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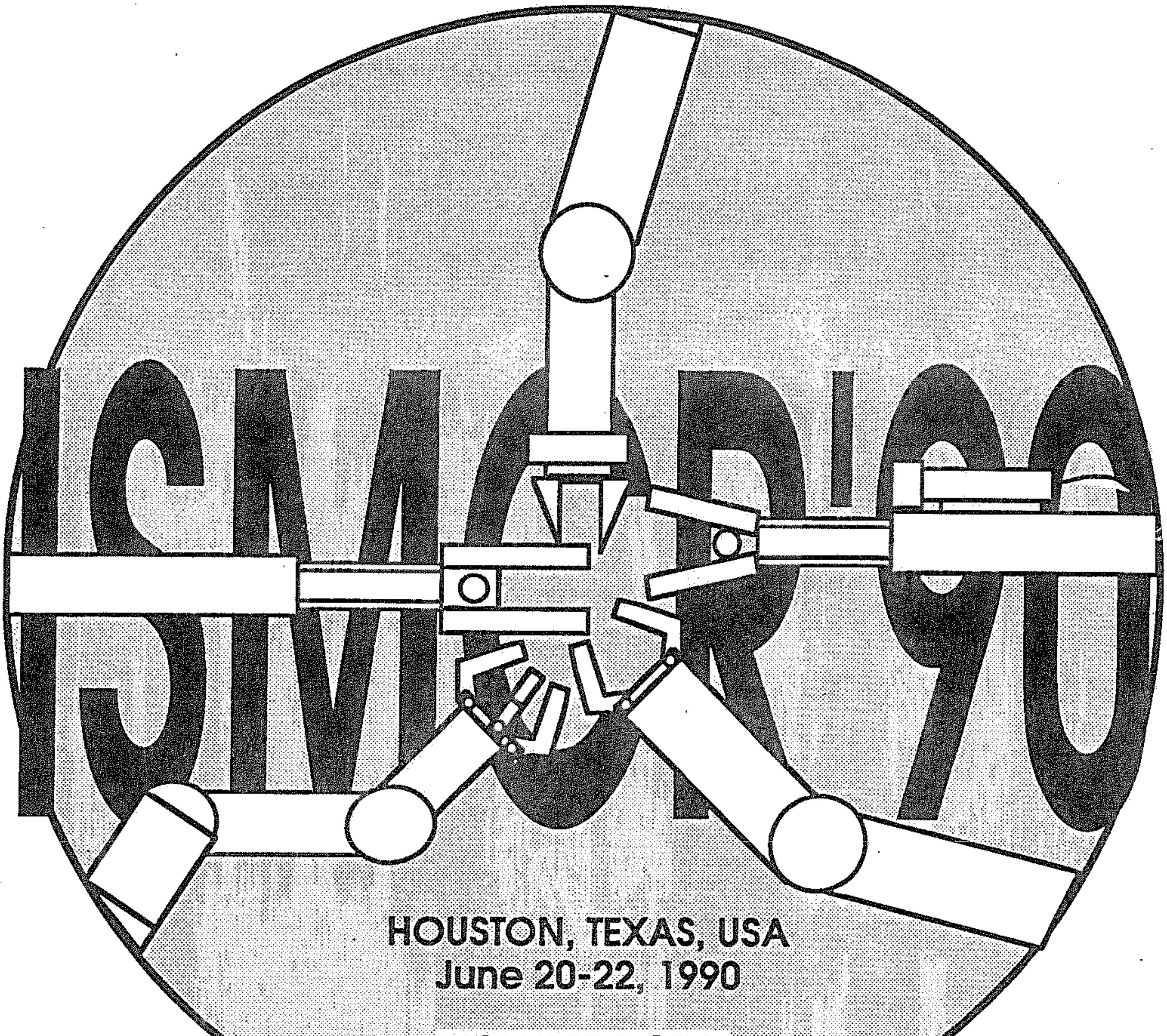

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SENSORIAL INTEGRATION
FOR A ROBOTIC DEXTROUS HAND

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Abstract

The paper examines the feasibility of integrating multicomponent force/torque sensors into the mechanical structure of an articulated hand, in order to achieve "whole-hand" manipulation capability, that is to use in a controlled way all the surfaces of the fingers and palm for contacting objects.

