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Design and Development of an Underactuated Prosthetic Hand

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Abstract -- **Current prosthetic hands are basically simple grippers with one or two degrees of freedom, which barely restore the capability of the thumb-index pinch. Although most amputees consider this performance as acceptable for usual tasks, there is ample room for improvement by exploiting recent progresses in mechatronic design and technology. This paper focus on an innovative approach for the design and development of prosthetic hands based on underactuated mechanisms, furthermore, it describes the development and a preliminary analysis of a first prototype of an underactuated prosthetic hand.**

Index Terms-- **Prosthetic hand, Underactuated mechanism, Differential mechanism.**

I. INTRODUCTION

The loss of his upper extremity has two different consequences for the amputee: a drastic reduction of the functionality (the amputee becomes unable to carry out most of the manipulation and grasping tasks) and the beginning of psychological trouble (the amputation modifies the cosmetic appearance of the upper extremity).

Despite of several research efforts aimed at innovating artificial hands technology, surveys on user's satisfaction in using prosthetic hands revealed that 30 to 50% of the upper extremity amputees do not use their prosthetic hand regularly [1,2].

The main factors that cause the loss of interest for myoelectric hand prostheses can be synthesized in three points [3]:

1. **Low functionality**; current prosthetic hands are simple grippers with one or two DOFs;
2. **Low cosmetic**; the lack of DOFs affects the grasping movement that results unnatural;
3. **Low controllability**; although advanced prostheses have been developed, the control of these devices requires a considerable training and a great attention during grasping activities (commercial prostheses are equipped with a limited set of sensors consequently feedback information to the user are poor and insufficient for a natural control).

This paper focuses on an innovative approach based on underactuated mechanisms able to solve the problems listed above and describes an experimental three fingered prosthesis, called RTR II, capable of adaptive grasp. Adaptive grasp is the ability of the fingers and thumb to adapt to the shape of the grasped object [4] in order to augment the contact points between hand and object. The adaptive grasp of the RTR II is passive and is based on an underactuated mechanism previously developed by S. Hirose [5]. The design and development of a three fingered underactuated prosthetic hand will also be described, including the kinematics analysis of an underactuated finger.

II. DESIGN APPROACH

A. Introduction

It is important to point out that prosthetic hands are designed primarily for grasping tasks and not for manipulative tasks; manipulation, in fact, requires: high dexterity, advanced sensors, complex control strategies and natural interfaces [6,7].

Although the research in the field of robotic hands has produced several sophisticated mechanical hands [8,9,10,11], some requirements are still not matched for two main reasons: the lack of a natural interface between the Peripheral Nervous System (PNS) and the artificial device [3] and the lack of light weight, compact actuators with high output torque [12].

Commercial hand prostheses have one or two DOFs providing finger movements and thumb opposition; due to the lack of DOFs, such devices are characterized by a low grasping functionality, in fact, they do not allow adequate encirclement of objects, in comparison with the adaptability of the human hand (see Fig. 1); as a result object must be grasped accurately to be held securely [4].

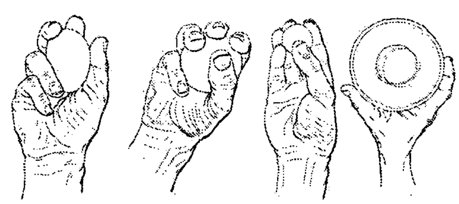

Fig. 1: Adaptability of the human hand

In conclusion, simple mechanical grippers, such as prosthetic hand devices, can lead to large grasping forces and are simple to implement and to control. However, they are not flexible and may easily lead to unstable grasps [6].

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B. Commercial Prostheses

In order to fit the myoelectric prostheses for different amputation levels, all the actuators have to be embedded in the hand structure (*intrinsic* actuation).

The *intrinsic* actuation choice combined with the use of traditional electro-magnetic actuators leads to an extreme reduction of available DOFs. Due to this, contact areas between fingers and grasped object are small, and thus high grip forces are required to succeed in the grasping task. In fact, the prosthetic device must rely on friction forces to maintain the object within the hand. The final consequence on the prosthetic hand design is that a stable grasp can be achieved only by means of large volume actuators, which must be able to supply enough force.

This approach produces artificial hands with a maximum of two DOFs, which are able to provide a pinch force of about 100 N; in this case, the motion of the phalanges is determined at the design stage and therefore no shape adaptation is possible [13].

These devices are simple and easy to build, but are not flexible enough to accommodate several objects.

As listed above, they present the following limitations: low functionality, low cosmetics and, due to sensory lack, low controllability.

