th the use of a multi-sensor environment information redundancy in the robot cell may occur. Especially in icult scenes sensor data can be verified by data of another sensor. In the future an advanced robot system must be to handle redundant information of a complex task.

r research efforts have first concentrated on individual problem areas. Our present work aims to integrate the ious parts to form a complete multisensory system. The concept presented in this paper is being implemented in eral computers, corresponding to the complexity of the tasks. These are VME-systems for the lower level and N- and micro VAX-computers for the higher levels.

knowledgement

is research work was performed at the Institute for Realtime Computer Systems and Robotics, Prof.Dr.-Ing. U. mbold and Prof.Dr.-Ing. R. Dillmann, Faculty for Informatics, University of Karlsruhe, 7500 Karlsruhe, Federal public of Germany.

TERATURE

] Albus,J.S. et. al.: Theory and Practice of Hierarchical Control, 23.IEEE, Washington, 113.-17. Sept. 1981

] Collins,K.,Palmer,A.J.,Rathmill,K.: The Development of a European Benchmark for the Comparison of Assembly Robot Programming Systems, Robot Technology and Application, S.187-199, Springer 1985

] Dillmann, R., Rembold, U.: Autonomous robot of the University of Karlsruhe, 15th ISIR, Tokyo, 13-17. Sept. 1985

] Ellis,R.E.: An Approach to the Integration of Vision and Touch for Robot Control, Symposium on Robot Control, Barcelona, 6.-8. Nov. 1985

] Foith, J.P.: Bildverarbeitung, Lecture Notice, University of Karlsruhe, WS 78/79

] Geissler,R.:Entwicklung und Implementierung eines Ultraschallsensors für Roboter, Master Thesis, University of Karlsruhe, Faculty on Computer Sciences, February 1985

] Hayes-Roth,B.: A Blackboard Architectur for Control, Artificial Intelligence 26:3 (1985) S.251-321

] Helke,H: Entwicklung und Implementierung eines Näherungssensors für Roboter mit Reflexlichtschranken, Master Thesis, University of Karlsruhe, Faculty on Computer Sciences, October 1988

] Henderson,T.,Shilcrat,E.:Logical Sensor Systems, Journal of Robotic Systems,S.169-193, 1984

0] Kleinschmidt,P.,Magori,V.: Ultrasonic Remote Sensors for Noncontact Object Detection, Siemens Forschungs- und Entwicklungsbericht Band 10, 1984

1] Meier,W.: Entwicklung und Implementierung eines Sensorverarbeitungssystems für eine Roboter-Kraftmeßdose mit sechs Freiheitsgraden, Master Thesis, University of Karlsruhe, Faculty on Computer Sciences, January 1985

2] Müller,R.: Anwendung eines Ultraschallsensors zur Erkennung von Werkstücken und Vermessung ihrer Oberflächen, Master Thesis, University of Karlsruhe, Faculty on Computer Sciences, October 1988

3] Nii, H.P.: Blackboard Systems: The Blackboard Model of Problem Solving and the Evolution of Blackboard Architectures, AI Magazine, S. 38-53, 82-106

4] Shafer,G.: A mathematical theory of evidence, Princeton University Press, Princeton, New Jersey, 1975

5] Shafer,S.A.,Stentz,A.,Thorpe,C.E.: An Architecture for Sensor Fusion in a Mobile Robot, IEEE Conference, 1986

6] Velthuijsen,H., Lippolt,B.J.,Vonk,J.C.: A Parallel Blackboard System for Robot Control, Proceedings IJCAI 87, Milano, August 23-28, 1987

7] Weiss,S.: Untersuchung der Anwendbarkeit von Fuzzy-Logik zur Interpretation von Sensordaten, Master Thesis, University of Karlsruhe, Faculty on Computer Sciences, May 1987

8] Harmon, S.Y., Bianchini, G.L., Pinz, B.E.: Sensor data fusion through a distributed blackboard, Proceedings 1986 IEEE Int. Conf. on Robotics and Automation, San Francisco, April 7-10, 1986

MULTI-SENSOR INTEGRATION FOR FINE MANIPULATION

M. Bergamasco *#, P. Dario *#, A. Bicchi #, G. Buttazzo *#

* Scuola Superiore S. Anna, Pisa
# Centro "E. Piaggio", University of Pisa, Italy

ABSTRACT

In this paper, sensory requirements for dexterous artificial hands for fine manipulation are discussed.

This analysis, which considers also robotic hand motion associated with the acquisition of sensory information, takes into account both proprioceptive and exteroceptive sensors. In particular, two classes of external sensors are discussed in detail: the force and torque resultant sensor and the tactile sensor, both to be positioned at the fingertip of the robotic finger.

