The Mechanical Design of the MARCUS Prosthetic Hand

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Abstract: The present article deals with the work carried out in the framework of the TIDE project No. 150 MARCUS, for the development of a new three-fingered polyarticulated myoelectric prosthesis. The prosthetic hand is equipped with position, force, slip sensors while a sensor-based control allows to maintain a stable grasping of the object without affecting the user attention. A general description of the whole system is given by emphasizing the mechanical solutions utilized for the three fingers. Force sensors at the level of the fingertips as well as palm sensors have been integrated in the structure. Results of sensors performances are also shown.

1. Introduction

The last decades have witnessed a researchers' growing effort in providing limb prostheses which better emulate the natural control of the limb. Although bioengineering has provided some of the most remarkable breakthroughs particularly in the area of artificial organs, which culminated in the implantation of an artificial heart into a human being (1982), in the area of prosthetic limbs the contributions by engineering and medicine are narrower than the gap in human capability they aspire to fill. Unavoidably the study of prostheses embraces different science branches (e.g. anatomy, neurophysiology, biomechanics), therefore the design and development of practical, functional, cosmetic artificial limbs goes beyond the state-of-the-art in micro processing, in energy storage and in electronic and mechanical efficiency, compactness and weight reduction. The ultimate goal of the research on prosthetics is to provide artificial limbs naturally controlled by the amputee's brain. This article aims to give a small contribute for the assessment of the above mentioned trend by describing in detail design methodologies and followed approaches in the design of a new polyarticulated myoelectric prosthesis. The particular emphasis given in the study of a system purposely designed for being directly interfaced with the patient's body render this topic particularly stimulating for discussion in the framework of a Conference dealing with techniques and modalities of interaction between humans and artificial machines. In the framework of the project TIDE No. 150 MARCUS (Manipulative Automatic Reaction Control and User Supervision) funded by the Commission of the European Union, a three fingered polyarticulated prosthetic hand equipped with different kinds of sensors and controlled via a microcontroller has been developed. The European consortium coordinated by the English company Technology Applications Group ,Alnwick,UK, and formed by the Oxford Orthopaedic Engineering Centre, Oxford, UK, the Centro Protesi INAIL, Budrio (BO), Italy, the Italian company S.M. Scienzia Machinale s.r.l., Pisa, Italy, and the University of Southampton designed, developed and tested four prototypes hands. The prosthetic hand is a 2 D.O.F. hand equipped with two separate motors, the first one driving the thumb movement and the second one driving the movement of the index and middle fingers which are mechanically coupled. The information provided by sensors are processed in order to automatically increment the force exerted on the grasped object when slippage conditions occur at the point of contact. In the following a description of the mechanical solutions devised for the construction of the hand prosthesis are outlined together with the description of all the sensory systems integrated in the device.

2. Mechanical Design Considerations

From a mechanical point of view, the goal of the MARCUS project has been that of designing and manufacturing a prosthetic hand capable of providing improved grasping capabilities with respect to existing prostheses, in terms of typologies and sizes of graspable objects, of force exerted on the object and of adaptability of the mechanical configuration of the hand to the object. A survey carried out on a sample of users of upper limb prostheses

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helped us to know the main improvements and requirements the MARCUS Hand would have had with respect to existing devices; moreover, in order to define in a single way the kinematics of the prosthesis, a limited subset of grasping procedures has been taken into account. The solution has been found by considering two main categories of prehensile movements: precision grip and power grip. When the human hand performs operations of precision grip, very often the grasped object is held in what it is called "tripod grip", in which the contact occurs at the fingertips of the thumb, index and middle fingers. On the other hand, power grip operations are characterised by a wider interested surface of contact with the object, in fact the grasped object is held in the hollow formed by the thumb, the palm and the finger. From the point of view of functionality the little and ring fingers are utilized for augmenting the stability of the grasped object during the prehensile movements performed by the thumb, index and middle fingers. For this reason a prosthetic hand with only three fingers (with a functionality close to those of the thumb, index and middle fingers) can satisfy the proposed aims. By taking as a reference the allowed volumes of an adult male hand, the dimension of the mechanical structure have been derived. In fact by using normalized values of the distances between the rotation centres of each link, the length of the distal, medial and proximal phalanxes have been obtained. The first step in the design of the mechanics of the MARCUS Hand has been that of studying the most appropriate kinematic solution in order to perform both precision and power grip movements. Precision grip operations show the thumb working in opposition to the other fingers (in this case the couple of index and middle fingers can be seen as a single virtual finger), while in power grip postures the object is held between the index, middle fingers and the palm (the thumb operates as a subsidiary system of the other fingers). From these last two considerations, it derives that the two kinematic chains of the thumb and virtual finger must possess independent movement and control. In the minimum solution two motors are required, one to drive the thumb and the other to drive the virtual finger. The number of two for the motors is also the maximum allowable from the practical point of view: in fact, in order to obtain a maximum force at the fingertips of 120 N, it is necessary to utilize motors plus gearboxes, which largely affect the total weight of the hand. In order to allow the fingers to automatically adapt themselves to the contact regions at the external surface of the object, it is necessary that the fingers possess a certain degree of adaptability of their kinematic configurations.