One possible solution to raise the prostheses flexibility could be to use smaller actuators (micro-actuators), addressing the objective of increasing DOFs [3].

The design approach based on micro-actuators is quite far to offer a real alternative to standard design approach based on traditional electro-magnetic actuators. This is mainly due to the lack of high torque micro-actuators and the difficulty to implement complex control scheme with a natural interface, in order to control all the DOFs.

According to [14] the prosthesis has to perform a stable grasp with a wide variety of objects with complex shapes and to adopt simple control scheme.

In order to enhance prosthesis flexibility by keeping the *intrinsic* actuation solution, and implementing simple control algorithm we present an innovative design approach based on underactuated mechanisms.

III. UNDERACTUATED MECHANICAL HANDS

A. Introduction

A mechanism is said to be underactuated when it has less actuators than degrees of freedom; traditional actuators (i.e. electro-magnetic motors) are replaced with passive elastic elements and mechanical stops. These elements can be considered as passive actuators, which cannot be controlled. They are small and simple and lead to a reduction of the number of DOFs.

When applied to mechanical hands, the underactuated mechanisms, lead to an *adaptive* grasp. Underactuated mechanisms allow the grasping of an object in a way that is closer to the human grasping than independent actuation [15].

B. Differential Mechanisms

The differential mechanism is the basis of an underactuated mechanism. Differential mechanism is a mechanism in which the amount of dynamical input from three ports acts in balance [12]. Fundamental examples of differential mechanism are shown in Fig. 2.

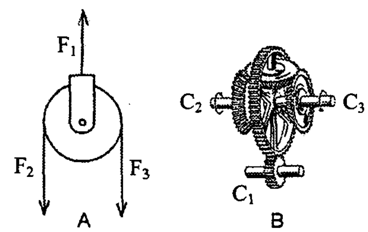

Fig. 2: Differential mechanisms: (A) movable pulley, (B) differential gear mechanism

These differential mechanisms can control multiple DOFs with a single actuator by combining it with elastic elements and mechanical stops; consequently, they are the main component of an underactuated mechanism.

C. Underactuated Mechanical Hands

The literature shows two different types of underactuated hands depending on the transmission system: underactuated hands based on tendon transmission [16,17] and underactuated hands based on link transmission [18,19,20]; tendon systems are generally adopted in order to minimize transmission dimensions but are limited to small grasping forces, while link systems are preferred for applications in which large grasping forces are required.

This class of mechanical hands has been developed for industrial and space applications in order to augment the flexibility, without raising the mechanical complexity and their adoption in the prosthetic field is not suitable due to size and weight restrictions and to reliability requirements. These devices and their underactuated mechanisms are, in fact, too complex and too bulky compared to a prosthetic hand.

A few underactuated passive (body-powered) prosthetic hands have been proposed [21,22]; in these references, however, the concept of underactuation is not analyzed in depth. In [4] an example of underactuated active (myoelectric) hand is presented. This device allows an adaptive grasping but only adaptation between fingers has been realized and no adaptation between phalanxes has been considered.

The RTR II hand has been created in an attempt to increase passive shape adaptation by addressing the problem of inter-phalanges adaptation.

IV. DESIGN AND DEVELOPMENT

A. Introduction

The design approach based on underactuated mechanisms allows reproducing most of the grasping behaviors of the human hand without augmenting the mechanical and the control complexity.

In general, for an underactuated hand, the correct choice of the characteristic of the elastic elements and the correct placing of the mechanical stops allows a natural wrapping movement of the finger around the object. In order to achieve a correct finger movement the object should touch first the proximal phalanx (B), then the middle (C) and finally the distal phalanx (D) (see Fig. 3) [21].

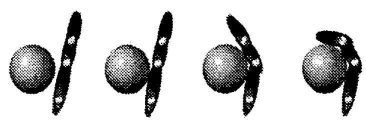

Fig. 3: Natural finger movement

During the grasping task the geometrical configuration of the finger is always determined by the external constraints related to the geometric characteristics of the object and the active coordination of the phalanges is not necessary. It is important to note that the sequence (A-D) showed in Fig. 3 could occur with the continuous action of only one actuator. The underactuated prosthetic devices can perform an automatic finger wrapping around the object without the amputee intervention.