The suitability of the mechanical design of the University of Bologna (U.B.) hand to such a kind of operations is briefly discussed and the need of improvements in actual sensorial equipment is emphasized.

Intrinsic Tactile (I.T.) sensing, based on the measurement of strain components induced by contact forces on a transducer placed inside a link, is evaluated as a suitable technique both for efficient measuring of contact parameters and for easy integration of sensors in the structure of the hand.

The design of built-in force-torque sensors, each of them designed to fit shape and size requirements of miniaturized fingers, is then presented and the general configuration of the version II U.B. hand is described. Issues on design optimization are examined and some remarks on the development of a computational architecture for the overall sensorial system are finally discussed.

Introduction

A way to exploit the full potential of dexterity of an articulated hand may be the adoption of a whole-hand manipulation concept [Vassura 1989], that is to use all its parts for locating contacts, as the human hand does, and not only its fingertips, as at present many robotic devices do.

The version I University of Bologna robotic hand [Belletti 1986] was designed in order to fulfill whole-hand manipulation requirements, a great diversification of the achievable grasps being possible due to the availability of global 10 degrees of freedom and to the capability of contacting the objects with all the phalanges of the three-fingered structure and with the palm. Sistematic investigation about the grasping modes of the Version I hand [Bologni 1989] put in evidence its suitability to grasp diversification.

A tool for categorization of achievable grasps was developed; it put into evidence that the adopted kinematic configuration, beyond its versatility in static grasping, has the potential for manipulation procedures based on evolution from one grasp configuration to another, due to the number and position of contacts that can be achieved on adjacent links. Many operating modes were tested in practice by the robot-mounted hand: some examples of achievable grasps are shown in fig.1, 2, 3, together with their classification pattern. The hand limited its activity to static grasping, no fine motion being yet imparted to the grasped object.

From testing the version I hand and from the consideration of the human hand model, some issues were drawn to improve the manipulation capability of the hand, concerning both mechanical design and sensorial equipment integration.

As far as the overall mechanical design was concerned, the adopted configuration proved to be satisfactory: even if it was designed on the base of a heuristic process, coping functional requirements with constructive and technological constraints, and not on the base of optimization algorithms, the limits it showed were not attributable to the kinematic design. On the contrary, the full opposability of the thumb against the two upper fingers, the use of a palm and the relative position of the fingers proved to be very effective in achieving a great diversification of grasping modes, so that the same kinematic design will be considered for the version II hand. No need was still felt of increasing the number of the fingers or the number of their degrees of freedom.

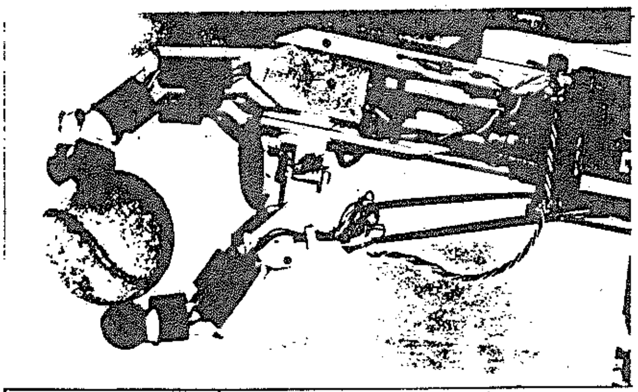
Some major suggestions on mechanical design were drawn by considering the contact distribution on the grasped objects and on the links and the overall robustness of the considered grasps. As taught by biological models, an elliptic or circular phalange cross section often provides well shaped contact areas for bodies of any shape.

Furthermore, 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. 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.

It must be added that 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.

