Whole-Hand Manipulation: Design of an Articulated Hand Exploiting All Its Parts to Increase Dexterity

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Abstract

It is a common observation that the human hand performs various manipulation tasks using not only its fingertips, but all the surfaces available for contact, i.e. intermediate phalanges and the palm. In the first part of this paper some such whole-hand operations are discussed, relating to different domains of fine manipulation such as grasping, exploration and micro-motion of objects.

The design guide-lines deduced by the analysis of whole-hand manipulation operations in humans are outdrawn in order to reproduce a similar behaviour in a robotic hand: requirements on mechanical architecture (to provide proper surface conformation and opposition of hand elements) and on sensory equipment (to allow the synthesis of satisfactory control procedures) result from this analysis.

A second part of the paper describes how these issues can be implemented in the version II U.B. Hand, currently under development. The propensity of version I kinematic architecture to whole-hand manipulation is exploited by integrating in the mechanical structure purposely designed force/torque sensors, according to the intrinsic tactile sensing concept: the external surface of each phalange in the fingers and that of the palm thus become integral parts of as many sensing devices.

The final part of the paper provides preliminary suggestions on how to use the proposed hand to perform some tasks requiring whole-hand manipulation.

Introduction

It can be observed, in many robotic applications, that the potential functionality of existing robotic devices is seldom fully exploited, often due to limitations in sensory equipment or control procedures, but sometimes also to limits in their original conception.

As an example, most present robots are designed to interact with the environment through their end-effector, thus limiting the range of possible operations and objects the robot can deal with; the *whole arm manipulation* concept, involving the use of most parts of the robot arm to accomplish an enlarged set of tasks, was only recently proposed by [Salisbury,87], and preliminary applications are being presently demonstrated.

In the field of articulated robot hands, the one this paper is concerned with, a parallel can be easily drawn with the above example: most present robot hands are designed (or at least are used as if designed) for manipulating objects using only their fingertips, while the human hand performs various manipulation tasks using all the surfaces available for contact, i.e.

fingertips, intermediate phalanges and the palm. This results in more powerful grasps, finer control of object motion, or better sensory information, which leads to enhanced dexterity of the hand.

In practice, the performances of some articulated hands, in spite of their complex and expensive multi-dof mechanical structure, are not so far from those of simpler and cheaper grippers. It is authors' opinion that some design criteria need to be revised in view of more effective mechanical and sensory equipment integration and that useful results can be obtained if the means for full exploitation of hand elements are provided in the design phase.

Borrowing the term from Salisbury, by *whole hand manipulation* (WHM) we mean that all the links of the multi-D.O.F. kinematic chain of the hand can be used to contact and sense the object. As in the whole arm manipulation case, the WHM concept has been derived from observation of a biological system, the human hand, but design solutions are not necessarily anthropomorphic.

The goal of the work reported in this paper is to realize an artificial hand that can perform some WHM operations. In order to do this, three main aspects have to be developed: i) the hand design must allow for suitable kinematics, ensuring proper mobility and opposability of hand's elements; ii) sensors must be integrated in all the parts of the hand that are used to contact manipulated objects, and iii) sensory control methods have to be developed to guarantee the necessary degrees of flexibility and adaptability to unpredictable environments. Although the main stress of the paper is on the design of the mechanical and sensory components, other aspects of the project will be addressed.

The implementation of the concepts discussed in this paper is being currently carried out: a prototype finger, suitable for whole hand manipulation, has been built and is described in this report. Previous experience with designing and testing the version 1 UB Hand, providing the basis for the mechanical arrangement of the newly proposed one, will be also briefly explained.

Examples of whole hand manipulation in human activity

The functionality of the human hand has been widely investigated in its various aspects; [Schlesinger,1919] [Keller,1947] [Tubiana,1981]; it is however intuitive to verify how *frequently each part of the hand (the palm, the phalanges and the fingertips) gets into contact* with the objects. In the following, some cases of human whole hand manipulation are commented on in order to extract suggestions for robotic hand design.