In this framework a first prototype of an underactuated prosthetic hand has been developed. The hand has three fingers: the middle, the index and the thumb. Underactuated mechanisms based on the Soft Gripper, proposed by Shigeo Hirose, have been applied to both fingers and thumb. The Soft Gripper model (see Fig. 4) has been developed in order to softly and gently conform the objects of any shape. It consists of N links (phalanges), which rotate freely about N axes. A pulley is fitted at each axis. The pulleys are coaxial to the axes and rotate freely about them. A wire runs from the tip to the root of the mechanism taking one turn about each pulley. N springs are fitted around each axes and iper-extension is prevented by N mechanical stops [5].

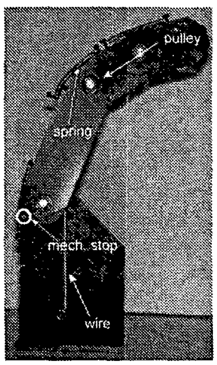

Fig. 4: Soft Gripper model

The force applied on the wire generates a moment in correspondence with each axis. These moments are proportional to the radius of the pulleys. The model in Fig. 4 guarantees an adaptive behavior of the phalanges with respect to the grasped object, has three DOFs and is actuated by a single wire. It is possible to vary the force distribution on the grasped object and the kinematic behavior of the phalanges, setting the pulley diameters and the spring stiffness.

The RTR II adopts this model for the index, middle and the thumb. The hand has two motors (see Fig. 5): motor A for the flexion and extension movements of all the fingers and the thumb and motor B for the adduction and abduction movements of the thumb.

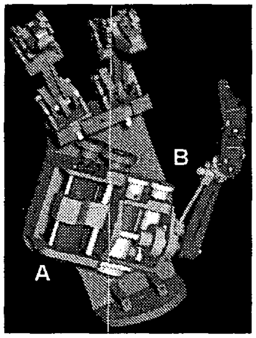

Fig. 5: Solid model of the prosthetic hand

In the next paragraphs the main components of the RTR II will be analyzed in depth.

B. Finger design

Index and middle are identical, both fingers have three phalanges (see Fig. 6). Pulley radii have been chosen in order to guarantee the static equilibrium during terminal grasps (involving only the distal phalanges). Pulleys can be easily changed in order to vary the kinematics behavior of the finger (see IV.E).

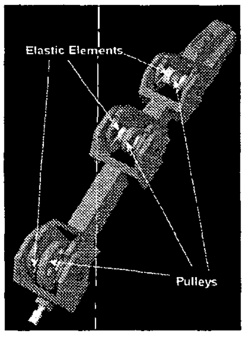

Fig. 6: Index/middle finger model

The wire, fitted around every pulley, generates the flexion movement; the extension movement is realized by torsion springs.

The two wires (respectively index and middle finger wires) are connected to the motor by means of an adaptive grasp mechanism based on a linear slider and two compression springs (see IV.C), the slider is connected to the motor through a leadscrew transmission.

C. Adaptive grasp mechanism design

In order to perform an adaptive grasp between the fingers, an adaptive grasp system has been designed. The system is based on compression springs: both finger wires are connected to a linear slider, through two compression springs (see Fig. 7). During a general grasp, index and middle fingers may not come in contact with the grasped object at the same time, one of the fingers and the thumb will come into contact first. When this occurs, in a conventional prosthesis, the other finger will no longer be able to reach the object to improve the grasp stability. Thank to the adoption of the compression springs this problem can be solved: when the first finger (e.g. middle finger) comes in contact with the object, the relative spring starts to compress, the slider is now free to continue its motion and the second (e.g. index finger) can flex, reaching the object.

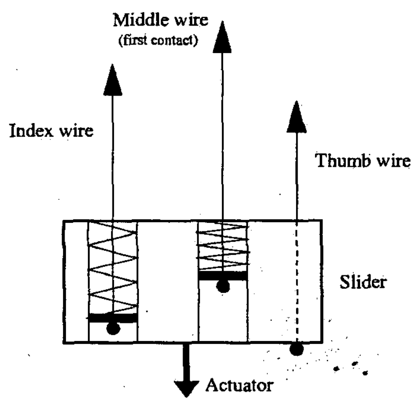

Fig. 7: Adaptive grasp mechanism schematization

When high forces are required, compression springs behave as a rigid link and all force is transmitted from the slider to the fingers. Note that the thumb wire is directly connected to the linear slider; this is the main advantage of using compression springs instead of extension spring.

D. Thumb design

The thumb has two phalanges, it is able to flex and extent using the soft gripper mechanism (see IV.A), the thumb wire is directly connected to the linear slider; it is also able to adduct and abduct; see Fig. 8 for the complete thumb assembly.

