modes, i.e. hook, precision, cylindrical or power, tip and lateral grips, of the human hand could be reached. Moreover, it was to incorporate force feedback in order to enable a higher chance of social and professional reintegration of the patient. Since the MANUS approach is a global one, the project also proposed and developed an adequate training device. The training device serves the purpose of starting functional rehabilitation immediately after upper limb amputation. It is based on Virtual Reality tools and enables muscle conditioning as well as command language learning.[7] Just after the training process is finished, the MANUS prototype can be fitted and real manipulative operation can be started.

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This paper describes the objectives, approach, results and validation of the MANUS prosthesis prototype. In the following, the objectives of the MANUS project are fully described. The remaining sections address the MANUS approach, design, integration and results of the prosthesis prototype.

II. OBJECTIVES OF MANUS

The overall objective of the MANUS project is to develop a universal prototype of hand prosthesis with enhanced mobility as compared to currently existing prosthesis and with force feedback capabilities.

The project proposed a three-fold modular approach to the development of the prototype:

- The control system is based on myoelectric signals whose number and characteristics are adaptable to user's residual capabilities.
- The number of grasping modes is also selected according to user's needs among a grasping set comprising five grasping modes (cylindrical, precision, lateral, hook and tip grasps), that would cover most of the basic natural hand grips.
- The modular approach to the mechanical design allows a stepwise extension of the functionality up to the shoulder.

This approach is complemented by a force interface that provides a feel of the manipulative strength and thus helps in integrating the user in the control loop.

In order to meet this global objective a number of partial objectives were defined that gave rise to different tasks within the project. These partial objectives are:

- Definition of technical requirements on the basis of amputee's needs.
- Analysis of all possible approaches for every prosthesis subsystem meeting the technical requirements above defined. Selection of the best concept to approach the design of the prosthesis and training platform and eventually design of every subsystem according to the chosen concept.
- Integration of prosthesis subsystems into a functional prototype.
- Clinical validation and evaluation of the MANUS prototype.

A VR training platform was also envisaged as an important tool for the functional rehabilitation of the operator. The objectives for the VR training platform can be specified as:

- Definition technical requirements on the basis of user needs and therapists opinion.
- Design of the VR training platform according to the technical requirements.
- Evaluation through clinical trials conducted at well experienced hospitals and rehabilitation centres.

Details of the VR tool are in Pons et al.[7]

III. METHODOLOGY & TECHNOLOGICAL APPROACH

As indicated, the MANUS project proposes a methodology that starting from a technical specification based on users' demands, leads to the design and integration to be completed with clinical trials. In this section, all these steps are considered in detail.

III.1. Definition of technical requirements

The MANUS consortium identified the two main actors who dictate the specification of a prosthetic device leading the task: namely, upper-limb prosthesis users and professionals of prosthesis fitting and rehabilitation. It is these choices which affect the capability of a person to interact with their environment. Consequently the goal for this task was to identify the main concerns and reflect them on the technical specification of the hand prosthesis.

The opinion of prosthesis users and professionals is quite often complementary:

(i) While users have direct experience of the use of upper-limb prostheses, their insight is in the particular, professionals can provide a more general view prosthesis use from their breadth of experience working with many users.
(ii) Commonly, users opinions are given in terms of functionality related to activities they can or would like to accomplish. Professionals, can provide a more abstract information on the need for the task or the means of accomplishing this functionality.

In order to address both complementary points of view, the consortium created two specific questionnaires.

The process of technically specifying the prosthesis from users' functional specifications was a joint approach of the entire MANUS consortium. The technical feasibility of the functional requirements was examined and a final specification was issued in terms of minimum and desired criteria.

III.1.1. Scope & statistical analysis of the sample. Two hundred users questionnaires were submitted to user's associations, social workers and previous known users. A further 150 questionnaires were submitted to professionals. In both cases an acceptable number of questionnaires (around 60%) were returned and considered within this analysis.

a) User's questionnaire

The questionnaire was distributed in Israel and Spain. The sample of users comprised 75% men and 25% women, being 36 years old on average.

The main cause of impairment was a traumatic amputation following accident (81%), and the distribution according to amputation level was as follows: 40% were upper-third transhumeral amputees, 47% were transradial amputees and 13% lower-third transhumeral amputees.

Concerning the amputation side; 56% of the amputations were of the right arm/hand and 44% were of the left. 89% of the amputees were previously right handed and almost the entire sample (93%), reported no problems in the contralateral limb.

Just 58% of the surveys reported they used any kind of prosthesis. This agrees with Burger et al.[8] who stated that a maximum of 70% of users successfully employ their prostheses.