The first example (see Fig. 1a,b,c,d) refers to a typical pick and place task for objects of similar shape (a rectangular prism) but different size and mass. Different grasp configurations, each one involving more contacts of larger area, are used by the human hand in order to improve stability.

Fig. 1 Four grasps with different extension of contact surface

The progressive involvement of further structural elements of the hand (the inner phalanges and the palm) leads to increased strength of the grasp against the weight of the body being lifted .

The second example relates to a task which requires a "power grasp" of a tool in a constraining environment. The tool must be initially grasped in a configuration which is compatible with the constraints (the hammer is lying on a plane), and then moved inside the hand towards a final grasp configuration which is suitable for the task accomplishment. This case is very common when operating in an unstructured environment, where many objects have limited accessibility for grasping; this fact imposes initial grasp configurations different from those required by the task. Another typical example is picking up a pencil in fingertip prehension, and then manipulating it to the final configuration of fig.3. The hand operates a first grasp acting on the available surface of the object, typically in fingertip mode (fig. 2a), then partially lifts it, while the object is forced to move through a number of intermediate configurations by controlled slipping or rolling or by fingers relocation (Fig. 2b). Once the final configuration (Fig. 2c) has been reached, the power grasp of the tool and the task accomplishment become possible. This example shows how the whole surface of the hand is used not only in final constraining, but is also crucial to implement internal manipulation procedures.

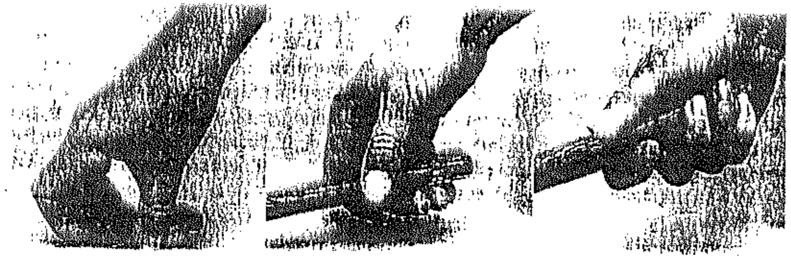


Fig. 2 Manipulation before final grasp

Finally, a third example relates to a fine manipulation task, which consists of holding a pen and writing. The pen, Fig.3, is usually held in a four contact grasp with a lateral contact on the medium fingertip (A), two contacts on the index finger, fingertip pad (B) and lateral surface of the proximal phalange (D), one contact on the thumb fingertip (C). The task of writing along a line is a combination of transverse motion of the pen tip, obtained by fine motion of fingers, and line motion of the hand, achieved by moving the wrist or even the arm. It is interesting to note that in points A, B, C no slippage or rolling usually occur and small

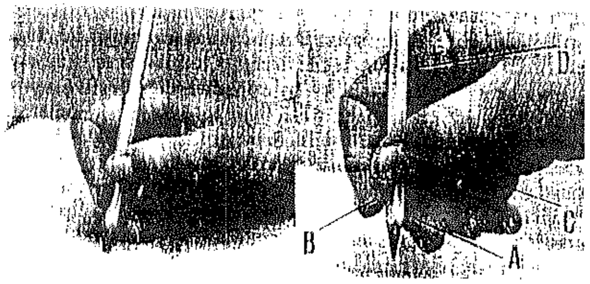


Fig. 3 Fine motion in writing

motion between the fingers and the pen is allowed by the compliance of pads, while in contact D slippage is frequent. It is also relevant to note that the stability and the precision of the grasp greatly depend on using contacts on the lateral surface of fingers.

The observation of the biological model proposes useful suggestions and encourages to implement them in robotic hands design. In the following section, some consequent design issues will be presented.

Design issues and requirements

In order to reproduce some of the capabilities of the human hand, including whole hand manipulation, a robotic system must exhibit a number of features inherent to its mechanical design as well as to its sensory equipment, control methods and computational architecture. In this section, some of these requirements are examined, trying to make the suggestions coming from the human model explicit.