The adduction and abduction movements are realized by means of a four bar link mechanism. The four bar link has been introduced in order to mimic the adduction and abduction movements of the human thumb, varying the rotational axis of the thumb during its movement. By designing the thumb able to adduct and abduct, the hand can perform more grasping patterns, increasing the prosthesis flexibility [4].

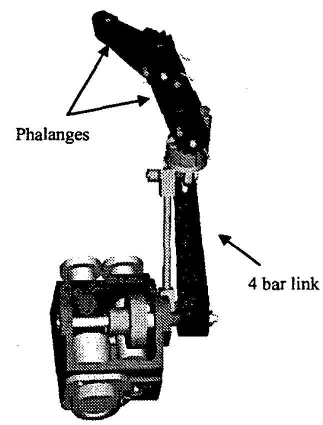

Fig. 8: Thumb model

E. Finger kinematics

We started the kinematics analysis considering one finger (e.g. index finger) as in fig. 4 and we analyzed the reaching phase of the object; only unconstrained movements of the finger are considered.

Our goal is to find the relation between the angular position of the motor θ_m and the angular position of every phalanx θ_i with i=1,2,3. Due to the finger design, the wire position y_s is related to the actuator angular position θ_m through the relation:

$$y_s = \frac{\theta_m p}{\tau_m} + c \qquad eq.(1)$$

where:

p = pitch of the lead screw transmission of the slider
τ_m = gear ratio of the motor
c = constant related to system geometry and wire length

Note that the presence of the compression spring for the adaptive mechanism is neglected in this model.

Starting from the wire inextensibility and from the following condition:

$$T \geq 0 \qquad eq.(2)$$

where T is the cable tension; the kinematics relation can be written as:

$$\begin{aligned} \theta_3 &= c_0 + c_1\theta_1 + c_2\theta_2 + c_3 y_s \\ \dot{\theta}_3 &= c_1\dot{\theta}_1 + c_2\dot{\theta}_2 + c_3\dot{y}_s \\ \ddot{\theta}_3 &= c_1\ddot{\theta}_1 + c_2\ddot{\theta}_2 + c_3\ddot{y}_s \end{aligned} \qquad eq.\ (3)$$

with c_1, c_2, c_3 constants related to system geometry and wire length.

To solve the kinematics problem and predict the movement of the unconstrained finger we need two more relations. These two equations can be found solving the finger dynamic.

F. Finger dynamic model

In order to evaluate the finger dynamic behavior during the reaching phase to the object, a bidimensional mathematical model has been developed. The model input is the wire position while the model outputs are the wire tension and the motion law of the lagrangian coordinates.

The finger model consists of three links; the geometric and inertial characteristics are computed starting from the solid model shown in Fig. 6. The inertial effects due to the pulleys, the pins and the torsional springs are neglected. The wire is supposed to be inextensible and all the friction and gravity effects are neglected.

The dynamic equations can be written starting from the Lagrangian formulation (see eq. (4)).

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_r}\right)-\frac{\partial L}{\partial q_r}=F_r \qquad r=1,2,\dots n \qquad eq.\ (4)$$

where:

L = $E - U$

and

E = kinetic energy of the system
U = potential energy of the system
q_r = Lagrangian coordinate
F_r = generalized force associated with q_r
n = number of DOFs of the system

In this model n = 3 and the lagrangian coordinates are θ_1, θ_2 and y_s which represents the slider position (see Fig. 9). θ_3 is a linear function of previous coordinates. This function is reported in eq. (3).

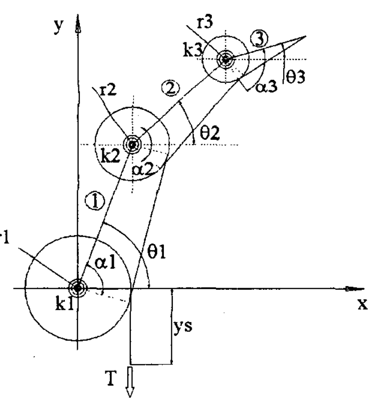

Fig. 9: Finger schematization

Assigning:

<u>geometrical variables:</u>

l_1, l_2, l_3 = link length
dg_1, dg_2, dg_3 = C.G. position

<u>inertial variables:</u>

m_1, m_2, m_3 = link mass
I_{O1} = moment of inertia of the link 1 with respect to the origin
I_{G2}, I_{G3} = moment of inertia of links 2, 3 with respect to C.G.

<u>elastic variables:</u>

k_1, k_2, k_3 = stiffness spring constant

and writing the Lagrangian equations we obtain a highly non linear second order system with these variables: θ_1, θ_2 and T.