The chosen model for the mechanical transmission is shown in Fig.1.

It can be noted that the cables rotate around pulleys, or pulley arcs and this fact allows to transmit a constant torque with respect to the centre of rotation of each joint. The angle of rotation, for each phalanx of the index and middle fingers, can be easily calculated by multiplying the angle of the previous phalanx by the transmission ratio between the two adjacent phalanxes. By using the above mechanical transmission system, the angle of rotation of the subsequent phalanx can be easily varied, by modifying the diameter of the pulley linked to the adjacent phalanx. In order to provide to the MARCUS Hand a certain degree of adaptability, a purposely conceived mechanical adjuster has been designed (see Fig. 2).

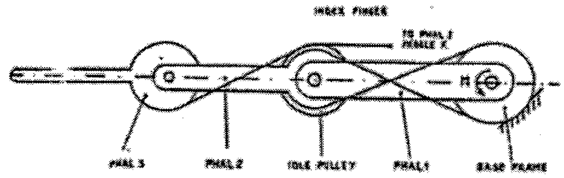

Figure 1: *Coupled finger transmission*

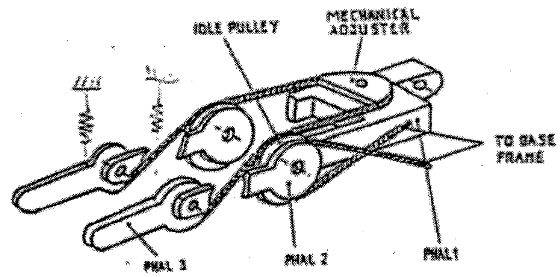

Figure 2: *Scheme of mechanical adjuster*

When for instance, the MARCUS Hand is grasping a bevel object, the contact could occur first at the fingertip of the middle finger. The reaction force, developed along the contact surfaces of the object and the fingertips of the middle, exceeds the force of the back drive spring and forcing the distal phalanx of the index to move in the direction of the object until when an equal reaction is developed at the fingertips of the index. Another interesting obtained result has been that of locating the position of the thumb with respect to the coupled fingers. In fact designers realized that the grasping capabilities of the MARCUS Hand would have been dependent from the correctness of the adopted mechanical solution. The position of the thumb of the human hand can be determined according to anthropomorphic considerations. In fact, the base frame of reference for the thumb kinematic chain can be described, with respect to a frame of reference on the third metacarpus head (MIII), by means of a homogeneous transformation matrix consisting of both a displacement vector pointing proximally and also of a rotation matrix obtained by three rotations about all the

