Control strategies for tendon driven devices

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ABSTRACT

The aim of this work has been to individuate and to propose solutions concerning the control of device oriented to fine manipulation tasks.

References for this work are, mainly, antropomorphic robot hands, robots and probes for surgery applications, where it is necessary a remote system driver, because of the reduced dimensions.

A typical transmission loop for robotic hands, developed by complex systems of tendons and pulleys, often introduces some problems such as friction phenomena, elasticity and positioning precision.

The low level control aspects, concerning the interaction between the system and the manipulated objects, will be considered, neglecting the kinematics aspects.

In particular, some kind of sensors which we are using are going to be shown. It is taking in account a sixteen degrees of freedom robotic hand, developed at the Department of Communication, Computer and System Science of the University of Genoa.

1. INTRODUCTION

A simple kinematic approach to the problem of fine manipulation of objects is not able to totally guarantee the achieving of the fixed task.

Phenomena such as the object compliance, slippage, wrong calibration of the manipulator, can conduce to a bad performance of the system.

It suggests to use some kind of sensors, in order to get the most important information between the interaction of the system and the external world, and the information concerning the system state.

In section 2, a description of the manipulator is shown; in section 3, the approach used in order to estimate the system state is described; in section 4, possible control schemes are shown, such as the intrisic torque sensor; finally, a tactile sensor based on conductive rubber is described in the section 5.

2. EXPERIMENTAL SET-UP

In this section the hardware and software architecture used to implement the real-time control system is described.

The DIST-hand dextrous gripper is shown in Figure 1.

DIST-hand is a *4-fingered* tendon-driven device with *16* degrees of freedom, designed for experiments in the area of grasping control, and manipulation [1], [2].

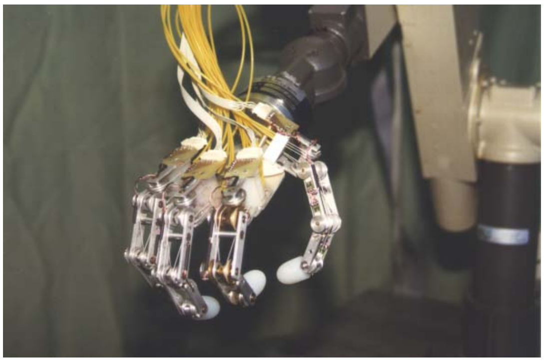

Figure 1: DIST-Hand Robot

The basic element of the DIST-hand is a *4* degrees of freedom finger.

The finger dimensions are close to that of a human one.

Each joint has a range of rotation which is larger than 90*deg* and is equivalent to that of a human hand.

The first two joints of the finger have orthogonal axes.

In particular, the first axis allows to rotate the *distal* plane (i.e. the plane which "contains" the finger).

The distal plane is orthogonal to the axes of joints 2,3,4 and is a plane of symmetry for the finger.

The distance between the first two axes has been kept as small as possible, in order to better emulate the *ball and socket* joint of the human hand.

Each finger is actuated by 6 tendons, routed through pulleys and driven by 5 DC motors.

In particular, tendons 5 and 6 drive the first joint; they are actuated by a single motor and are passively pre-tensioned.

The other 4 tendons are, instead, independently controlled by the remaining motors used to drive the last 3 joints.

The mapping between tendon tensions $\mathbf{f}$ and resultant joint torques τ is expressed by the following linear equation

$$\tau = \mathbf{A}^t \mathbf{f} \tag{1}$$

where $\mathbf{A}$ is called *structure matrix*.

It is a constant matrix, and its entries are the radii of the pulleys, through which each tendon is routed in order to generate any desired joint torque.

The relationship between motor angles **α** and displacement of the tendons **x** is expressed by the following equation

$$\Delta \mathbf{x} = \mathbf{B}\, \Delta \alpha \qquad \textbf{(2)}$$

where the entries of matrix B are the radii of the pulleys mounted on the motors.

Combining the above relationships, the mapping between joint angles **q** and motor angles **α** is

$$\mathbf{q} = \mathbf{A}^{\#}\mathbf{B}\alpha \qquad \textbf{(3)}$$

We have developed rotation sensors mounted on each joint.

Using these sensors it is possible to implement servo loops around the perturbations due to the elasticity and partly to friction. The sensor is based on the use of a solid state Hall effect transducer. The sensor is shown in figure 2.