A few examples of integration of information obtained by the two types of sensors are discussed. Two simple experiments we have carried out illustrate classes of operations in which the sensor information could be either fused or considered as redundant.

1. INTRODUCTION

End-effectors are fundamental components of advanced robotic systems able to interact with, and control operations against, the external environment [1].

Any interaction with the environment implies a) relative movement between the robotic end-effector and the external object, b) the ability to actuate and control the relative movement with the desired compliance in order to execute the actual task, and c) the availability of a sufficient set of internal and external sensory information which allow the end-effector to actively drive the control procedures. These requirements become even more severe when the end-effector is an anthropomorphic mechanical hand carrying out manipulative tasks.

At present, manipulation capabilities in robots are still rather poor, although great efforts are being devoted to the development of appropriate systems. The fascinating and effective behavior of the human hand represents the ultimate goal to be pursued for the design of a robotic hand.

The main attractive feature a human hand possesses, and an artificial hand tries to imitate, is a high degree of dexterity, i.e. the ability to manipulate accurately complex objects or perform complex operations by appropriately controlling forces and movements. The grace, beauty and sensitivity of the human hand in performing complex motion sequences are still very difficult to reproduce by artificial hand design.

Dexterity for mechanical hands, in fact, still represents an unsolved problem in the context of fine manipulation for robots. It is conceivable that every single component of a botic end-effector plays a significant role in gaining the desired degree of dexterity. The chanical structure of the hand must have the sufficient number of degrees of freedom in order assume suitable spatial configurations during dexterous operations; the actuation system must ssess favourable characteristics and performances inside the wide range of forces and ovements the end-effector is involved, while such qualities as robustness, flexibility and fast ne-response are required for the control system.

During last years several dexterous hands have been presented [2][3][4], each possessing ractive solutions both in terms of mechanical structure and actuation systems. However, due the lack of sensory systems directly positioned at the end-effector, the high-level control of sent anthropomorphic hands remains critical for typical operations of fine manipulation. In dition, the lack of exteroceptive sensors does not allow the control system to obtain necessary formation about the relative physical conditions of the contact between the external vironment and the end-effector surfaces. In fact, magnitude and direction of the forces exerted the contact regions are fundamental information for controlling the fingers during grasping erations. Other parameters extracted by active touch, such as the physical properties of the fferent manipulated materials are also very important.

The awareness of the importance of sensory systems incorporated in the end-effector is necessary premise for the design of anthropomorphic dexterous hands.

In this paper we describe the concepts underlying the integration of sensory information acquired during manipulative tasks by the sensory systems of a robotic hand. Both oprioceptive and exteroceptive sensory systems, which we assume to be fundamental for tificial manipulation, are described.

Examples of fusion of the sensory information are given for the case of specific robotic rdware.

2. SENSORY REQUIREMENTS FOR FINE MANIPULATION

Three major aspects should be considered in the analysis of the functioning of a multi-gree-of-freedom artificial hand:

- the application of the artificial hand;
- the actuation system of the hand and of the associated kinematics configuration of the finger nks and joints;
- the sensory systems, including both proprioceptive and exteroceptive sensors.

These three aspects are not separated, but play collectively an important role in defining e correct control sequence for a specified task.

Achieving dexterity in an artificial hand implies particular requirements for the three pects considered above.

The applications of robotic hands can be divided in two main categories: i) heavy erations, such as grasping and manoeuvering objects, and ii) delicate operations such as, for ample, exploratory or fine manipulation procedures.

Exploratory procedures require the hand to follow unknown contours of objects by fully ploiting its dynamic characteristics. Slow and delicate exploratory procedures can be in fact mplementary to precise and fast hand repositioning during fine manipulation procedures. On e other hand, the kinematic configuration of the hand is fundamental for stably wrapping up a avy tool during grasping operation. The spectra of the frequency of operation required for the uation system strongly differ with respect to the particular application (see Fig. 1).