-**Number of fingers.** The minimum number of frictional contacts necessary to firmly grasp a generic object is three [Salisbury,82]; therefore, to obtain general enough grasp capabilities, three fingers are the least possible number. With three properly designed and controlled fingers is also possible to move the grasped object in all directions and orientations. A fourth finger is useful (but not strictly necessary) in some cases, e.g. when an exploration of the surface of the object being grasped is required. A fourth or even a fifth finger are useful to augment the strength of the grasp in heavy tasks.

-**Number of DOF's.** The minimum number of independently actuated joints in the fingers to obtain full mobility of the grasped object is three, if slip motions between the finger pads and the object surface are allowed [Salisbury,82]. On the other hand, if the capability of rolling the fingertips relative to the object is desired, then at least three parallel joints per finger are necessary.

-**Opposability of fingers and palm.** Besides by increasing the internal mobility of the hand, manipulation dexterity can take advantage by proper configuration of the DOF's in the kinematic chain. From this point of view, the position and the excursion of each joint can greatly affect the resultant manipulatability [Kerr,86]: e.g., the ability of the "thumb" to rotate about an axis normal to the palm surface permits the opposability of the lateral surfaces of the "index" fingers.

-**Shape of the phalanges.** The smoothness of the surfaces of the hand links plays a key role in allowing controlled fine motions of an object, obtainable by rolling and/or slipping. As taught by biological models, an elliptic or circular phalange cross section often provides well shaped contact areas for bodies of any shape. Another important requirement is related to the smoothness of surface connections between adjacent links: a conical or cylindrical shaping of the whole finger allows in the possibility to easily move the contact point from one link to another during manipulation and to extend contact area to more than one link when operating with large, flat objects.

-**Material properties of the pads.** Some characteristics of the finger surface are desirable for dextrous manipulation: High friction, low stiction, and rather compliant materials can greatly increase grasp stability, by extending the effective contact surface with smooth objects or by reducing edge effects when sharp bodies are manipulated.

-**Proprioceptive sensory equipment.** Sensing the internal variables of the hand is necessary to realize effective low-level control loops of actuators. In particular, joint position sensors must have high resolution to allow fine control of finger motions. Joint torque sensors can be used to close a control loop around the disturbance source (mainly friction in mechanical transmission of power from actuators to the joint), thus achieving better control performance; however, these sensors are not necessary if good transmission means are adopted.

-**Exteroceptive sensory equipment.** The role of exteroceptive (i.e., relating to interactions with the environment) sensory information in dextrous manipulation has been widely recognized ever since a relevant literature appeared in this field. Indeed, their importance results intuitively when considering how the human hand can perform innumerable tasks effectively. Notwithstanding this, the analysis of functional requirements for the exteroceptive sensory equipment of a dextrous hand has not yet been carried out satisfactorily. The fundamental work of Harmon (see e.g. [Harmon,82]) in the field of tactile sensing, for instance, consisted in reporting what a group of industrial and academic researchers felt to be the necessary features of tactile sensors. These opinions, though influential, derived from the assumption of biomorphic models for sensors more than from objective functional analysis. The development of analytical methods for dextrous manipulation and the appearance of innovative non-anthropomorphic contact sensors offered a new viewpoint for the statement of sensory requirements (for an introduction of these themes, see [Mason,85]). In the following text we will briefly discuss some functional considerations on the sensory equipment of dextrous hands, with particular reference to whole hand manipulation. A subdivision of dextrous manipulation tasks in three main classes will be considered: micro-motion, grasp, and exploration of manipulated objects.

a) **Micro-motion.** The accomplishment of fine motion of objects held by an articulated hand necessitates of three basic steps: i)determination of the kinematic relationship between object motions in cartesian space and motions of the contact points between the object and the hand phalanges and palm (i.e., identification of the grip transform, see [Mason,,85]); ii)determination of the kinematic relation between motions of contact points and motions of hand joints (i.e., the hand Jacobian); iii)control of joint position along specified trajectories. For a precise determination of both the grip transform and the hand Jacobian, the accurate knowledge of contact points is mandatory. Hence, sensors in the hand must primarily provide information about the position of every zone of contact between the object and any element of the hand (finger phalanges and palm).