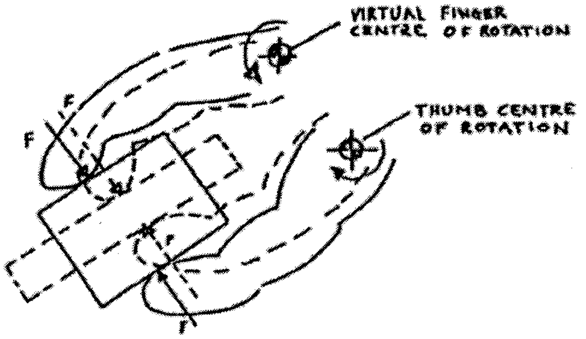

Figure 3: *Scheme of the MARCUS Hand*

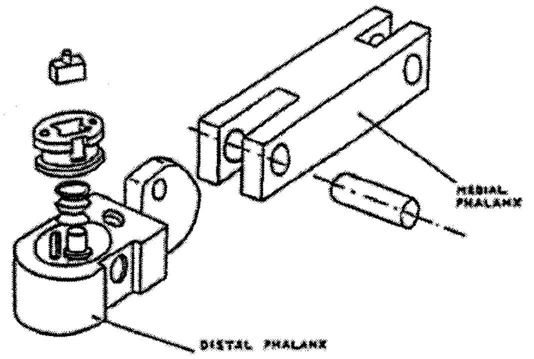

Figure 4: *Exploded scheme of the integrated version of the force sensor*

three axes. Nevertheless, in the human hand, the opposition movement, which allows the thumb to present, at the fingertips, a contact plane which is always parallel to the contact plane of the other fingers, is obtained by means of the thumb kinematic chain possessing 5 DOF.
In the MARCUS Hand, constraints imposed by mechanics complexity, control and weight increase do not allow to independently command 5 D.O.F.. Moreover the weight constraint does not allow to introduce more than one motor for driving the thumb movement, and consequently only one DOF has been devised for the thumb movement.

In order to locate and orient the thumb link the following hypotheses have been then assumed:

a) the overall length of the thumb must be the same of that of a human male hand;
b) the location of the base frame of the thumb link must be the same of that of a human male hand.

The above mentioned assumptions can be easily justified from a cosmetic point of view; in fact by respecting the above mentioned hypotheses the MARCUS Hand mechanical structure will result closer to the structure of the human hand. The spatial geometry of the thumb link has been choosen in a way that the sensorised part of the sensors embedded in the mechanical structure opposes the virtual finger for those objects whose size is between 0 and 50 mm. A scheme of the mechanical structure of the MARCUS Hand is depicted in Fig. 3, where it is shown the rotation axis of the thumb that allows the thumb link to oppose the virtual finger in its curling plane.

In order to allow the adjustment of the position of the thumb of the MARCUS Hand, the motor housing has been equipped with a further degree of freedom. By adding this passive D.O.F. it has been possible to adjust the position of the thumb during the assembly and to facilitate the releasing operation in case of malfunction of the hand.

3. Sensor Design / The sensory system

The integration of exteroceptive and proprioceptive sensors is an innovative concept with respect to the state-of-the-art of present prosthetic hands. In fact, by introducing these systems, it is possible to improve the grasping capabilities of the prosthetic device without affecting the patient's attention during the operation. The functionality of the sensory system's components have been defined from the analysis of the possible types of grasping configurations the prosthetic hand can assume.
Two separate categories of exteroceptive sensors have been defined: *static* and *dynamic* sensors, while only one category for proprioception: kinaesthetic sensors. For each sensor category, the following characteristics have been defined:

- functionality;
- technical specifications;
- geometrical arrangement of the hand structure;
- mechanical and electronics interfaces;

3.1 Force Sensors

The main characteristic of the force sensors is that they must be located at the fingertips of the three fingers of the MARCUS Hand. The shape of the force sensors has been conceived in order to present the integration of the slip sensor (developed by Oxford Orthopaedic Engineering Centre). A scheme of the integrated Force sensor is depicted in Fig. 4.

The force sensor is based on a mechanical elastic structure capable of withstanding the maximum desired load of 120 N. The external applied load is translated, through the elasticity of the system, into a displacement of the sensor plate; the relative movement of the magnet with

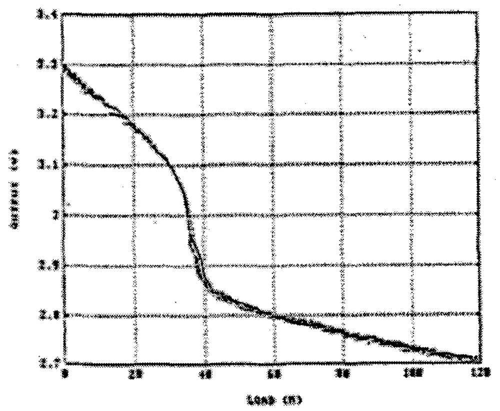

Figure 5: *Calibration curves for the force sensor; output voltage versus applied load characteristics*