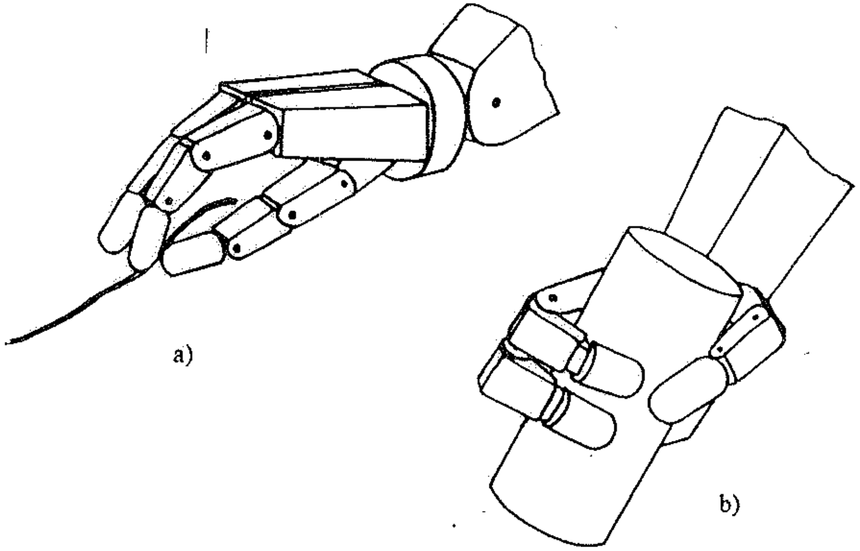

Fig. 1 : Two operations performed by a multi-fingered robotic hand: a) fine manipulation procedure and b) stable grasp of a general object.

The particular task also affects the requirements concerning the range of force exerted by the actuation system. The hand must be capable of exerting low forces during fine manipulation tasks, e.g. during the handling of fragile materials or wires, whereas the magnitude of exerted forces has to be much greater for stable grasp of heavy objects. Thus, due to the different operation conditions, the design of the actuation system and of the associated force control system must tend to maximize the ratio between the maximum force and the minimum force exerted.

The performances of a robotic hand are also affected by the availability of appropriate sensory systems for different applications.

While proprioceptive sensors are fundamental for acquiring information on the spatial configuration of the hand (joint rotation sensors) and on the torques or forces exerted at the joint level (internal force sensors), the use of appropriate exteroceptive sensors depends on the specific application. For example, during grasping operations on external force sensor, positioned at the fingertip and inside each phalanx, could be used in order to monitor the forces and the torques exerted by the robotic hand on the external object at each contact location.

In order to manoeuvering heavy tool, stably grasped inside the hand, it is not usually ecessary to acquire detailed information about the characteristics of the grasped object/tool urface.

However when more sophisticated operations are considered, such as for example xploration procedures, the information of some features of the external environment/object can lay an essential role for the whole process. In fact, the more delicate is the operation to be erformed, the greater is the need for accurately measuring the different parameters of the xternal object wich must be taken into account during the fine manipulation procedure. At this vel of task complexity, not only pure external force and torque information must be processed, ut sometimes even the object geometrical characteristics and the physical and chemical roperties of the contact area. The higher is the complexity of the task in terms of recognition rocedures on the external object, the more sophisticated will be the hierarchical control trategy and thus the greater will be the amount of information to be processed. For example, he use of exteroceptive sensors, such as tactile sensors, plays a predominant role in the efinition of the geometry of the contact regions. This information can be utilized, for example, o finally resolve the orientation of small objects gently grasped between two counteracting ingertips in order to control the successive manipulation procedures.

An important aspect to consider when dealing with fine manipulation tasks is the ossible use of a video camera capable of resolving the absolute position and orientation of the xternal object to be manipulated. However, in this paper onlyexteroceptive sensory systems ositioned directly on the robotic hand are discussed. In particular, the roles of fingertip force esultant sensors and of tactile sensors are analyzed.

3. FORCE/TORQUE AND INTRINSIC TACTILE SENSING

The term 6-axis force sensor, or Force/Torque (F/T) sensor is used to designate a ransducing device that measures the three orthogonal components of resultant force and torques tatically equivalent to the generic load applied to the sensor. Such sensors have been initially eveloped for applications in such fields as wind-tunnel testing or machine tool adaptive ontrol. More recently, these sensors have found very fertile applications in robotics, where they re usually employed in the "wrist" section of the manipulator: in fact, a F/T sensorized wrist nables the robot to measure (and hence is a prerequisite to accurately control) the interaction orces originated by the contact of the robot hand with the objects forming its environment.

A novel application of F/T sensors has been recently proposed by J.K.Salisbury [5]. This pplication consists of the interpretation of contact geometries based on the measurements of a /T sensor fixed to one of the contacting surfaces. Bicchi and Dario [6] proposed the enomination "Intrinsic Tactile (IT) sensors" to indicate devices for contact sensing inspired to hat approach, i.e. based on the measurement of the force/torque resultants of the distributed ontact pressure.