b) **Grasp.** The grasp of an articulated hand on an object can be described by the number and position of finger-object contacts and by the wrenches exerted through the contacts. In order to synthesize a grasp, the hand controller has to determine i)where to put the finger phalanges and the palm with respect to the object surface, and ii)the intensity and direction of the wrench in each contact. The former is basically a planning problem, which can be approached on the base of an a priori knowledge of the object shape (see e.g. [Nguyen,86]) or with the help of global sensors like vision. The choice of optimal contact wrenches can be carried out, in the assumption that grasp geometry and external load is exactly defined, by criteria as those proposed by [Kerr,86] and [Bologni,88]; an adaptive method for choosing grasp forces in changing conditions has been proposed by [Bicchi,89]. Effective control of contact wrenches requires a sensor to feedback (besides contact positions) the 3-component vector of contact force and the 3-component vector of contact torque, where contact force and torque mean the resultants of distributed pressures over the contact area. Slippage avoidance (or control) is also a major concern in object grasping: a sensor able to evaluate slippage danger at each contact, and to detect when slippage actually occurs, would be very useful for grasping operations.

c) **Exploration.** By the use of active exploration of objects by an articulated hand, it is possible to obtain a very rich information about the object characteristics otherwise achievable with difficulty. As an example, one could manipulate the object to know its shape, the texture of its surface, its hardness, its thermal or even chemical properties, etc. Sensory equipment for achieving these information might consist of several transducers based on different principles. However, we will consider here only the features that the hand sensors must exhibit in order to allow the basic explorative movements which are prerequisite for most active perceptual tasks, i.e. to move a finger along the object surface while exerting a controlled pressure on it. To do this, control algorithms can be developed (see [Bicchi,89]) which require information about contact position and measurement of contact forces and torques on the hand surface.

It should be pointed out that so far we referred to contact points as if contacts occurred at single points on the object and hand surfaces. This assumption is not verified when rather compliant materials are employed to cover hand's surfaces (or the object itself is compliant). In this case, a small-area contact will occur most often; information about contact area shape, and possibly about very small object features contained in such area, could be required to the sensory equipment of the hand. In most cases, though, it could suffice to know approximately the position of the contact area on the hand surface, by knowing the position of one of its points.

Robotic end effectors: an overview

The idea of using all the parts of the hand to manipulate objects is the obvious result of the observation of the human example; thus, the tendency to reproduce this capability with artificial devices can be traced back to the earliest prosthetic hands, developed several tens of years ago. Of course, the lack of any sensory and control capability prevented such devices from achieving any autonomous dexterity.

A review of the state of the art of robotic devices puts in evidence that, while some attempts have been made to design mechanical structures exploiting all their elements for some manipulation tasks, their application has been hindered again by the unsuitability of sensory equipment and by practical limitations of control algorithms. In most cases, manipulation control methods have been defined (and sometimes implemented) for multifingered hands operating with their fingertips only: significant contributions to the analysis of multifingered hand capabilities are in [Yoshikawa 85], [Kerr,86] and [Li,88]; the recent work by [Li,89] provides an elegant formalization of manipulation modes, where rolling, slipping and finger relocation are considered.

Robotic end-effectors with a palmar surface acting in opposition to the fingertips have been proposed by [Skinner,75] and [Rovetta,77], while an adaptable grasping device with many contact surfaces distributed all along the kinematic chain of each finger (resulting in an articulated tentacle) was designed by [Hirose,78]. A multifingered gripper capable of adaptable grasping with many contacts enveloping an object was proposed by [Vassura,80]. An articulated, three fingered hand proposed by [Okada,79] fulfilled some of the structural requirements to perform WHM: even if a palmar surface was not present, and only joint position sensors were employed, the finger design was suitable for locating contacts on lateral surfaces of distal and intermediate phalanges and some exhibitions in fine motion of objects were performed. The Utah-MIT Hand design [Jacobsen,84], being basically anthropomorhic, is in principle suitable for whole hand manipulation tasks, even though the sensorization and control of the device have not yet been perfected. The Stanford-JPL Hand of [Salisbury,82] rather emphasizes fingertip manipulation, being however at present capable of very fine manipulations by exploiting sensory feedback from built-in force-torque sensors located on the fingertips. Other known dexterous hands projects, as the Karlsruhe [Doll,88] and the MITI [Kaneko,88] hands, seem mainly oriented to fingertip manipulation.