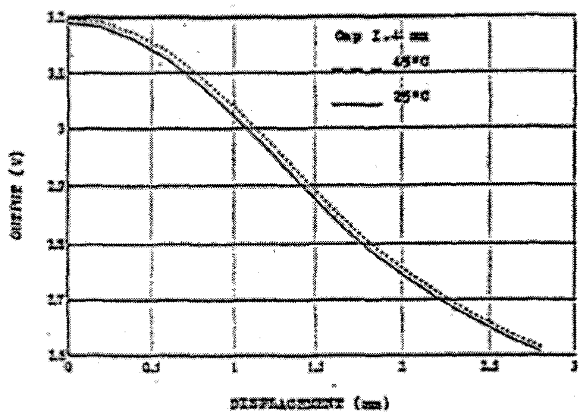

Figure 6: *Output curves of the Hall effect sensor at temperature of 25 and 45 Celsius degrees*

respect to an Hall effect sensor embedded in the spot-facing generates an increasing signal with the increase of the applied load. The external load is counterbalanced by a series of variable stiffness Belleville washers located at the bottom of the seat and guided by the pin. The sensor ranges from 0 to 120 N showing a different resolution with respect to the applied loads. In Fig. 5 various curves obtained by different calibration tests are shown. In order to assess the effect of environmental conditions on the force sensors, an analysis about temperature dependence has been carried out. Response curves were gathered either at room temperature (22.5 Celsius) and at 45 Celsius (the maximum estimated operating temperature reachable by the prosthesis).

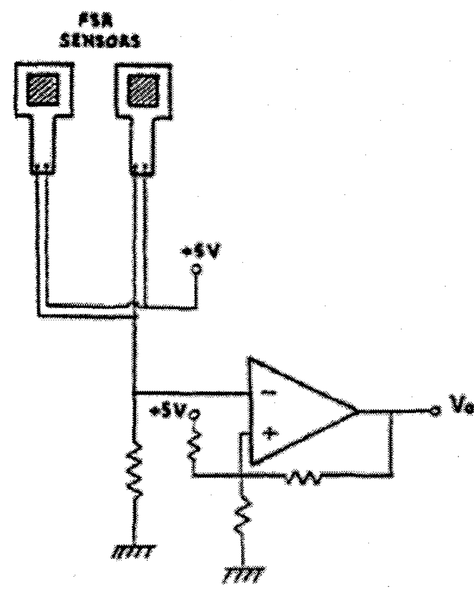

Figure 7: *Palm sensor electronic acquisition circuit*

3.2 Palm Sensor

Palm sensors are devoted to detect the contact occurring between the palmar regions of the prosthetic hand and the external grasped object. Information extracted from palm sensors are used by the MARCUS controller in order to select one of the two possible types of grip configurations the hand can perform. Due to its great sensitivity at incipient contact loads and small thickness, the FSR sensor, manufactured by the company Interlink Luxembourg has been selected as the palm sensor. The acquisition circuit, utilised for processing the sensor signals, consists in a voltage divider connected with the FSR and an appropriate resistor. The output signal is triggered with an hystheresis comparator, as depicted in Fig. 7.

3.3 Kinaesthetic Sensors

The function of kinaesthetic sensors is that of recording the joint rotation of the prosthetic hand in order to provide to the control system geometrical information about the grasping configuration. The main constraints for the design of the kinaesthetic sensors are the available volumes of the mechanical structure in which the sensors must be integrated. The addressed solution has been that of exploiting the Hall effect sensor technology which allowed the reduction of the overall volumes and the arrangement of the sensors. The approach followed to extend the linear region of the sensor output consists in appropriately combining the magnetic field generated by a defined arrangement of magnets in order to obtain an