Accordingly, an IT sensor consists of a 6-axis force/torque sensor located inside the ingertip of the robot end-effector, whose surface, unlike a skin-like (or "extrinsic") sensor urface, is not sensorized.

An IT sensor not only detects, as usual for F/T sensors, the resultant load omponents,but it is also capable, under easily satisfied hypotheses of providing very useful nformation about characteristic features of the contact, such as:

1) the location of the contact area on the contacting surface;

2) the intensity of contact force;
3) the intensity of the local (friction) torque exerted through the contact area;
4) the inclination of the contact force with respect to the surface normal, which can be compared with the limit friction cone to assess contact stability against slippage.

An IT sensor would not work either if adhesive forces were exerted between the contact surfaces, or if multiple contacts acted on points that are "far" away from each other (where "far" is meant with respect to the curvature radii of the contacting surfaces). Salisbury [5] has showed that, if the analytic description of the surface to which the F/T sensor is fixed (the fingertip) is available, some of the above information on contact geometry can be obtained at least approximately. Bicchi [7] provided a closed-form exact solution for all such information, in the slightly more restricted case that the fingertip has ellipsoidal surface (including the limit cases of spherical, cylindrical and plane fingertips).

The basic contact mechanics underlying intrinsic tactile sensing can be implemented in rather simple devices. As already mentioned, the active part of an IT sensor consists only of a six-axis, force/torque sensor.

The vast majority of force sensors so far designed and applied are based on extensometry, i.e. on the measurement of the strains caused by the load on the sensor structure. In fact, very accurate, reliable and cheap strain-gages (mechano-electrical transducers that can be glued to the sensor mechanical structure, and whose electrical resistance varies as the strain varies) are currently available. Since the application of force/torque measurements to tactile sensing has been proposed only recently, not so many sensors have been designed thus far to fit the fingertips of a robot hand. Of course, sensor miniaturization is the major issue in this case; robustness, light weight, economy, and above all accuracy are other concerns of the designer.

The first force-sensorized fingertip has been presented by Brock and Chiu [8]. The force/torque sensor is realized with 16 strain-gages applied on the four legs of a maltese cross, built in an block of stainless steel; the arrangement of the strain gages on the legs of the cross is such that their signals can be simply combined to give a decoupled measurement of the six components of force/torque.

The analysis of error propagation in a force sensor based upon linear algebra and numerical computation methods,[6] led to the development of an innovative force/torque sensor, whose design privileges simplicity: the sensor structure consists of a thin hollow cylinder, and only six strain-gages (the minimum necessary number) are used to measure load components. A computer-aided optimal design technique has been employed to choose design parameters so as to optimize sensor accuracy, according to the condition number criterion thoroughly discussed in [7].

The electrical resistance variation of each strain gage, due to the strains imposed to the cylinder by the load, is separately measured. This information can be processed in the form of six orthogonal components of the applied force/moment by solving the set of linear equations which model the elastic compliance of the structure; the equations are obtained by using beam theory or by calibrating the cell experimentally. Conventional algorithms for linear system solution, e.g. Gaussian elimination, are adequate for this purpose. However, the peculiar arrangement of the strain gages on the cylindrical surface of the sensor allows a more time-efficient algorithm, almost decoupling the cell readings.

The small size of the sensor, its low cost, and its simple structure, make it attracting for being integrated in the mechanical structure of robot hands or robot end-effectors for fine manipulation.

Sensitivity and accuracy results comparable to those of more complex and expensive sensors have been obtained with this sensor, whose dimensions are slightly larger than a human ingertip. Some performance figures obtained experimentally from a not fully engineered chnology prototype sensor are listed in Table 1.

Table 1

Active cell size:	10 x 10 x 16 mm^3
Force range:	0.1 to 30 N
Torque range:	0.1 to 30 Ncm
Crosstalk :	4% FSO
Precision :	2% FSO

The thickness of the cylindrical beam is a free parameter which determines the loading range f the sensor. Temperature variations can be compensated by using an extra strain-gage, bonded o the stiff base of the sensor structure.

4. TACTILE SENSORS

Although the importance of tactile sensors for improving robot performance in the xecution of many tasks is widely recognized, practical applications of tactile sensing-based trategies are still very limited. This fact is due in part to the lack of truly usable tactile sensors, nd in part to the incomplete understanding of the very same function of tactile sensing in ifferent situations.

Whereas the present paper is intended for contributing to elucidate the peculiar role of ctile sensing in the framework of multiple, and sometimes seemingly redundant, sensing for obotic manipulation, in this paragraph we propose a few representative examples of recent dvances in tactile sensing design and technology, and describe an integrated force and tactile ensor device we have developed to investigate robotic active touch.