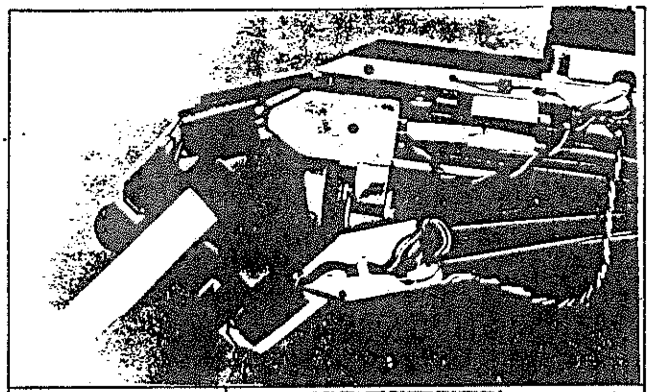
For what concerned the exteroceptive sensory equipment, the version I adopted rough one-component force sensors on fingertips and on intermediate phalanges: it proved to be the weakest point of the system in order to achieve that manipulation capability allowed by the mechanical design.

It became prioritary to develope a new prototype, whose features are described in the following, that could integrate a new mechanical design of fingers with sensorial equipment distributed on all the active links, so that whole hand manipulation procedures and consequently more dexterity might be achieved from the existing articulated configuration of the hand.



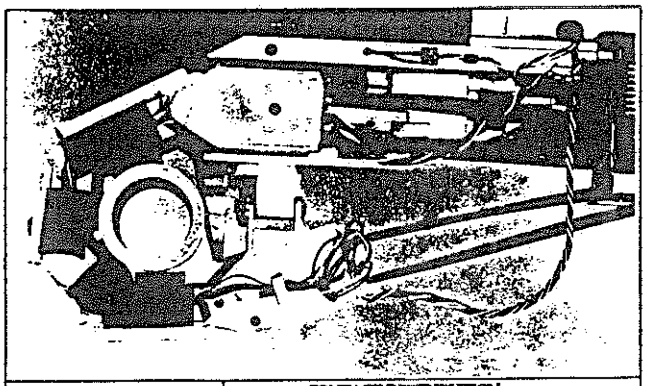
OPPOSITION MODE: FINGERS Vs. THUMB	CONTACT DISTRIBUTION								
	FINGER 1			FINGER 2			THUMB		PALM
	P	I	D	P	I	D	P	D	
			●			●		●	

Fig.1 Grasping with fingertips



OPPOSITION MODE: FINGERS Vs. THUMB	CONTACT DISTRIBUTION								
	FINGER 1			FINGER 2			THUMB		PALM
	P	I	D	P	I	D	P	D	
		●	●		●	●		●	

Fig 2 Grasping with fingertips and intermediate phalanges



OPPOSITION MODE: FINGERS & THUMB Vs. PALM	CONTACT DISTRIBUTION								
	FINGER 1			FINGER 2			THUMB		PALM
	P	I	D	P	I	D	P	D	
	●	●	●	●	●	●	●	●	●

Figure 3 "Whole-hand" grasp

Choice of the sensorial equipment for the version II U.B. Hand

An analysis of the state of the art in tactile sensors for dexterous hands development [Nicholls 1989] shows two basic orientations, the distributed surface sensing approach and the intrinsic sensing approach.

The former approach is oriented to a detailed mapping of the contact phenomena which are transduced by arrays of elementary sensors located as near as possible to the contact area itself, that is on the "skin" of the robotic limb. A great number of parameters can be measured, ranging from normal or tangential contact pressure to temperature and thermal conductivity, and so on. Accurate informations can be obtained on the distribution of the observed parameters all over the contact surface and useful exploration and recognition procedures become possible.

The latter approach is based on remotely located transducers and is usually limited to the measurement of the effects induced by the contact forces applied at the surface of the robotic limb, that cause multiaxial straining of a purposely shaped mechanical element which links the esternal shell, where the contact occurs, to the inner structure of the limb itself. This kind of sensorial functionality requires algorithms for proper reconstruction of the contact pattern, which is determinable in terms of global effects and not of detailed distribution over the contact area.The intrinsic-type sensoriality can allow, as widely demonstrated by theoretical and experimental work [Brock 86, Bicchi 87, Bicchi 89] to measure the force/torque components of resultant contact interactions between the limb and the touched object. Under the assumptions of known shape and reduced compliance of the bodies in contact, the centroid of the contact area can be determined by computational algorithms. Furthermore, it was demonstrated [Bicchi 89] that recognition of friction parameters is possible by means of tactile exploration with fingers driven by intrinsic tactile sensing and that slippage preventing procedures can be implemented on the base of this kind of information.