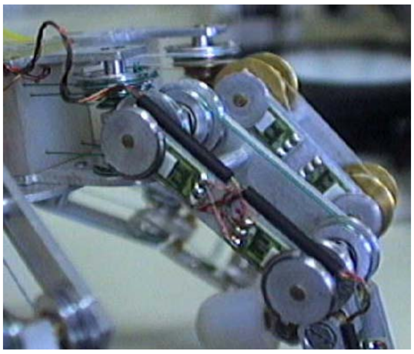

Figure 2: Hall effect sensor

The sensor is contactless; therefore, it does not affect the motion of the joints.

Furthermore, it has a significant immunity to noise, with respect to other transducers of comparable size.

The control hardware which has been adopted is VME based and it includes two Motorola 68040 based CPU boards and four IP modules for I/O purposes.

The *piggy-back* modules are two IP Precision ADC (sampling both hall sensors and potentiometers) and two DENSE-DAC (sending torque commands to the various motors).

The Simulink and Real Time Workshop MATLAB's Toolboxes, jointly with the Wind River's TORNADO development environment, have been used to design and implement the real-time controllers [3].

3. INTERNAL STATE ESTIMATION

The following statements about the tendon-driven devices usually hold true, for the system we are dealing with:

- There is a tendon tension vector **f** that is able to produce, for each joint, a required torque vector **c** (Caratheodory theorem).

- A desired tension can be applied to each tendon (One motor for one tendon).

For the sake of simplicity, we can consider the simple scheme in figure 3: it is a one degree of freedom device where the previous hypotheses are satisfied. If we apply a displacement vector **α**, such that the following equation is satisfied

$$r \cdot k_1 \cdot r_1 \cdot \alpha_1 = r \cdot k_2 \cdot r_2 \cdot \alpha_2 \qquad \textbf{(4)}$$

the motor motions do not affect the joint positions though they modify the tendon tension vector f, as well as the system internal state.

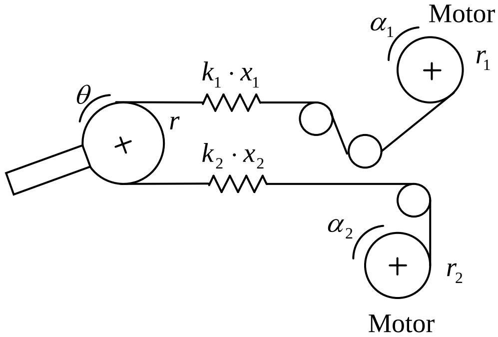

Figure 3: Tendon driven device

We can deal with the DIST–Hand to describe how a real-time monitoring of the manipulator state can be handled.

The transmission system tendon-sheath can be modeled as a spring with a known elastic constant K.

Otherwise, it is possible to demonstrate that, in general, only the applied force-tendon extension ratio is needed even if it is not linear.

The absolute joint and motor positions are required at each time instant; in the DIST-Hand, they are provided, respectively, by the hall-effect sensors and by the potentiometers mounted on the motor axes.

We can obtain an estimated measure of the required vector **f** using the scheme in figure 4.

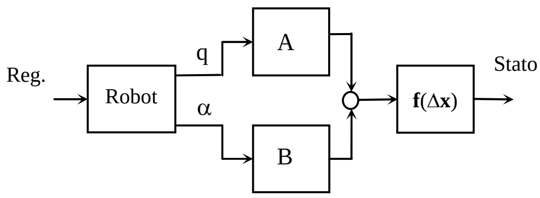

Figure 4: Internal state estimator

In the following section, we will describe how this information can be used for the design of control schemes, in order to implement the grasping and manipulation tasks.

4. DESIGN OF CONTROL SCHEMES

There is a variety of operations that a gripper should be able to carry out, and the actions of the control system may vary according to the tasks the manipulator has to carry out.

During the inspection of an object or a surface, for instance, the robot’s finger, acting as a probe, should show compliant behavior. In that way it is able to follow the uneveness and retrieve information about the object under consideration.

However, in order to control the grasping force, it is necessary to act on the rigidity of the system.

The contrary holds true in the case of an unconstrained movement, i.e. without physical interactions with external objects: minimizing the tensions applied to the tendons allows to reduce to a minimum the problems related to internal frictions.

In the latter case, it has to be noted that the effect on the control deriving from the monitoring of the internal tensions cannot be reproduced by means of *exterioceptive* sensors.

In the follows, we will analyze the control schemes that are capable to provide the robot with some of the aforementioned characteristics.

Imposing that the length of the tendons be constant at every time instant, leads to realize a control scheme which tries to eliminate the variations of the internal tensions with respect to the idle position.

Consequently, the system would show no reaction to external solicitations, rendering it perfectly compliant.