The type of prosthesis the respondents usually wear are cosmetic in 9% of the cases, body-powered in 32%,

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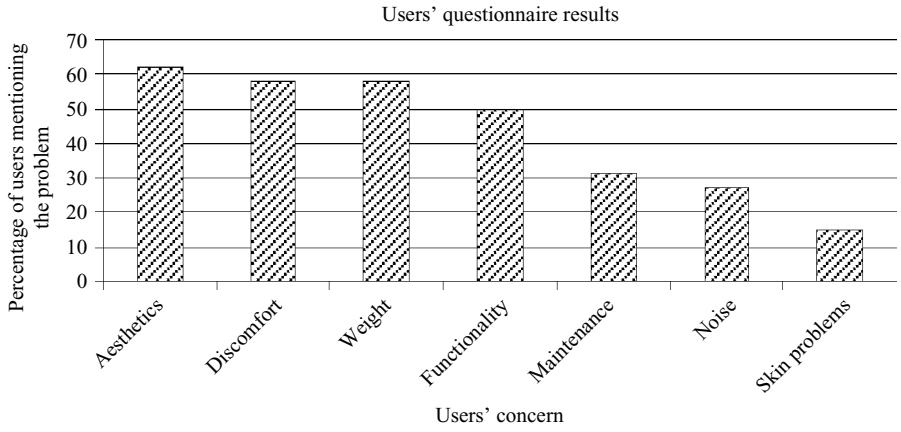


Fig. 1. Relative weight of users' concerns: aesthetics and comfort are regarded as the most relevant user demands.

myoelectric in 41% and hybrid in a 18%; 15% have not worn a prosthesis prior to their current device.

In general, the degree of satisfaction with current commercial prosthesis in the sample was rather high (65%), of which only 19% were very satisfied. 35% of the amputees were unsatisfied, data in accordance with previous studies as reported by Burger et al.[8] Figure 1 shows the relative concerns of prosthesis users according to our study.

b) Professional's questionnaire

The professional's survey attempted to cover the different professional communities dealing with prosthesis fitting and rehabilitation training of upper limb amputees. The therapists' sample comprised occupational therapists (45%), physiotherapists (5%), medical doctors (15%) and orthopaedists (35%).

The main causes to be improved as identified by our professionals for a prosthesis to be satisfactory are poor functionality (80%), weight (40%), difficulty to use and expensive (25%) and limited autonomy (5%).

Most of them (53%), think the wearer uses his/her prosthesis occasionally and a 23% think they use it only for aesthetics. Nevertheless 73% of the therapists would always advise the use of a prosthesis to an amputee (bilateral or single side loss).

They believed that a prosthesis should provide the five main types of grasps, namely; tip grips (55%), hook grips (50%), precision grips (45%), cylindrical grips (35%) and lateral grips (30%).

When asked about the importance of the sensorial information most of therapists answered positively (88%), and consider the best biofeedback would be tactile (59%).

III.1.2. Technical specification. According to the functional requirements issued from users and professionals, a technical specification was developed in terms of the minimum and desired criteria. This technical specification translated functional needs into mechanical, electronic and software requirements for the prototype.

These criteria were technically evaluated for feasibility and classified into functional, cosmetic and performance specifications, Table I summarises this and partially presents the specification. The technical evaluation assessed the feasibility of each specification in terms of available technologies and, based on this evaluation, introduced slight modifications to the technical specification, (see the last column of Table I).

III.2. Design of prosthesis subsystems

The design of the different prosthesis subsystems followed a stepwise approach starting from a conceptual design phase through a technical selection of best concepts to a refined design.

The conceptual design stage analysed all feasible solutions to the prosthesis specifications. These solutions were then technically evaluated and the "best concept" was selected. In a final design phase, the selected solution was fully developed. This process was repeated for every prosthesis subsystem. Even when this approach does not guarantee the optimal solution for the overall system, it ensures that the technical specifications are met, which of course arose from functional requirements as reported by users and professionals. In the following paragraphs this approach is presented for the analysis of mechanical, actuation and sensing subsystems.

III.2.1. Mechanical concept. The user and professional questionnaire led to a set of requirements, including the grasp types (cylindrical, tip, lateral, and hook), the grip force and the closing time. Size, weight and energy use were investigated and different kinematic concepts were examined and compared.

The mechanical concept contains several innovations with respect to commercial prostheses. In summary:

- the number of active axes are increased to 10 in the Manus prototype, a maximum of three active axis can usually be found in commercial protheses,
- a crossed-tendon mechanism is used in the fingers instead of the traditional bar mechanism,
- the thumb movements are coupled by means of a Geneva-wheel based mechanism, which makes it possible to use one actuator for thumb movements in two planes corresponding to abduction-adduction and flexion and extension.
- prototypes of ultrasonic motors were built to be used as actuation technology,

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Table I. Technical specification of MANUS prosthesis prototype.