The version II Belgrade hand [B&L,89] is able to grasp objects using its phalanges and palm; the variable configuration gripper designed by [Ulrich,88] emphasizes the role of the palm in order to enhance its grasping capability. No provision is made in these projects for dextrous manipulation control through sensory feedback.

An interesting implementation of a prototype hand has been presented by [Oomichi,88]: tactile and force sensors are integrated also in intermediate phalanges and the palm is exploited in power grasps.

As a conclusive remark, it can be observed that, even if a widespread opinion holds that most important research topics in the area of dexterous manipulation are related to control algorithms and task planning, much is left to do also in hand design, since a satisfactory integration between mechanical structure and distributed sensory equipment enabling the achievement of dextrous, whole hand manipulations is still far from being completed.

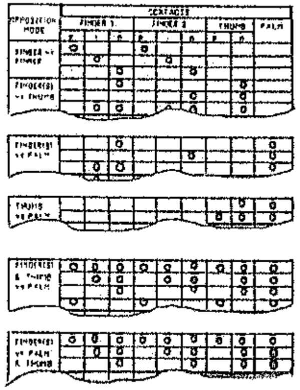
The U.B. Hand

The first version of the U.B. Hand [Belletti,86] [Bologni,88] started working on a test frame in March 1988 and has been operative on a IBM 7565 gantry robot since the beginning of 1989; most of the experimental work carried out so far has consisted of examining the reliability of the proposed device and evaluating its effectiveness in dexterous manipulation tasks, with particular reference to grasping.

In order to provide a quantitative measurement of the hand grasping ability, to enable a comparison of different hand designs, and hence to guide in the choice of possible solutions, the need has been felt to overcome the limitations of previous grasp classification methods, which where found to be qualitative and insufficiently detailed. A method for the classification of all the achievable grasps has been proposed by [Bologni,88].

The proposed method is based on the generation of a table of the feasible contact configurations, where all possible oppositions of the hand elements (proximal, intermediate, and distal phalanges of the two "index" fingers with each other or with the thumb and the palm) are enumerated (see Fig.4).

The version I U.B. Hand has been evaluated according to this method, showing that its kinematic configuration was suitable for whole hand manipulation. Experimental tests confirmed the hand effectiveness, especially in grasping: some whole hand grasps, mimicking the above presented human hand examples, are shown in Fig.5. In order to further improve mechanical effectiveness and reliability, and to exploit the propensity of version I kinematic architecture to whole-hand manipulation, a second version of the



OPPOSITION MODE	CONTACTS								
	FINGER 1			FINGER 2			THUMB		PALM
	P	I	D	P	I	D	P	D	
FINGER vs FINGER	○			○					
		○			○				
			○			○			
FINGER(S) vs THUMB			○					○	
						○		○	
		○	○			○		○	
FINGER(S) vs PALM			○						○
						○			○
		○	○						○
THUMB vs PALM								○	○
							○	○	○
FINGER(S) & THUMB vs PALM	○	○	○	○	○	○	○	○	○
		○	○		○	○		○	○
			○			○		○	○
	○			○			○		○
FINGER(S) vs PALM & THUMB	○	○	○	○	○	○	○	○	○
		○	○		○	○		○	○
			○			○		○	○