The control scheme that implements this *active compliance* is shown in figure 5.

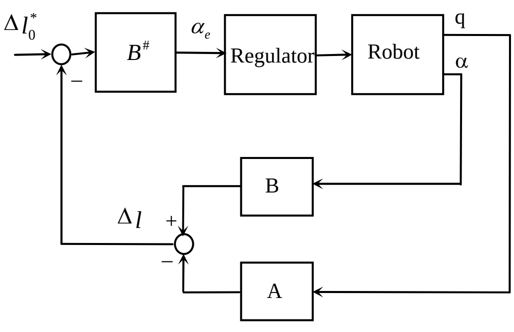

Figure 5: The active compliance control scheme

It is worth to note that, by not allowing the tendons to relax too much, the control scheme proposed above prevents the tendons from coming off the pulleys.

The behavior opposite to that considered so far, consists in improving the grasp by stiffening the fingers.

In this way, it is not necessary to tighten the grasp by means of higher grasping forces, but simply by increasing some of the tendon tensions in order to stiffen the system with regard to the external solicitations.

This option can be especially useful when manipulating particularly fragile objects; the strategy to be employed, in this case, is that one proposed at the beginning of this section.

Equation 3 demonstrates the kinematic relationship between the angular joint displacements and the corresponding motor displacements.

In the system considered here, the matrix $A^\# B$ is rectangular with **n** rows (where n represents the degree of freedom of the kinematic chain), and at least **n+1** columns (Caratheodory theorem).

Imposing a displacement vector on the motors α_n such that:

$$\alpha_n \in \ker(A^\# B) \quad \textbf{(5)}$$

the tendon tensions can increase without generating joint displacements.

Thus, the finger of the hand is stiffened while maintaining the initial posture.

Figure 6 shows the control scheme implemented by us for this experiment.

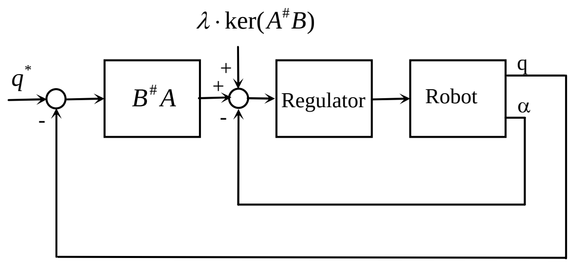

Figure 6: The stiffness control scheme

The external loop realizes the control of the joint positions, while the inner loop regulates the manipulator’s stiffness.

By means of the control scheme of figure 4, the effective tension imposed on the tendons can be monitored; this is done with the help of the tensioning term $\lambda \cdot \ker(A^\# B)$ where λ is a constant.

The control methodology based on the estimation of the internal system’s state offers a further interesting application: the opportunity to implement the control of the joint torques.

To do so, it is necessary to know the relationship between the elongation of the sheath-tendon system Δx and the force f applied to the tendon itself.

Such relationship strongly depends on the materials employed for the actuation system.

In our case, the sheath consists of a plastic ∅2mm-pipe and the tendons are made of a ∅0.8mm-polyester yarn plaited of multiple fibers.

The corresponding characteristic curve is of the kind of that depicted in figure 7.

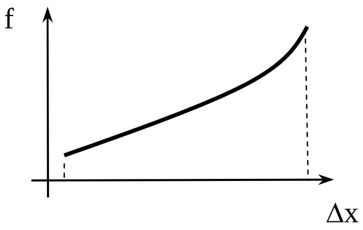

Figure 7: Force-extension characteristic

Such a curve gives *f(Δx),* which enables us to obtain the force applied to the tendons.

In figure 8, the control scheme for the joint torques is represented.

From such a scheme, the entity of the joint torques, applied to every joint of the hand, can be extracted.

That is why we have called this scheme intrinsic torque sensor.

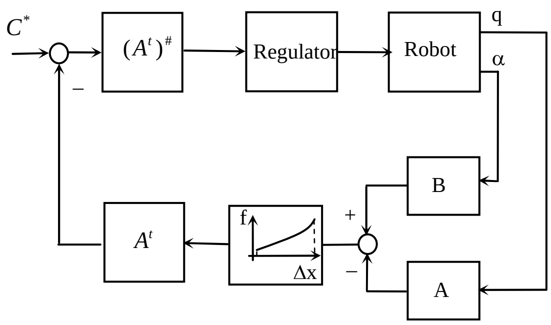

Figure 8: The torque control scheme

Having analyzed the *proprioceptive* part of our sensorial system, in the following is described the tactile sensor based on conductive rubber.