Feature	Minimal	Desired	Feasibility evaluation
		Functional Specifications	
Opening span	100 mm adults 60 mm children	100 mm adults 60 mm children	100 mm adults (only one universal prosthesis)
Opening velocity	15 to 55 mm/sec	110 mm/sec	Accepted
No. of active fingers	3	4	Accepted
Prono–supination *range*	170 degree, +/-7 degree accuracy	170 degree, +/-7 degree accuracy	Accepted
Prono–supination *velocity*	20 to 60 degree/sec	10 to 90 degree/sec	Accepted
Prono–supination *torque*	0.2 kg*m	0.3 kg*m	Accepted
Modes of grasping	Hook, cylinder, fine grip	hook, cylinder, pitch, fine grip, lateral	Hook, cylinder, fine grip & lateral
Power and characteristics of grasping	15 N One grip mode For children the maximal grip force is between 800 gr to 5 kg	60 N Differential grasping between various fingers. The thumb must be able to carry out opposition. The thumb may act independently by a metacarpofalangical joint with range of 0 to 70 degree, and interphalangical joint range of 0 to 40 degrees.	Accepted, differential grasping decision left for a more thorough study
Flexion–extension		90 degree, 60 degrees/second, 0.3 kg*m torque	No active flexion–extension of wrist
Lifting	10 kg	14 kg	
Locking position: Hand wrist flexion/extension prono-supination power/gripping for each position	One "stop and freeze" position; Default two intermediate positions	One "stop and freeze" position; Default two intermediate positions and one programmable default position	Accepted
		Cosmetics Specifications	
Weight of the prosthesis, including cover and battery for adults (children)	850 g (200–300 g)	400 g (200–400 g)	Maximum 800 g + belt battery up to 500 g.
Cosmetic gloves disturbance to pronation/supination movement	Limited disturbance	No interference	Accepted
Noise during activation	No noise	No noise	Accepted
		Performance Specifications	
Build-in battery tester			Alarm if low then permitted voltage
Battery position	On the prosthesis	On a trouser belt	Both options combined
Charging time	12 hours	6 hours	Option to recharge through the car special socket.
Battery	6 V, 1000 mA/H, 200 cycles, 200 gr weight	6 V, 1300 mA/H, 400 cycles, 165 gr weight	To be studied.

- the fourth and fifth fingers are provided with a martensitic structure which makes it possible to put them manually in any position (holding the shape for long term, aesthetic grips).

Each aspect of the design is detailed below.

MANUS proposes a prosthesis having ten axes of which three are actuated independently. Different mechanisms couple the other axes to the actuated ones. The three independent mechanisms are the finger, thumb and wrist mechanisms. Furthermore, the functionality of the fourth and fifth fingers was enhanced by using a martensitic structure so they can be placed manually in a position and assist the index and middle fingers. Figure 2 shows the total kinematic concept and Table II shows a comparison of commercial prostheses and the MANUS concept. Robotic dextrous hands could also have been compared, but the application oriented approach of the MANUS project means a comparison with state of the art commercial prosthesis is more relevant. The reader is referred to literature reviews in the matter,[11] or to specific comparisons between prototypes in the literature,[12] for further details.

In Table II, the grasping modes are described according to the taxonomy analysis by Schlesinger[2]. Referring to Table II,

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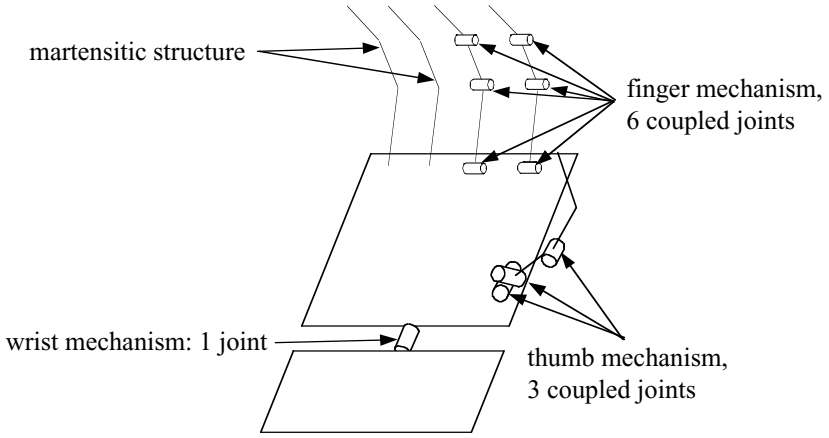


Fig. 2. The global kinematic concept: index and middle fingers are coupled via crossed tendons whilst thumb performs a 2dof motion based on a Geneva mechanism.

Table II. A comparison of commercial prostheses and the MANUS concept.