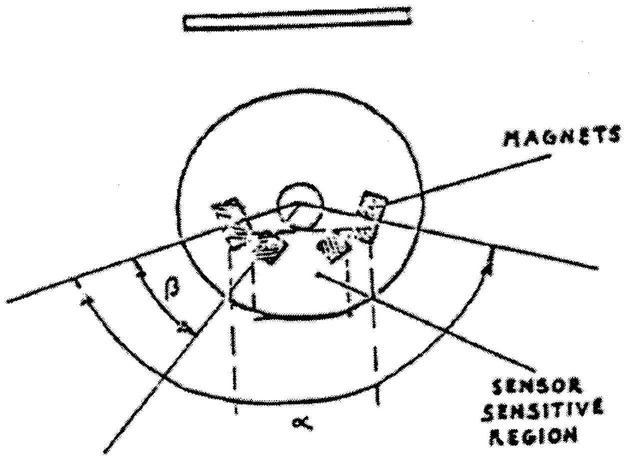

Figure 8: *Arrangement for the magnets of the kinaesthetic sensors*

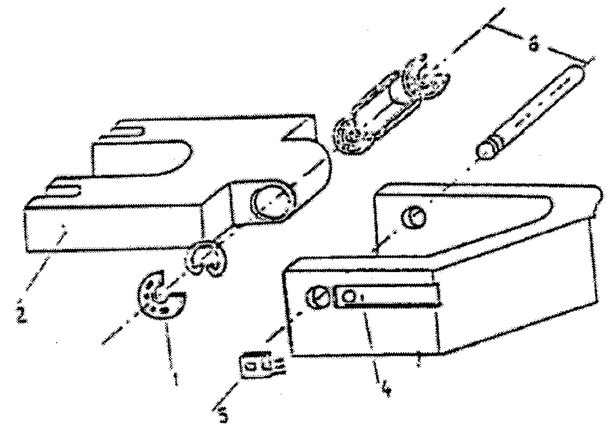

Figure 9: *Arrangement of the kinaesthetic sensors for coupled fingers*

overall linear response over the complete range of rotation. The geometrical arrangement of the sensors is depicted in Fig. 8.

In order to cover the maximum required measurement range of 120 degrees the optimal layout of the magnets has been studied by means of an analytical model. The arrangement of the kinaesthetic sensors for the coupled fingers is depicted in Fig. 9. The metal plate (1) is fixed to the first phalanx structure (2) of the coupled fingers and rotates with respect to the joint rotation axis (6). The Hall effect sensor (5) is fixed to the metacarpus phalangeal joint (4).

The behaviour of the sensor is satisfactory linear as can be seen in the plot of Fig. 10.

The kinaesthetic sensor of the thumb has been directly integrated into the irreversibility mechanism structure of the thumb. In particular, as depicted in Fig. 10, the Hall effect sensor (4) is located into the mechanical structure (2) supporting the gearbox (1) and connected to the fixed frame of the hand. In this version the metal plate is integrated in the circular structure (3) fixed to the gearbox shaft and supporting the cylinders (5) of the irreversibility mechanism. The Hall effect sensor (4) will detect the rotation movement of the thumb (8) through the transmission chain (7), (6), (5) and (3) of the irreversibility mechanism.

3.4 Slip Sensors

The slip sensors, developed by Oxford Otrhopaedic Engineering Centre and Technology Applications Group, are integrated at the fingertip level. A very small microphone is able to detect vibrations produced by the slippage of the object.

4. Conclusions

The result of the MARCUS project is a prosthetic hand controlled by the user through myoelectric sensors. The hand is equipped with position, force and slippage sensors through which a microprocessor automatically controls the interaction of the hand with the object. The control strategy allows to automatically increment the force on the grasped object if slippage conditions occur. The approach of the design of the thumb and the mechanical adjuster can be considered completely innovative. In fact traditional prostheses maintain the rotation axis of the thumb link parallel to the rotation axis of the fingers. Although the above solution has the undoubtely advantage to avoid components of the forces directed in a way to push the object outside the hollow formed by the fingers and palm, it confers to the hand a cosmetic compactness. The mechanical adjuster integrated into the structure of the MARCUS Hand gives intrinsic adaptability of the posture of the prosthesis to the grasped object. Clinical tests have been performed on sveral patients at the INAIL Prosthetic Centre in Budrio, Bologna, Italy and at the Oxford Orthopaedic Engineering Centre, UK.

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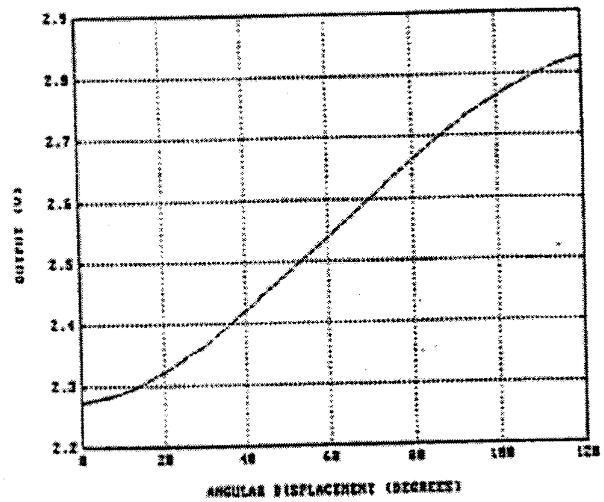

Figure 10: *Response of the kinaesthetic sensor manufactured for the MARCUS Hand*

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