Thorough discussions of state of the art in tactile sensing have been presented recently 9] [10]. Trends in the design of tactile sensors are towards different directions: a) simple, ugged and more usable sensors; b) high performance sensors; c) sensors incorporating some ignal preprocessing.

Type a) sensors have been proposed, for example, by Ghani and Rzepczynsky [11] and y Holman et al [12]. Both sensors are based on the technology of piezoresistive elastomers. ven if authors recognize the serious drawbacks of this technology (nonlinearity, hysteresis, imited bandwidth), piezoresistive sensors are a convenient choice if cheap, high resolution ctile sensors are desired. Limitations can be alleviated by careful design and appropriate lectronic signal processing [12] [13], or perhaps eventually solved by progress in piezoresistive naterials technology [14]. It is worth noting that capacitive-based tactile sensors also possess ttractive features as type a) sensors, and have in fact elicited considerable research interest 15].

Increasing attention has been devoted in the recent past to the development of tactile ensors with the potential cabability of providing the robot controller with more information on lifferent aspects of contact conditions. Examples of this type of sensors are the optical sensors leveloped by King and White [16], and by Begej [17]. Not only optical sensors generate tactile" images detectable by conventional and inexpensive solid-state cameras, but they can

also provide information on the spatio-temporal distribution of normal and shear forces applic at the sensor surface [16] [18].

A conceptually interesting sensor has been described by Clark [19], who pointed out th importance of compliance for tactile sensors, and proposed a general approach for producin sensors that have both high compliance and high resolution. A highly compliant, gel-like sensc has been proposed also by De Rossi et al. [20].

The potential role of dynamic tactile sensing, defined as tactile sensing during motion, i contrast to the sequences of static pressure measurement made by most tactile sensors has bee emphasized by Dario and Buttazzo [21] and more recently, also by Cutkosky and Howe [22 who pointed out that the type and quality of information available from static and dynami approaches are different.

A number of type c) tactile sensors are being developed in different laboratories. A example of sensors incorporating all required circuity to scan the sensor array and providin digitized data has been described in [14].

A tactile sensing system conceptually very sophisticated and potentially capable c providing high-speed access of tactile data has been proposed by Jacobeen et al. [23], who mad use of field-based miniature force transducers for detecting six-degree-of-freedom movement at the contact surface.

Tactile sensors with the intrinsic ability to preprocess the pressure signals originated b contact have been described by Cameron et al. [24] who used a layer of photoelastic material a primary sensing element, and by Wolffenbuttel and Regtien [25], who used elastomer-base capacitive transducers on top of a silicon wafer containing the addressing logic and the signal conditioning circuits. Both tactile sensors are intrinsically suitable for edge detection, a featur similar to that of the sense of touch in humans.

Finally, the recent trend towards the use of neural network principles for preprocessin tactile signal is worthy of mention.[26].

The approach we have pursued in our laboratory in the design of tactile sensors is base on the use of ferroelectric polymer (PVDF) as primary sensing element. PVDF possesses number of attractive properties as transducing material (low cost, easy workability, excellen linearity, wide bandwidth and dynamic range), but also some important limitations for tactil sensing applications (only dynamic response, sensitivity to temperature variations, difficul signal processing). Our PVDF film-based tactile sensors evolved from a simple planar desig [27], to an industrialized version suitable for robot gripper [28], and to a multiple-sensin curved sensor for fingertip sensing [29].

The latest version of our fingertip tactile sensor resulted from a fundamental analysis o the distinct, although complementary, roles of force and true tactile sensing for robotics activ perception [30]. The sensor, depicted in Figure 2, incorporates the 6-axis force sensor describe in paragraph 3 at the basis, and multielement PVDF polymer sensor at the fingertip.

Conceptually, the force-torque sensor has the function of measuring the intensity, lin and point of application of the resultant contact force, whereas the PVDF film sensor (the tru tactile sensor) is intended for dynamic sensing of local contact features. The main potentia merit of this approach is to allow separating functionally the role of sensing contact force, a required for controlling manipulation, from that of true tactile sensing, aimed primarly a exploring different object features. According to this conceptual distinction, the requirement for tactile sensor are substantially different from those usually described in the literature [31 thus privileging such figures as dynamic range and bandwith to other features like, for instance static sensitivity and sensor resolution.