	Commercial prosthesis	MANUS concept
Number of actuators (= number of independent mechanisms)	standard 1, maximum 2	3
Manual positioned axes	standard 1, minimum 0	0
Number of axes	3	10
Cylindrical grip possible	yes	yes
Tip grip possible	yes	yes
Hook grip possible	no	yes
Lateral grip possible	no	yes

it should to be noted that the cylindrical and hook grips are rarely possible in anthropomorphic prostheses.

(i) Finger mechanism

Fingers having a fixed shape rotating about one joint, as usually seen in commercial prosthesis, do not move in a natural way and limit the grasping functionality. If for example the fingers are shaped for a cylindrical grip, the shape will not be suited for a hook grip and vice versa. Non-commercial prosthesis have been proposed with three active fingers with coupled interphalangeal joints.[9] In a similar manner, MANUS proposes to use fingers having three joints. A closing pattern is imposed on the fingers by fixing the relation between the joint angles. In the design this is achieved by using crossed-tendon mechanisms linking the rotation of every phalanx to the previous one as depicted in figure 3. In this way, both functionality and aesthetics of the prosthesis are improved. The proximal joints of the index and middle finger are coupled which means that one single actuator is driving six joints.

A complete description of the different concepts analysed to reach this solution is beyond the scope of this work. However, it is worth mentioning that a number of different solutions were considered, namely, non-adaptive finger mechanisms based on bars, tendons and gears and adaptive finger mechanisms based on springs and slip couplings. The adaptive mechanisms have a higher functionality but also a higher complexity than the non-adaptive mechanisms and have been implemented in some prosthesis prototypes.[10] Because of this, the weight of the adaptive mechanisms is much higher, therefore in the MANUS hand, a non-adaptive

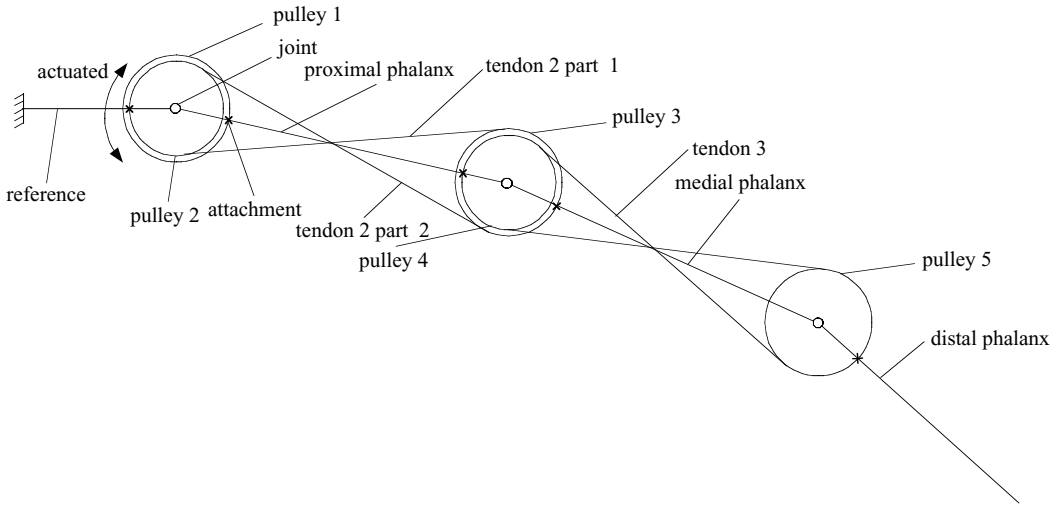


Fig. 3. Crossed-tendon mechanism for actuating the middle and distal joints of the fingers.

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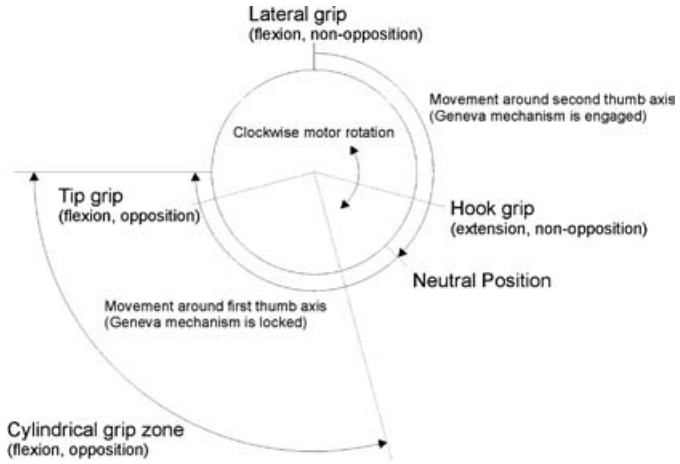


Fig. 4. Thumb cycle implemented via the Geneva mechanism: one motor rotation is mapped into lateral and precision grips with an intermediate neutral position.