5. TACTILE SENSOR

The use of conductive rubber, in order to build tactile sensors, represents a good economic and versatile technology [4][5].

Moreover, the mechanical features, such as the compliance, make it able to be a good cover of the finger-tips [6].

This kind of silicone rubber are made of a *doped* silicon rubber, mixed with silver and graphite.

The final product shows a little resistivity variation related with a pressure; but it shows an important variation of the contact resistance depending on the applied force.

In figure 9 the tactile sensor developed is shown.

All the measurements are related to a single rubber-covered electrode.

In the common set-up, every *tactel* is at the crossing between a raw and a column; in our case, an electric coupling is not present.

This allows to make an acquisition of the whole image of the sensor in the *one-shot* mode; from the other hand, in this case the number of connections rise from *n* to *n+1* (where *n* is the number of tactels).

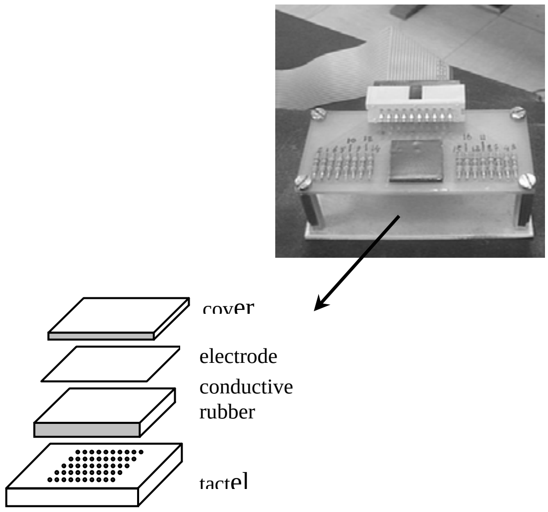

Figure 9: Conductive rubber based sensor

At this point, it seems necessary to spend some words about the main technique of data acquisition coming from a tactile sensor.

Vision systems based on artificial retina have a strong analogy with tactile sensors; this is true both from the hardware point of view, and from the data processing point of view.

Nowadays, a larger and larger number of analog circuits, able to convert luminous signals in electric signals, are developed with the VLSI techniques[7][8].

In figure 10, the scheme of the Silicon Retina designed by Kwabena Boahen [9] is shown.

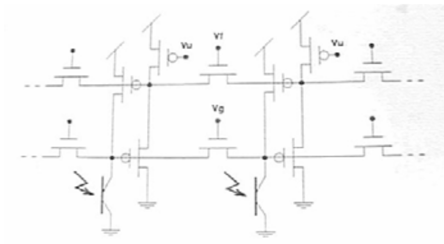

Figure 10: Silicon retina

This kind of devices allow to analyze the luminosity value in terms of pixel level, with respect to the standard approach.

It has been used an analog circuit, and the operations were performed totally in a parallel way; the images can be locally processed in real time, on the same chip which manages the acquisition task.

This leads to re-define the design of the same scheme, by replacing the *photosensitive* elements (pixel) with the *piezoresistive* elements (tactels).

In this way, it becomes a tactile sensor, which is able to faster acquire tactile images.

This solution provides the local data acquisition and processing; the problem of the greater number of wires is not very important in this case.

Indeed, the high speed of the whole sensor scanning is the most important feature.

Talking about the sensor, some tests have been performed in order to rebuild the tactile image; the results are shown in figure 11.

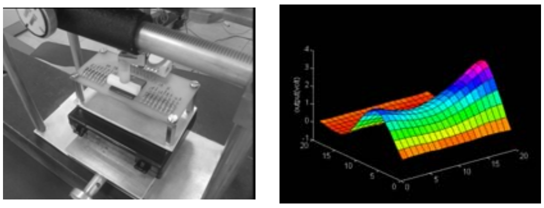

Figure 11: Shape recognition

A very interesting aspect of the conductive rubber is connected to the variations of his resistivity.

Even if the variation of the contact resistance is ,of course, the main effect, the second one shows an interesting feature, as depicted in figure 12.