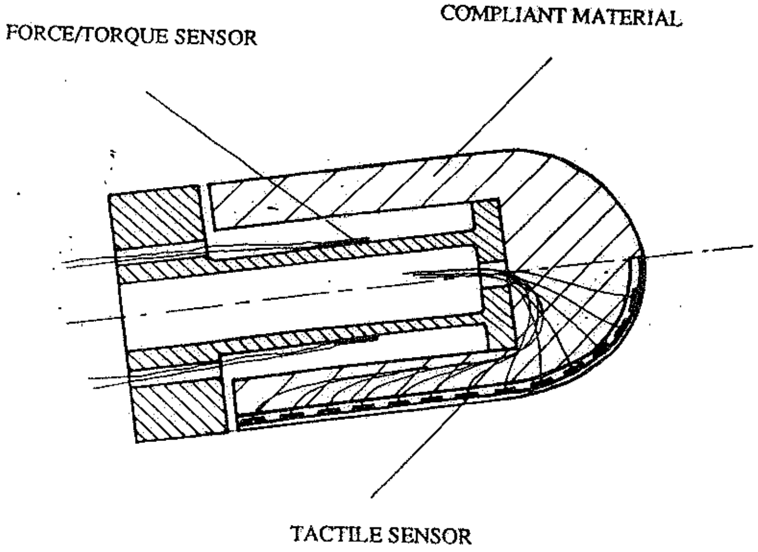

Fig. 2 : The sensorized fingertip with Force/Torque and Tactile sensors

The integration of force and tactile sensing capabilities in the same sensor structure has ny intringuing implications on the design of robot control architecture. In order to investigate ropriate methods for exploiting this multiple sensing capabilities, we have fabricated two ferent devices, representing two different fields of application of robotic systems: a fingertip sor incorporated in a robotic finger purposely designed for exploratory tasks, and a sorized gripper for industrial robots. The main constructive features and some applications of se devices are illustrated in the following paragraphs with the aim of demonstrating their fulness in investigating fundamental issues on redundant sensing and sensory fusion for otic manipulation.

5. TWO EXAMPLES OF FORCE AND TACTILE SENSORY INTEGRATION FOR ROBOTIC MANIPULATION

Implementing haptic perception in a robotic system is a problem involving motor control tegies, sensory data integration, and a close communication between the motor control cess and the sensory data process.

Consider, for instance, the act of palpation performed by an articulated robot finge equipped with proprioceptive and cutaneous sensors [32]. Sensing a hardened inclusion in a sof environment by touch requires the execution of sensory-motor procedures aimed at stimulatin the tactile sensors in order to produce a signal related to the hardened region.

The robot system we have designed with the aim of investigating tactile exploratory paradigms, has been described in previous papers [33] [34]. The characteristics and the components that are relevant to the palapation task we have considered are: 1) a high level "expert" system, at the top of the control hierarchy, which decides the sequence of tactile exploratory subroutines coordinated at the intermediate control level; 2) a middle-level block that controls the execution of tactile subroutines; and 3) a low-level block comprising the hardware components: a tendon-actuated, 4-degree-of-freedom finger, with sensors, motors and drivers, and a preprocessing electronic unit.

During the execution of the exploratory act for the palpation procedure, the system "attention" is almost completely engaged by the analysis of the information provided by the cutaneous sensors. Sensory data produced by epidermal sensors, as well as proprioceptive information, such as joint position and joint torques, are integrated in order to generate an internal representation of material hardness at each point of the explored region. Joint angles and joint torques are also fed back to the motor controller in order to finely adjust finger position, orientation and contact forces during exploration.

This example illustrates how different contact-related signals are processed at different control levels: force/torque data are used for controlling the sensory motor procedures; tactile data originated during those procedures are processed at higher control level, where "interpretation" tasks can be carried out.

As another example of integration of propoceptive and exteroceptive information to augment the sensing capabilities of a robot system, let us consider the case of an electric gripper equipped with distributed tactile arrays and force/torque sensors.

In a sense, the information produced by these sensors is partially redundant, because the resultant gripping force can be either directly measured by the F/T sensor or reconstructed from the tactile array, by integrating the pressure distribution over the contact area. However, these sensors have two distinct roles during a manipulative task:

- the F/T sensor is much more reliable in force/torque measurements and, therefore, is utilized to provide stable grasps and to control contact forces during insertion operations;

- the distributed tactile array is capable of producing a tactile image of a grasped object and, therefore, is used to extract geometric information on the contact area, such as shape of the object indentation, and position and orientation of the object with respect the gripper reference frame.

A suitable strategy for combining force/torque and tactile information can be utilized to provide the system with additional tactile capabilities. As proved in [35], force and tactile information can be integrated to prevent translational and rotational slippage which may occur in the gripper during manipulative tasks.