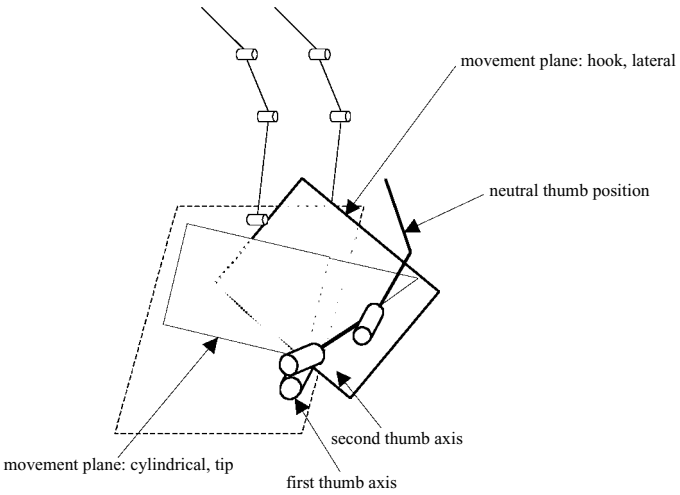


Fig. 5. Thumb neutral position concept: the moment when the Geneva mechanism is engaged is regarded as the neutral position.

approach was implemented. The reader is referred to the work of Reynaerts,[11] for a thorough discussion on this matter.

(ii) Thumb mechanism

The thumb movement is implemented as a composition of an opposition movement (abduction-adduction) and a flexion-extension movement. MANUS introduces the concept of a neutral position, in which the thumb movement is obtained around two intersecting axes by means of an intermittent mechanism, (Geneva mechanism) (see figure 4).

The thumb moves from non-opposition and flexion (in which a lateral grip is available), through non-opposition and extension (in which the hook grip is obtained) until the neutral position is reached (i.e. natural looking free hand). From the neutral position, upon further rotation of the motor, the cylindrical grip zone is entered. At the end of this grip zone, the precision grip area is reached. This way, moving around the first axis gives the closing pattern for the cylindrical and tip grip. Moving around the second axis gives the closing pattern for the hook and lateral grip (see figure 5).

The rotation of the wrist is independent of the other movements and is thus actuated by a separate actuator. To

Table III. Importance of actuation properties.

Properties	Importance
Performance	Very important
Energy storage capacity	Very important
Specific power	Very important
Required transmission	Very important
Self braking	Very important
Noise	Very important
Safety	Very important
Robustness	Important
Volumetric power	Important
Bandwidth	Less important
Controllability	Less important

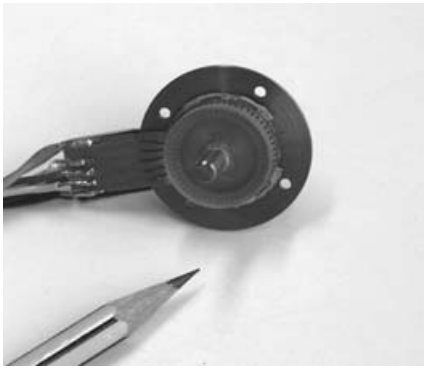


Fig. 6. Ultrasonic motor for wrist actuation: its compact and flat construction makes it adequate for a short wrist mechanism.

the authors' knowledge, no commercial prosthesis uses ten joints and is able of carrying out such a variety of grasping modes as the proposed MANUS concept.

III.2.2. Actuation concept. In order to evaluate the quality of the actuation types within the MANUS project, 11 properties were used. These properties have been selected on the basis of our analysis of the users and professionals' questionnaire. Table III lists the importance of each property relative to each other and to the target application.

Commercially available actuator technologies together with non-traditional actuators, i.e. Shape Memory Alloy actuators and Ultrasonic motors, were evaluated according to the above-indicated properties. For each technology and property, a quotation was given (excellent, good, sufficient, insufficient and poor) and the overall quotation was compared according to the Dominic method.[13]

After comparison, two actuator technologies were selected, Brushless DC motors and ultrasonic motors. Due to the limited performance of ultrasonic motors, extensive research was conducted to improve the properties. Eventually, a combination of these two technologies was implemented. DC motors drive fingers and thumb while the wrist prono-supination is based on high torque ultrasonic motors. Figure 6 shows one of the ultrasonic motor prototypes developed for driving the prosthesis.

III.2.3. Sensing subsystem. Force controlled grasps require exact computation of equilibrium conditions. Such equilibrium computation relies on feedback information

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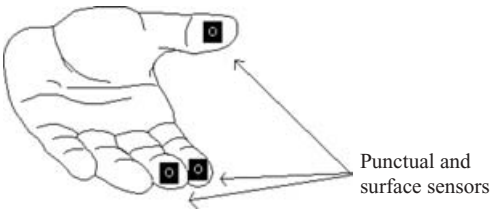


Fig. 7. Force sensor allocation for compliance control: Hall-effect sensors are located at index, middle and thumb tips.

about points of contact between grasped object and fingers as well as on precise estimation of grasping forces. Measuring contact point force for a whole hand grasping operation requires a large number of force and contact sensors, making the whole system complex.