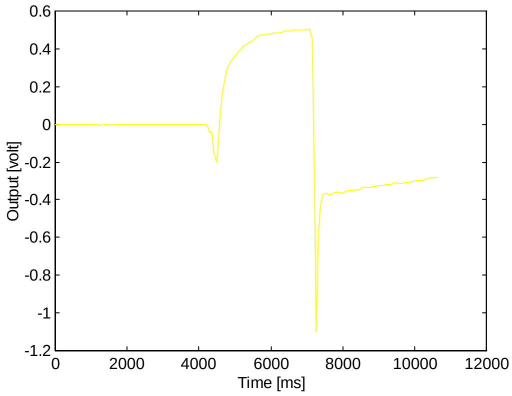

Figure 12: Pulse stimulus (2.5 sec)

By applying a costant force for a small time (in this case, about 2.5*sec*) two spikes can be seen, corresponding with the start and the end of the applied force, in addition to the decreasing of the resistance detected by the increasing of the voltage amplitude.

In particular, a 100*ms* spike can be always detected in the presence of any kind of external force disturbance.

It depends on the increasing of the resistivity. The analysis of the structure of the conductive rubber can help us to understand this phenomena.

The bond between the silicon rubber and the dopant (graphite) is a physical bond. It means that the graphite particles are not chemically bonded with the rubber ones, but they are embedded in the rubber, as shown in figure 13.

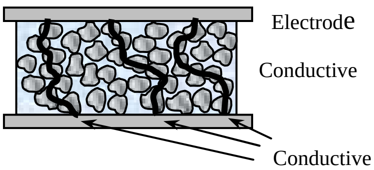

Figure 13: Conductive rubber

In the *idle* condition, a resistance R_0 is present between the electrodes applied on the rubber, through a number of *conductive paths*.

Any kind of mechanical perturbation, connected to an impact on the sensor structure, will induce vibrations which will interrupt some conductive paths, as shown in figure 14.

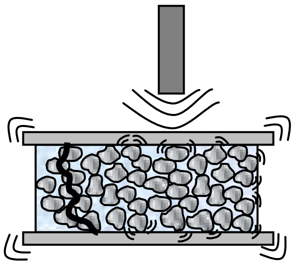

Figure 14: System submitted to vibrations

By this way, the resistance R_0 increases rapidly; as the transitory time is finished, the system elasticity will tend to restore the idle condition, and the resistance will back to the R_0 value.

This hypothesis has been confirmed by making a macro model of the rubber-graphite system; as shown in figure 15, some micro-spheres have been embedded inside an elastic membrane (the last one emulates the holding effect of the silicon rubber).

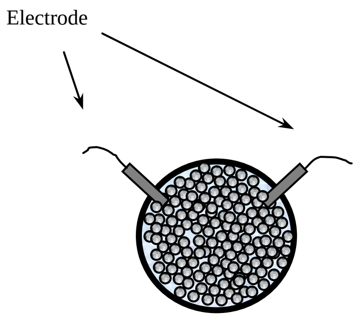

Figure 15: Macro model

By perturbing the system, the same spike detected in the presence of the conductive rubber is revealed by the electrodes (figure 16, on the next page).

If weak forces are applied, the spike is still present; a sequence of micro-impacts generates a sequence of spikes easy to detect; so, it could be used as contact trigger signal.

Some vibrations (such a sequence of micro-impacts) are induced in a scraping body; this is true because of the *catch-snap* phenomena [10][11], which happens during the slippage of a elastic material on rough surface.

This kind of vibrations are strictly connected to the surface features of the material under investigation, and they could be detected by the sensor.

The vibration will generate a dense sequence of spikes.

6. CONCLUSIONS

An effective controller for the DIST-Hand robot has been designed and implemented. Moreover, various solutions for the control of tendon driven devices have been introduced.

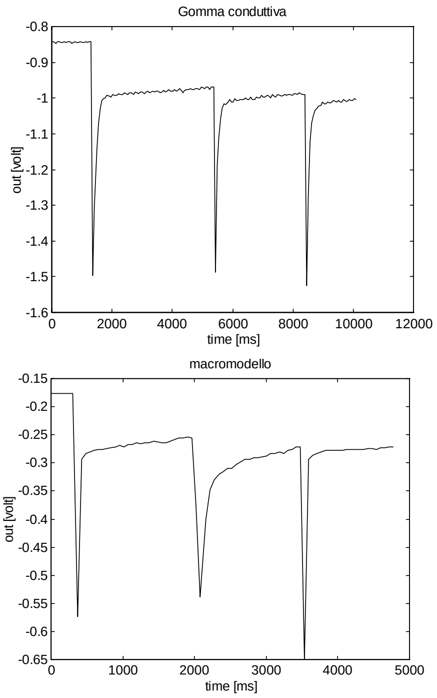

Figure 16: Comparison between Conductive rubber (Top) and Macro model (Bottom).

Further improvements will concern the integration between tactile sensors and the robotic hand; their use will allow the execution of fine manipulation tasks.

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