By computing the ratio of tangential and normal components of the resultant force, and by comparing this ratio with the friction coefficient estimated for the current grasp condition, incipient translational and rotational slippage can be predicted. Periodic evaluation of tactile images, on the other hand, permits direct verification of possible slippage motion of the object in the grasp.

Slippage prevention increases grasp stability and system flexibility during manipulation. general insertion procedure using this capability has been outlined in [28], for a robot rkstation performing autonomous assembling tasks.

6. CONCLUSION

In this paper we have presented some basic ideas we are pursuing in order to investigate tificial haptic perception and dexterous manipulation in advanced robotics systems.

We have considered first the requirements for the sensory systems of a dexterous robotic nd, by dealing also with the important aspect of the "motion" of the robot subsystem cessary for executing a truly active exploratory procedure. Furthermore, we have pointed out at when fine manipulative tasks must be accomplished the availability of sensor-based control of primary importance.

The roles of force/torque resultant sensors and tactile sensors during the execution of fferent manipulative procedures have also been illustrated. Both type of sensors have en discussed, and examples of integration of force and tactile information have been given for cases of a palpation procedure executed by a robotic finger and of a grasping operation rformed by a robotic gripper. While in the case of the gripper the information related to the rmal contact force can be extracted by both force and tactile sensors (a typical case of dundant information) the case of the finger is a typical example of sensory "fusion". In the tter case, and in many other (for example in the procedure we have presented for slippage oidance for the robotic gripper) the information deriving from two different sensors can be sed in order to obtain data which are not provided by each individual sensing modality.

The considerations and the results presented in this paper can be considered as eliminary in our laboratory, a more complete study of sensor integration modalities is under vestigation for a number of different cases both in the fields of industrial assembly and of vanced robotics.

ACKNOWLEDGEMENTS

We wish to acknowledge the technical assistance of Fabrizio Vivaldi, Raffaello ancesconi and Riccardo Di Leonardo.

The work described in this paper has been supported, in part, by MPI, C.N.R. (P.F. ADESS and ROBOTICS), NATO Scientific Affairs Division, Axis S.p.A., I.B.M. Italia p.A. and Polysens S.p.A.

REFERENCES

1. S.C. Jacobsen, C.C. Smith, K.B. Biggers, E.K. Iversen: "Behavior Based Design of Robot Effectors", Robotics search: R. Bolles and B. Roth Eds., The MIT Press, 1987.