Fig.4 The table of opposition modes

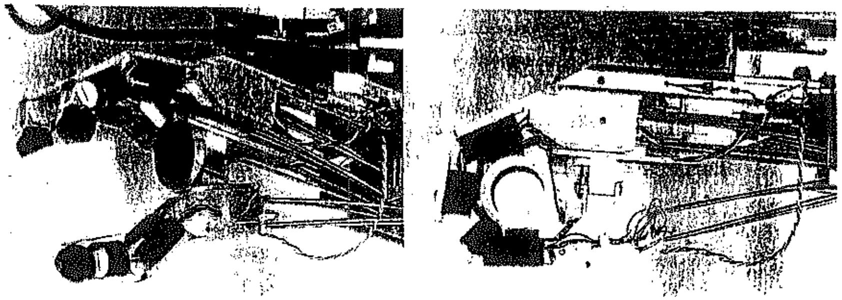


Fig.5 The U.B.Hand

hand is being developed.

The fingers of the version II UB Hand are designed according to a biomorphic skeleton-and-flesh model: in each phalange, an external shell, covered by a compliant high friction layer, and capable of sensing contacts, is connected to an inner rigid element of the kinematic chain.

The skeleton structure is composed of CNC machined links, connected through ball bearing revolute pairs. The design emphasizes modularity and tends to permanent assembly solutions in order to increase reliability and reduce the number of parts. The actuation of the 11 joints of the fingers is obtained through tendons and pulleys. The adopted configuration permits an easy removal of the external shell, so as to allow thorough accessibility and easy intervention on tendons. A detailed sketch of one of the "index" fingers of the hand is shown in Fig.6.

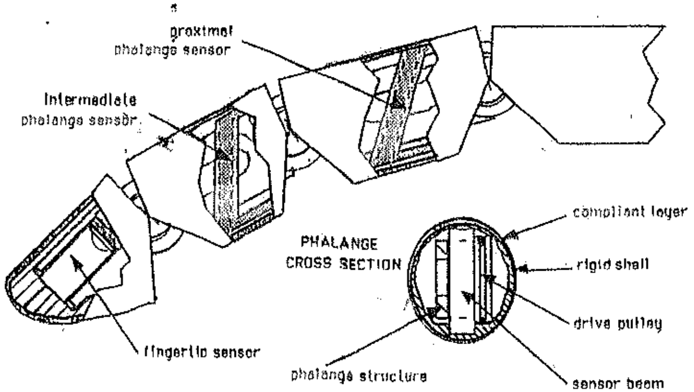


Fig.6 Integration of sensors and mechanical structure

The shape of the external shell of finger phalanges has been chosen so as to provide a regular surface for contacts all around the finger axis. The intermediate phalanges are covered with a cylindrical surface with elliptic cross-section, while the fingertip shells are revolution ellipsoids with the longitudinal axis inclined 20 degrees in the upward direction. A flat surface in the upper region enhances the approach capability, as shown in Fig.7. Finally, the palm surface has been designed as a portion of the convex surface of a large radius sphere.


U.B. Hand version I

U.B. Hand version II

Fig. 7 Fingertip approach capability

The general view of the version II UB Hand can be seen in Fig.8: the modular design will allow the synthesis of different configurations, e.g. by varying the relative position of fingers with respect to the palm. The adduction-abduction movements of the upper fingers are independent, so that syncronous lateral movements of both fingers are allowed.

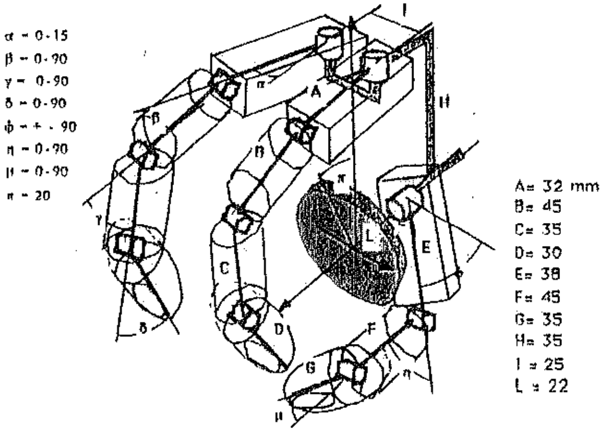


Fig. 8 Kinematic architecture of the U.B. Hand

The sensory equipment of the hand consists basically of joint position sensors (conventional shaft encoders on motor axes) and contact sensors, realized by means of the Intrinsic Tactile sensing method [Bicchi,87]. In fact, this approach seems to satisfy most of the functional specifications above examined, while its implementation does not require too complex hardware and software means.