According to these considerations, a set of intrinsic force/torque sensors seems to be a viable solution for equipping a manipulation oriented hand, giving a satisfactory functionality.

The application to the version II U.B. Hand seems to be recommendable mainly for the following aspects:

- it is suitable for the control of a large number of grasp and manipulation procedures, even if it is limited in local sensing and not suitable for some tactile exploration procedures;
- it can be designed at a good level of miniaturization, it does not present problems due to the curvature of external surfaces, it requires reduced wiring and it is easily integrable into the mechanical structure;
- it is however compatible with a further integration of distributed epidermic sensoriality with surface-mounted tactile sensors.

Considerations on Intrinsic Tactile sensor design

An I.T. sensor is very simple in its constitutive parts, which are a 6-axis, force/torque sensor, which can be differently shaped, and a cover shell whose surface (the phalange or palm surface) has a known geometry.

According to the results of [Bicchi,89], if the I.T. 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;

-intensity and direction of the resultant contact force applied

at the contact centroid;
-intensity and direction of the resultant contact torque.

By comparing this information vith that needed for a manipulation-oriented sensory system, it is revealed that most conditions for whole hand manipulation are fulfilled by I.T. sensing; the exception is the capability of fine imaging of features inside the contact area.

In the design phase, the shape of the transducer has to be carefully chosen, as the compliance matrix of its mechanical structure may be greatly influenced by coupling effects induced by unsuitable design or by errors caused by a problematic calibration.

For this reason, whatever the shape, an optimization approach must be employed to maximize sensor accuracy notwithstanding the small size that is required for mounting inside miniaturized robotic fingers. 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 δV 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 δC will result from modeling inaccuracies or from experimental errors.

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

$$\underline{V} + \delta\underline{V} = (C + \delta C)\,(\underline{P} + \delta\underline{P}) \qquad (2)$$

Eq.2 represents the true load-measurement relationship idealized in (1); $\delta\underline{P}$ 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:

$$\varepsilon_P = (\varepsilon_V + \varepsilon_C)\,Kp(C) \qquad (3)$$

where $\varepsilon_V = \|\delta\underline{V}\|/\|\underline{V}\|$, $\varepsilon_C = \|\delta C\|/\|C\|$, and $\varepsilon_P = \|\delta\underline{P}\|/\|\underline{P}\|$, 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:

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

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 the 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.

Integration of I.T. sensors into the mechanical structure of the U.B. hand

In order to accomplish the required functional capabilities of the sensory system for whole hand manipulation, I.T. sensing was realized in each phalange and in the palm, making a total of 9 sensors for the U.B.Hand architecture. A crucial problem in I.T. 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.

In order to allow the integration of the sensors in the mechanical structure of each phalange, 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. Each connecting elements is the body of a force/torque sensing device and its design has been affected by severe contraints due to limited available space and to the shape of the external shell. The structure of the sensors realized inside the fingertips and the intermediate phalanges are shown respectively in fig.4.

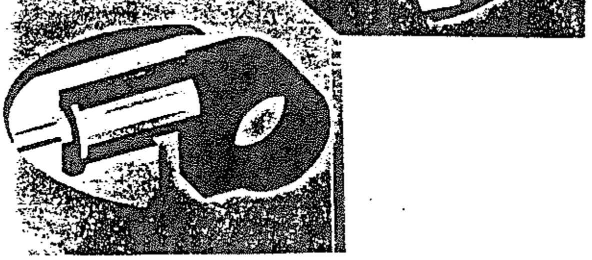


Fig.4 Sensor configuration for fingertip and phalange

The structure of fingertip sensors simply consists of a thin walled cylinder, on which strain-gauges 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 an internally drilled beam with rectangular cross-section is fixed to the phalange 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, the position and orientation of the gauges have been chosen following the previously described optimal design procedure.

The skeleton structure of each finger is composed of CNC machined parts, 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. It also offers a free cross area between the inner structure and the outer shell all along each finger that is used for wire routing. A detailed sketch of one of the "index" fingers of the hand is reported in fig.5.