The input is $y_s(t)$ while the outputs are $\theta_1(t)$, $\theta_2(t)$ and $T(t)$. The system non linearity arises from the kinetic and potential energy expressions (see eq. (5) and eq. (6)).

$$E=\frac{1}{2}A_1\dot{\theta}_1^2+\frac{1}{2}A_2\dot{\theta}_2^2+\frac{1}{2}A_3\dot{\theta}_3^2+ A_4\dot{\theta}_1\dot{\theta}_2\cos(\theta_1-\theta_2)+A_5\dot{\theta}_2\dot{\theta}_3\cos(\theta_2-\theta_3)+ A_6\dot{\theta}_1\dot{\theta}_3\cos(\theta_1-\theta_3) \qquad eq.(5)$$

where:

$$A_1=I_{O_1}+m_2l_1^2+m_3l_1^2$$
$$A_2=I_{G_2}+m_3l_2^2+m_2d_{G_2}^2$$
$$A_3=I_{G_3}+m_3d_{G_3}^2$$
$$A_4=m_2l_1d_{G_2}+m_3l_1l_2$$
$$A_5=m_3l_2d_{G_3}$$
$$A_6=m_3l_1d_{G_3}$$

$$U=\frac{1}{2}k_1\left(\frac{\pi}{2}-\theta_1\right)^2+\frac{1}{2}k_2(\theta_1-\theta_2)^2+ \frac{1}{2}k_3(\theta_2-\theta_3)^2 \qquad eq.\ (6)$$

θ_3 has been replaced with the kinematic equation shown in eq. (3), which represents the holonomic constraints of the finger model.

The system (see Fig. 10) solution has been achieved using the SIMULINK package associated with MATLAB™.

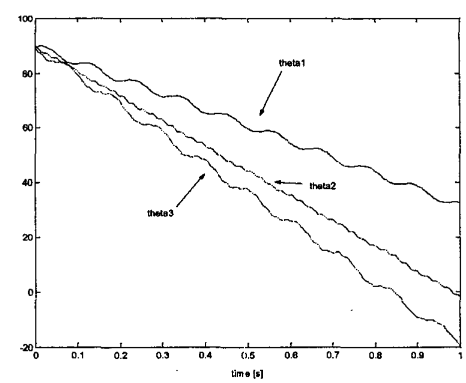

Fig. 10: Angular position of the three phalanxes (linear input: $y_s(t) = 138.45 + 10\,t$)

Pulley radii and spring stiffness affect the dynamic behavior of the finger model. So, this tool can be useful to define these parameters in order to mimic the human finger movements.

According to the results showed above, the finger bends, tracking the linear movement of the slider, with little vibrations whose amplitude depends on the link inertia.

G. Prosthesis Development

Following the design principle described above, a first prototype of an underactuated hand based on the Soft Finger model has been designed and fabricated (see Fig. 11).

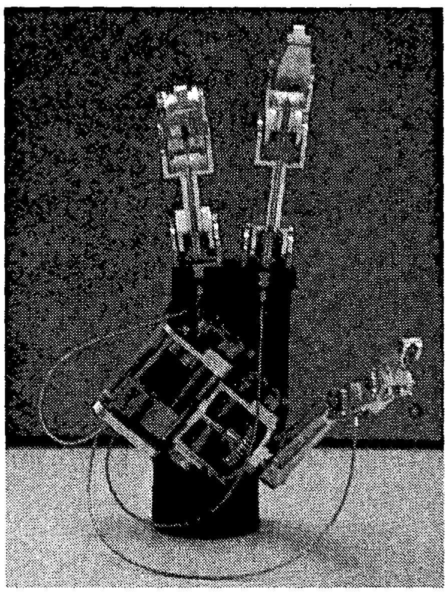

Fig. 11: The RTR II prosthetic hand

V. CONCLUSIONS

The design approach based on underactuated mechanism has been proposed and applied to the prosthetic field with the aim of rising the prosthesis flexibility maintaining the intrinsic actuation solution and implementing simple control algorithm. The proposed dynamic model represents a useful tool for simulating the expected grasping capabilities. Suitable control strategies will be investigated in order to develop a user-friendly control interface for the prosthetic hand.

Finally, it is important to note that the tendon transmission structure applied in the RTR II hand is observed with human finger. In the human hand the *flexor digitorum profundus* acts in the same way as the wire transmission in the Soft Gripper [23].

VI. ACKNOWLEDGEMENTS

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