An IT sensor is very simple in its constitutive parts, which are a 6-axis, force/torque sensor and a cover shell whose surface (the phalanx or palm surface) has known geometry.

According to the results of [Bicchi,89], if the IT sensor shell contacts an object with a small area-type contact, and adhesive forces are not exerted through the contact, by elaboration of the force/torque and geometrical information it is possible to know:

-the position of the contact centroid, that is a point on the shell surface which is assured to be internal to the contact area;

-the resultant contact force applied at the contact centroid, in intensity and direction;

-the resultant contact torque, in intensity and direction.

By comparing this with the information needed for a manipulation-oriented sensory system, it is revealed that most conditions for W.H.M. are fulfilled by IT sensing; the exception is the capability of fine imaging of features inside the contact area. We decided to postpone the realization of such fine imaging, since it would have required very high resolution skin-like tactile sensors which, if at all available at present, would represent a computational bottleneck for the whole system.

In order to accomplish the required functional capabilities of the sensory system for whole hand manipulation, IT sensing had to be realized in each phalanx and in the palm, making a total of 9 sensors.

A crucial problem in IT sensing implementation is the miniaturization of the 9 force/torque sensors employed in the hand. Different design schemes have been adopted in order to fit them in different parts of the hand, namely the fingertips, the intermediate phalanges and the palm. All sensors however employ semiconductor strain-gauges applied to deformable aluminum structures: common to the design of all the force/torque sensors is also the optimization approach employed to maximize sensor accuracy notwithstanding the small size of the sensors. This approach uses a modellization of force/torque sensors in terms of linear operations on the vector of strain measurements $\underline{V}$ obtained from strain-gauges:

$$\underline{V} = C\,\underline{P} \qquad (1)$$

where C is the compliance matrix of the mechanical structure of the sensor, relating the load vector $\underline{P}$ to the measurements $\underline{V}$. The load vector $\underline{P}$ is composed of the unknown six components of the force and torque acting on the sensor in a specified reference frame; the components of P are normalized with respect to the nominal value of each component, so that the norm of $\underline{P}$, $\|\underline{P}\|$, is always less than or equal to 1.

Such modellization of the force/torque sensor leads to some considerations about sensor design: the first is that, if a 6 components load vector P is to be measured, then obviously only 6 measurements are strictly necessary. In the design of a force/torque sensor with stringent size limitations, keeping in mind this fact, though trivial, may be useful.

Numerical stability analysis techniques may be applied to the linear model of the sensor in order to evaluate its accuracy. The causes of errors in a multicomponent sensor can be in fact divided into three main groups:

i) errors in strain measurements, caused by instrumentation inaccuracies, noise etc. These errors reflect in a term dV which is summed to the measured strain vector V.

ii) errors in the compliance matrix coefficients, due to the lack of exact knowledge of the load-strain relationship for the sensor structure. The C matrix can be in fact evaluated both numerically (e.g. with beam theory or with finite elements methods) and directly, by calibrating the sensor with known loads; anyway, an error matrix dC will result from modeling inaccuracies or from experimental errors.

iii) possible amplification of the errors above can occur while solving the linear system (2):

$$\underline{V} + d\underline{V} = (C + dC)\,(\underline{P} + d\underline{P}) \tag{2}$$

Equation 2 represents the true load-measurement relationship idealized in (1); $d\underline{P}$ is the error resulting on the ultimate information of the force sensor, the load vector $\underline{P}$.