In order to keep system complexity at a manageable level, the possibility of implementing stable grasps based on actively programmable finger compliance was studied. In this approach the object is fixed to the palm via compliant linkages in such a way that each individual finger behaves as a spring with its two ends attached to the palm and the object. In such a configuration, provided enough contact points are present, the systems has stable equilibrium poses, see section 4.2 for more details.

This approach is shown to provide stable grasps with a minimum types and number of sensors. Based on a sensor allocation scheme as shown in figure 7 just five sensors are required for grasp control:

- two force sensors allocated at the index and medium finger tips,
- one force sensor at the thumb tip,
- one position sensor for index and medium (remember that finger motion is coupled and one shaft rotation determines finger placement)
- one position sensor for thumb (positioning in the abduction-adduction and flexion-extension planes is obtained from a single shaft rotation thus the thumb position is uniquely determined by using a single sensor)

A number of force sensing technologies were evaluated in a similar manner to the actuation technology. Among the different technologies considered were: force sensing resistors, FSR, piezoresistive devices, strain gauges, PVDF sensors and Hall effect sensors.

Linearity, hysteresis, sensitivity, robustness, thermal drift and costs among others were the main properties analysed for force sensors. A similar approach was conducted on position sensing technologies. Ultimately, Hall–effect sensors were chosen for both position and force sensors.

Hall-effect sensors are sensitive to magnetic fields. In both configurations permanent magnets were used to create the magnetic field. In the case of position sensors, both magnet and Hall-effect pickup were placed opposite to each other and fixed to an external frame. In between, a cam was linked to the shaft rotation. The cam was manufactured in ferromagnetic steel so that the effective reluctance between magnet and pickup was modified in a linear fashion according to the shaft rotation. As a consequence output voltage is linearly related finger and thumb position.

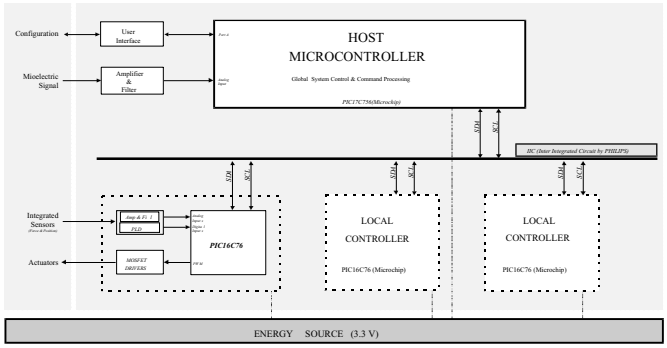


Fig. 8. Electronic architecture for prosthesis management: a host controller performs hand coordination, local controllers are in charge of low level control of each joint.

Force sensors were developed in a similar way. In this application an air gap was used between a fixed pickup and a moving magnet. The magnet was mounted on the finger tip structure which in turn was mounted on springs. This time voltage is linearly dependent on magnet position which is related to force applied to stretch the springs.

IV. PROSTHESIS INTEGRATION

The prosthesis prototype was integrated around a flexible electronic control architecture. The architecture has to be flexible enough to support the real time control of three active axes, real time identification of EMG commands and computation of control loops and force biofeedback. A modular architecture based on a host and three local microcontrollers was selected. The three controllers communicate through a fast I2B bus with the host controller. The functions supported by the host controller are:

- Calibration of EMG signal
- Computation of control commands out of EMG signals
- Computation of set points for local controllers
- Perform force biofeedback
- General status and error management

Among the functions supported by local controllers are:

- Low level control of actuators
- Monitoring finger force and position
- Providing information for force biofeedback

Every local controller is associated to an active joint or actuator whilst the host controller is in charge of the general functionality of the prosthesis. The electronic scheme supporting these functions is given in figure 8.

In the following paragraphs the main functions supported by this architecture are introduced.

IV.1. Calibration and computation of EMG commands

A new command language has been developed as the driving interface between user and prosthesis.[7] However, this serves as an introduction to those aspects of the command language related to the prosthesis control.

Each command comprises a set of three EMG bits, i.e. a set of three consecutive EMG bursts made up from three consecutive muscle contractions. The prosthesis controller decodes

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each three-bit command and, once the associated grasping mode is determined, set points are generated for the different motion controllers (local controllers), see Pons et al.[7]

According to the command encoding procedure, this language allows up to 27 three-bit words. All those commands starting with "0" are not considered, since there would be no possibility of distinguishing "0XY" and "XY0" patterns. In addition, the pattern "X00" was also removed in order to provide a robust interference rejection, i.e. any interference EMG peaks would not be considered as valid commands.