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 to objects in presence of contraints, and is very useful in picking-up small objects that lie on a plane.

Finally, the palm surface has been designed as a portion of the convex surface of a large radius sphere.

The palm sensor, sketched in fig.6, consists of three thin flexures, placed behind the palm surface, on which strain-gauges are placed. The flexures are inclinated and are spaced 120 degrees apart. Again, the inclination angle, and the location of strain-gauges on the flexures are chosen to optimize sensor accuracy.

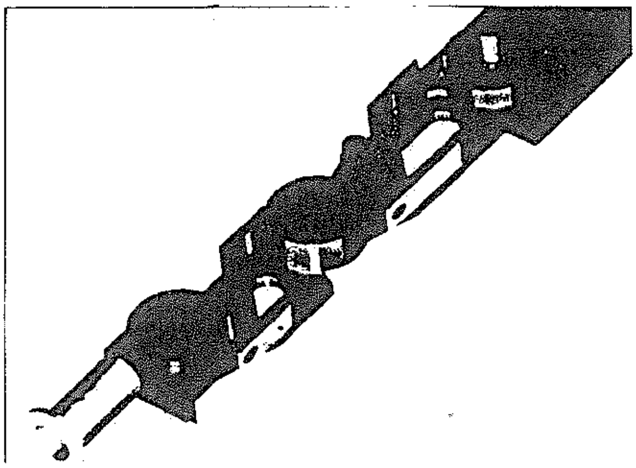


Fig.5 Sensors mounted into the finger skeleton

Computational Architecture for the sensorized hand

The integration of the 9 complex sensors into the U.B. hand is a very challenging task from the computational point of view, as several are the problems to be solved and the costraints to be respected.

Conceptually, three levels of problems have to be solved.

At the I.T. sensor level, the designer can choose between foil-type or semiconductor-type gauges. The better gauge factor of the latter type is coupled with a stronger influence of temperature changes on this parameter, which, in any case, asks for proper compensaction actions.

Besides a carefully designed measuring electronics, a non minimal sensor can help solving this problem. A non-minimal solution is adopted with seven semiconductor-type strain-gauges. As pointed out in [Bicchi 1989], the seventh strain-gauge is located on a rigid part of the sensor. It can be used to pre-compensate the other measurements, maintaining the size of