In case a minimal sensor design is adopted, i.e. as many strain gauges are used as the load components are, the generalized form of Wilkinson's formula for error propagation can be applied to give an a priori estimate of the relative error on P:

$$e_p = (e_v + e_c)\,Kp(C) \tag{3}$$

where $e_v = \|d\underline{V}\| / \|\underline{V}\|$, $e_c = \|dC\| / \|C\|$, and $e_p = \|d\underline{P}\| / \|\underline{P}\|$, are respectively the relative errors on strain measurements, on calibration and on the results. The propagation factor Kp(C) has an upper bound that is close to the condition number of the compliance matrix C:

$$K_p \cong N(C) = |C|\,|C^{-1}| \cong 1$$

If more strain-gauges are employed in the sensor than are strictly required, a slightly more complex propagation formula can be obtained (see [Bicchi,89]).

From this analysis of the causes of errors in force/torque sensors, it follows that possible means to increase accuracy are substantially two: a)to reduce the source errors i) and ii), by basically employing more sophisticated technologies in strain measurement and calibration, and b)to reduce the amplification of source errors by minimizing the condition number of the compliance matrix. While further source error suppression will conflict at some point with given technological or economic limitations, error propagation can be limited by carefully designing the sensor. Hence, in designing the various force/torque sensors employed in our articulated hand, we used an optimization method whose merit criterion was the minimization of the condition number of the sensor compliance matrix.

The structure of the sensors realized inside the fingertips, the intermediate phalanges and the palm are shown respectively in Fig. 9 a,b,c.

The structure of fingertip sensors simply consists of a thin walled cylinder, on which strain gauge s are applied at optimal locations and orientations. The sensor arrangement has some attractive features, which have been discussed in [Bicchi,87].

In the intermediate phalanges sensors, one end of a rectangular cross-section, internally drilled beam is fixed to the phalanx shell, the opposite end being fixed to the finger frame (the skeleton, so to speak). Gauges are bonded on the beam surface; the length of section sides, the radius of the internal hole, theposition and orientation of the gauges have been chosen following the above described optimal design procedure.

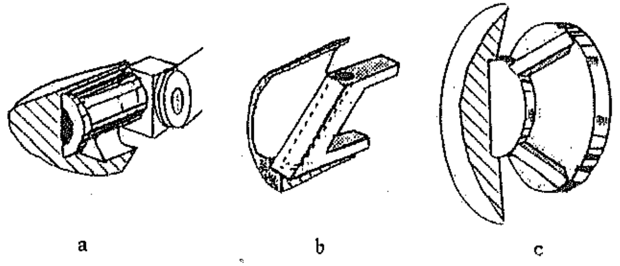


Fig. 9 Sensor configuration for fingertip, phalange and palm

Finally, the palm sensor sketched in Fig. 9c consists of three thin flexures, placed behind the palm surface, on which strain-gauge s are placed. The flexures are inclinated and are spaced 120 degrees apart. Again, the inclination angle, and the location of strain-gauge s on the flexures are chosen to optimize sensor accuracy.

Conclusions

The paper has reported on the design issues of both mechanical and sensory equipment of a robotic articulated hand, by which tasks will be accomplished with full exploitation of the available links. Following from an analysis of some dextrous manipulation operations performed by the human hand, some design requirements have been derived: it should be possible to touch manipulated objects with every part of the hand surfaces and it should be possible to detect the position of each contact point and to measure the forces and torques exerted by contact.

The basic idea of integrated and distributed Intrinsic Tactile sensoriality in a purposely designed mechanical configuration, the version II U.B.Hand, has been presented, and its practical feasibility illustrated. The mechanical and sensory equipment design are the first step towards the implementation of a complete system for dextrous manipulation, of which some elements are still being developed. However, a prototype finger designed according to the proposed principles has been realized, and preliminarly tested.

Despite the broad potential of the device, deriving from the 11 D.O.F.'s and thorough sensorization, the resulting design appears to be reasonably compact and feasible, both for its mechanical structure, due to simplification in machining and assembly process, and for sensory equipment and data integration, due to the peculiarities of intrinsic tactile sensing.

Future work will be mainly focused on the design and implementation of suitable computational architecture and sensory control procedures.

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