The role of the host controller regarding EMG management will be described in more detail.[7] Briefly, the main function performed by the Host controller concerning EMG command is calibration and command computation.

The calibration process is performed once the prosthesis is worn for the first time and can be programmed to be automatically repeated after a certain period of time. The calibration process is based on a statistical analysis of the EMG signal and determines particular muscle and user's thresholds as well as maximum time window allowed for command generation. The calibration process takes between 15 and 20 seconds and makes the prosthesis less sensitive to EMG electrode placement.

The command computation is a process initiated after calibration and running while the prosthesis is on. The Host processor samples the EMG channel at a frequency of 5 kHz during the calibration process. This enables a good determination a of noise level. During computation of EMG commands, EMG is sampled at 400 Hz and the statistical analysis of the signal is launched once the EMG amplitude reaches the first threshold for the first time. If a valid command is identified it is translated to a functional command. Each functional command specifies a grasping mode (including wrist pronation and supination) and a force level (or velocity level) associated to that grasping mode.

IV.2. Grasp control

After command computation a grasping mode is identified. As already described in the previous sections, in order to avoid the need of a detailed geometrical description of the grasped object, a compliance control approach was proposed. The idea behind this approach is making the fingers and thumb to behave as springs with a neutral position in full flexion. The compliance of the springs allows grasp accommodation to object size and weight. In this approach the different force levels are obtained by modifying the equivalent spring stiffness of the fingers.

From a control point of view, for the finger to behave as a spring just information local to that finger is required, i.e. the current finger position, the force being exerted and the neutral position. Therefore the overall control of the grasp is organised around the local controllers. Each of these controllers performs the control scheme depicted in figure 9. The local Hall-effect force and position sensors are used to close the control loop.

From figure 9 it is seen that, for each active joint "i", two parameters are defining the grasp being performed, i.e. the neutral position, θ_{di}, and the equivalent spring stiffness, K_{di}. For instance, if θ_{di} is defined for thumb and index to be full flexion, then a cylindrical grasping pattern is obtained. The more extended the thumb and finger the more force is applied to the object. If grasp strength is to be increased this is easily done by increasing K_{di}.

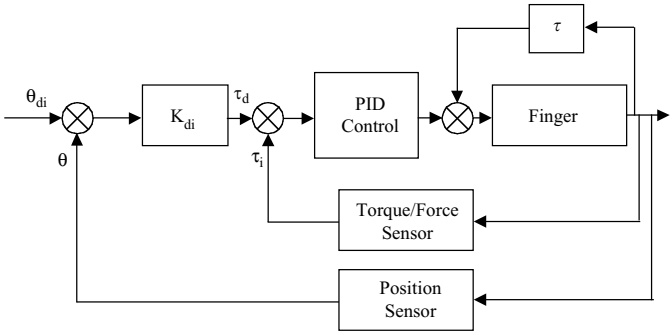


Fig. 9. Control scheme performed at each active joint: the finger behaves as a virtual spring, thus enabling stable grasps.

The resulting control approach, if the user is considered, is an open loop approach in which the amputee simply commands a desired grasping mode and Host and local controllers ensure this through a compliance scheme.

IV.3. Force biofeedback

As both force and position information are available to the local controllers for the compliance control task, this information can be used to integrate the user in the control loop. This is supported by the MANUS prosthesis through a force biofeedback device in combination with the possibility of complementing the digital EMG management with analogue or proportional capabilities.

Different approaches to develop the force biofeedback have been analysed. In particular, visual, acoustic and tactile feedback schemes were studied. It is well know that prosthesis users use the acoustic information provided by the driving motors to get an idea of the force level being exerted. However, acoustic feedback was rejected because of the concern shown after the users' questionnaire on discomfort related to noisy prosthesis.

Visual feedback demands too much attention from the user and does not contribute to user acceptance. Therefore, a tactile biofeedback device was developed. In this approach the force information is encoded in a frequency modulated signal. This signal drives a vibrating device similar to those present in mobile phones. Since the MANUS approach only allows controlling the grasping force in a discrete fashion, the force biofeedback device only provides vibration at discrete frequencies.

V. LABORATORY TESTS

The validation of the MANUS system, comprising both the Virtual Reality training platform and the multifunctional prosthesis prototype involved fifteen amputees. It was conducted in Spain, at the Centro de Recuperación de Minusválidos Físicos and in Israel, at the Flieman Hospital (Fig. 10).

One single MANUS hand prototype was built and shared during the laboratory trials between both rehabilitation

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Fig. 10. The MANUS prosthesis during validation a) precision grasp and b) cylindrical grasp.

centres. All individuals gave informed consent to the experimental procedures.