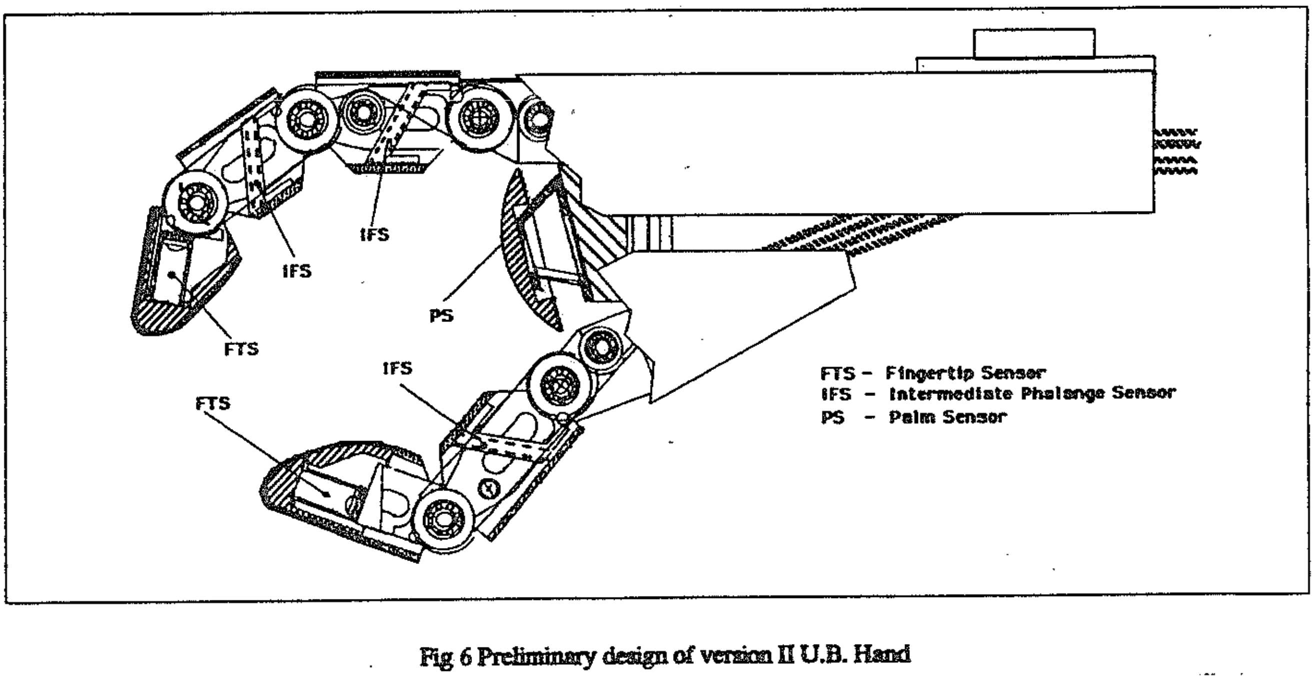


Fig 6 Preliminary design of version II U.B. Hand

6 in the C matrix in (1), or used as an additional measurement in a redundant sensor with a C matrix of size 7.

At the measuring electronics level, the classical Wheatstone bridge circuit would require four times more gauges. Due to the space constraints, all of these gauges cannot be located into the finger itself.

Using surface-mounting technology and special-purpose devices, boards for conditioning, amplification and analog to digital conversion of strain-gauges signals are under development at an Italian firm.

At the computational level, each sensor requires the solution of the linear constant coefficient matrix equation (1). Since the resulting force vector is to be used in a feed-back force loop, the vector force equivalent sampling time has an upper bound depending on the external force signal dinamics.

In the U.B. hand the external contact forces to be measured are usually generated during grasping actions. Considering the very low inertia effects involved in the contact, a relatively high dinamics, lower however than that of the driving motor torque, can be considered for the external force.

From these remarks, it results that a powerful sensor data acquisition and computational system must be designed.

Assuming to use the redundant sensor configuration, as many as 63 signals (9 sensors with 7 signals each) have to be sampled and 9 linear matrix equations solved (approximately 1000 floating-point operation) in some milliseconds at a reasonable cost and size. Moreover, in the design of the data acquisition system, another important specification is the delay among the sampling of the different strain-gauges in the (obviously) multiplexed measurement system. In fact such a delay must be neglegible with respect to the signal dinamics, to meet the parallel measurement hypotesis implied in equation (1).

A computational architecture for the fully sensorized robotic U.B. hand is under an advanced development stage according to the general scheme presented in Fig. 7.

Following the modular design of the U.B. hand, the computational architecture reflects the same phalange/finger/hand structure.

At the hand level, the sensor computations are embedded into the real-time hand controller. It is built around two powerful floating-point Digital Signal Processor (DSP) boards, housed in a standard IBM Industrial AT Computer. The I.T. sensors computations are performed by a Communication Automation & Control board based on an AT&T DSP32 NMOS device operating at 16 MHz. For structured computation (scalar products), it can reach peak performance of 8Mflops. The computation of one force vector (linear matrix equation only) requires about 20 μs.

The processing unit is connected to the data acquisition system by means of a serial high-speed link, directly supported at the DSP chip level. A 16/32 bit 2Mbit/s protocol ensures the transfer speed required for the application.

At the finger level, Analog to Digital conversion of the strain-gauges signals is performed and the digital outputs are organized in the format most suitable for the serial transmission to the hand controller

At the phalange level, i.e. for each sensor, a small board, housed near the hand wrist, provides for proper referencing, amplification, filtering and multiplexing for the 7 strain-gauge signals.

Conclusion

The feasibility study proved that enough sensing capability can be achieved by an articulated hand by adopting I.T. sensing equipment, that can be distributed all over the hand structure by integrating a sensor in each active link. This approach seems to be competitive with different surface-mounted systems, mainly in terms of easier miniaturization, reduced wiring, better compatibility with complex shaping of active links.