The validation plan was structured in several stages:

(i) Validation group selection
(ii) Learning of EMG management
(iii) Learning of the digital EMG language
(iv) Associate commands with grasping modes and active prono-supination
(v) Generalise these grasping modes in activities of daily living (basic)

The first four steps were developed both with the VR training platform and with the prosthesis prototype.[7] Some conclusions from the validation process can be drawn.

In general, the test results were satisfactory. It was quite easy and simple for the subjects to learn the command language and perform the generation of signals after a very short period of time (between 1 hour- 1 ½ hours). All the subjects were able to generate at least 12 commands of the three-bit language without errors, and all were able to achieve the four types of grasping as well as the pronation and supination of the wrist.

All the subjects were enthusiastic about the novelty of the prosthesis, with the extended range of functions and the similarity to a natural hand.

The generalisation of these grasping modes in activities of daily living was undertaken at the Spanish centre, once the final integration of the Prosthesis was performed. There were several days of co-ordinated work between the technical developers and the co-ordinators of the evaluation tests regarding the use of the whole integrated system.

A provisional socket was used, which was adjustable with Velcro and with a supracondilar extension, obtaining a good fixation and it proved to be adaptable to the several stumps as was required for the validation.

The first subject of the evaluation was a man, 45 years old, with a congenital middle-third transradial amputation, see figure 10. He had never used prosthesis before and he also collaborated in the VR training platform validation. He was able to generate fifteen commands of the "three-bit language" of MANUS without difficulties. There was a good fixation degree with the provisional socket, and after some training the user was able to achieve the precision, cylindrical, and lateral and hook grasping modes.

He liked MANUS appearance, and although at the beginning he found the prototype a little heavy, in a few minutes he was used to wear the prototype and felt comfortable with it. This user collaborated in the validation during several days and the results were quite satisfactory. Two other subjects, males, 32 and 28 years old and with a trans-radial amputation of traumatic origin were also engaged to continue validation of MANUS prototype with similar results.

During these trials some technical problems and design limitations in the prototype, were found:

(i) Problems in the lateral grasping of small objects due to the state of the prototype mechanical structure of the thumb.
(ii) Difficulties in force control. It is necessary to improve sensor's sensibility and range to obtain a better control of force.
(iii) Excessive noise of the thumb motor.

Despite these technical problems, the functional specification referred to in Table I was fully met. Cosmetic appearance and performance specifications were partially met. This is explained in more detail. All specified grasping modes were obtained (power, precision, lateral and hook). Additionally, the technical specifications regarding opening and closing grasping speed, force and range were met for all grasping modes.

The overall weight resulted higher than specified (1,200 g as compared to 800 g) but margin for weight reduction is left by material optimisation and size reduction (the actual size of the hand is approximately 20% larger than an average hand). The required grasping force at the finger tip was 60 N and this value was met in the MANUS hand. The use of adaptive finger mechanisms would have enabled a force reduction at the specification stage, but this also would have resulted in increased weight.

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A battery life of a maximum of four hours on a single battery charge was obtained. The main source of energy consumption in the system (due to its low efficiency, around 40%) is the ultrasonic motor. The issue of energy consumption reduction will be specifically addressed in a second version of the MANUS prototype. It is also worth noting that, the electronic control circuit was clearly over sized in this first prototype for the sake of flexibility, and as a consequence margin for energy savings is available.

In this approach, one single motor drives six axes (those corresponding to index and medium fingers). It could be argued that this limits the possible dexterity of the system that could be reached with independent (uncoupled) joints. This is the approach introduced by others.[14] However, the aim of this solution was to adopt a simpler kinematic concept with the aim of ensuring the grasping modes specified by the users and professionals.

VI. CONCLUSIONS

The MANUS project develops a global approach to multifunctional upper limb prosthetics. The concept tries to enhance social and professional reintegration of upper limb amputees and in so doing a Virtual Reality training platform and a multifunctional EMG prosthesis was developed.

This paper presented the objectives, approach and results of the multifunctional hand/wrist prosthesis. The development has rested on a user-based technical specification of functional requirements for such a prosthesis. It is the contention that the approach to developing system mechanics, electronics and control management is innovative and have been experimentally tested.

The enhanced functionality of the prototype rests on a novel hand comprising ten axes, three of them actively actuated. The innovative concept of the thumb based on a Geneva mechanism allows both opposition and flexion with just one motor.

The flexible electronic architecture supported by compact position and force sensors supports a broad-band man-machine interface and active compliance control of the grasp. Force biofeedback is also included in our approach.

The prototype has been integrated and preliminary laboratory tests conducted. Up to fifteen amputees were involved in the tests of VR training platform and prosthesis prototype. They were trained in the generation of EMG commands and were able to successfully implement them after a very short training period (1-1$^1/_2$ hours). All the initially planed grasping modes were available even when some problems related to sensitivity of force sensors and kinematics of the thumb were identified. Further research is required regarding the development of actuation technologies with more power density.

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