In terms of informations that are made available for manipulation control purpose, I.T. sensors can fully satisfy the

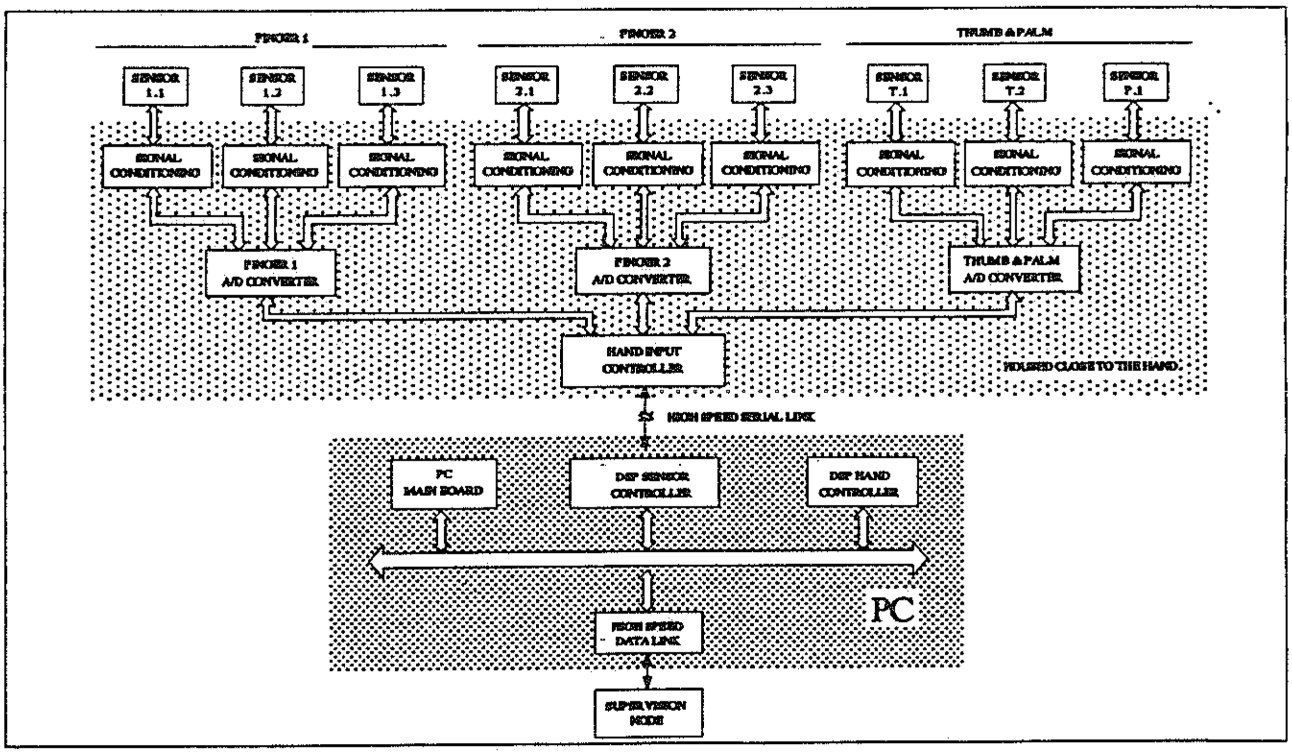


Fig.7 Computational architecture for the I.T. sensorial system

demand for what concerns the determination of contact force components and contact centroid position, thus providing input for grasp analysis tools, even in the case of redundant grasping modes. No propensity to detailed mapping of surface contact phenomena is shown, but in most cases it is not strictly required: the design of the hand for I.T. sensors housing seems however to be compatible with further integration of surface-mounted skin-like devices.

As it was pointed out in the paper, the problems to solve for achieving satisfactory results are bound not only to sensor design and calibration, but also to the set-up of an efficient computational architecture: integration is not only a problem from the mechanical point of view, but also a hard matter for the connection of the sensing equipment to the whole control system of the hand.

From this point of view the adopted DSP-based architecture seems to be suitable for full accomplishment of real-time computation requirements.

The work is in progress: a prototype finger of the fully sensorized hand has been built and test activity began. The DSP architecture is already running inside the AT PC for evaluation on the version I U.B. Hand frame.

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