[2]. J.K. Salisbury, J.J. Craig:" Articulated Hands: Force Control and Kinematic Issues", Int. J. Robotics Research, Vol. 1, No. 1, 1982.
[3]. S.C. Jacobsen, J.R. Wood, D.F. Knutti, D.F. Biggers, E.K. Iversen :"The Utah-MIT Dextrous Hand: Work IN Progress", Int. J. Robotics Res., Vol. 3, No. 4, 1984.
[4]. Y. Nakano, M. Fujie, Y. Osada:" Hitachi's Robot Hand", Robotics Age, Vol. 6, No. 7, 1984.
[5]. J.K. Salisbury :" Interpretation of Contact Geometries from Force Measurements", Robotics Research, M. Brady and R. Paul Eds., The MIT Press, 1984.
[6]. A. Bicchi, P. Dario :" Intrinsic Tactile Sensing for Artificial Hands", Robotics Research, R. Bolles and B. roth Eds., The MIT Press, 1987.
[7]. A. Bicchi :"Methods and Devices for Dextrous Manipulation Sensory Control", Doctoral Dissertation, Univ. of Bologna, 1989.
[8]. D. Brock, S. Chiu :"Environment Perception of an Articulated Robot Hand Using Contact Sensors", Proc. ASME Winter Annual Meeting, Miami, FA, Nov. 1985.
[9]. P. Dario, M. Bergamasco, A.S. Fiorillo :" Force and Tactile Sensing for Robots", in "Sensors and Sensory Systems for Advanced Robots", Dario P. Ed., Springer Verlag, 1987.
[10]. J.G. Webster (Ed.) :" Tactile Sensors for Robotics and Medicine", John Wiley and Sons, New York, 1986.
[11]. N. Ghani, Z.G. Rzepczynski :"A Tactile Sensing System for Robotics", Proc. of Intern. Conf. Intelligent Autonomous Systems, Elsevier Science Publishers, Amsterdam, The Netherlands, 1986.
[12]. P. Holmbon, O. Pedersen, B. Sandell, A. Lauber :"Tactile Sensors for Industrial Robots", Report 1987-08-13, Linkoping University, Linkoping, Sweden, 1987.
[13]. H. Van Brussel, H. Belien :"A High Resolution Tactile Sensor for Part Recognition", Proc. of Ro.Vi.Se.C 1987.
[14]. B. Tise :" A Compact High Resolution Piezoresistive Digital Tactile Sensor", Proc. of 1988 IEEE Intern. Conf. on Robotics and Automation, Philadelphia, PA, 1988.
[15]. D.M. Siegel :"Contact Sensors for Dextrous Robotics Hands", MIT AI Lab Technical Report 900, Jun 1986.
[16]. A.A. King, R.M. White :" Tactile Sensing Array Based on Forming and Detecting an Optical Image", Sensors and Actuators, Vol. 8, 1985.
[17]. S. Begej :" Fingertip-shaped Optical Tactile Sensor for Robotic Applications", Proc. of 1988 IEEE Intern. Conf. on Robotics and Automation, Philadelphia, PA, 1988.
[18]. D. Femi, P. Dario, P. Lombardi, R. Francesconi :"An Optical Fiber Based Multicomponent Tactile Sensor", Proc. of IASTED Robotics and Automation, Lugano, Switzerland, 1987.
[19]. J.J. Clark :"A Magnetic Field Based Compliance Matching Sensor for High Resolution, High Compliance Tactile Sensing", Proc. of 1988 IEEE Int. Conf. on Robotics and Automation, Philadelphia, PA, 1988.
[20]. D. De Rossi, L. Lazzeri, C. Domenici, A. Nannini, P. Basser :" Tactile Sensing by an Electromechanochemical Skin Analog", Sensors and Actuators, Vol. 17, No 1-2, 1989.
[21]. P. Dario, G. Buttazzo :"An Anthropomorphic Robot Finger for Investigating Artificial Tactile Perception", Int. J. Robotics Res., Vol. 6, No. 3, 1987.
[22]. M.R. Cutkosky, R. Howe :" Dynamic Tactile Sensing", Proc. of Ro.Man.Sy. 1988, Udine, Italy, 1988.
[23]. S.C. Jacobsen, I. Mac Cammon, K.B. Biggers, R.D. Phillips :"Design of Tactile Sensing Systems for Dextrous Manipulators", IEEE Control Systems, Vol. 8, No. 1, 1988.
[24]. A. Cameron, R. Daniel, H. Durrant-Whyte :"Touch and Motion", Proc. of 1988 IEEE Intern. Conf. on Robotics and Automation, Philadelphia, PA, 1988.
[25]. R.F. Wolffenbuttel, P.P.L. Regtien :" Integrated Tactile Imager with an Intrinsic Contour Detection Option", Sensors and Actuators, Vol. 16, 1989.
[26]. Y.C. Pati, D. Friedman, P.S. Krishnaprasad, C.T. Yao, M.C. Peckerar, R. Yang, C.R.K. Marrian :" Neural Networks for Tactile Perception", Proc. of 1988 Intern. Conf. on Robotics and Automation, Philadelphia, PA, 1988.
[27]. P. Dario, D. De Rossi, C. Domenici, R. Francesconi :" Ferroelectric Polymer Tactile Sensor with Anthropomorphic Features", Proc. of 1984 IEEE Intern. Conf. on Robotics, Atlanta, GA, 1984.

[28]. G. Buttazzo, M. Bergamasco, A. Bicchi, P. Dario :" A Robot Workstation for Autonomous Assembling", Proc. of Ro.Vi.Se.C. 1989, Stuttgart, FRG.

[29]. G. Buttazzo, R. Bajcsy, P. Dario :" Finger Based Explorations", Proc. of 1986 SPIE Intelligent Robots and Computer Vision, Cambridge, MA, 1986.

[30]. P. Dario :" Contact Sensing for Robot Active Touch", in "Robotics Science", M. Brady Ed. The MIT Press, 1989.

[31]. L.D. Harmon :"Automated Tactile Sensing", Int. J. Robotics Res., Vol. 1, No. 2, 1982.

[32]. P. Dario, M. Bergamasco, A. Sabatini :" Sensing Body Structures by an Advanced Robot System", Ptoc. of 1988 IEEE Inter. Conf. on Robotics and Automation, Philadelphia, PA, 1988.

[33]. P. Dario, A. Bicchi, F. Vivaldi, P.C. Pinotti :" Tendon Actuated Exploratory Finger with Polymeric Skin-like Sensor", Proc. of 1985 IEEE Intern. Conf. on Robotics and Automation, St. Louis, 1985.

[34]. P. Dario, A. Bicchi, A.S. Fiorillo, G. Buttazzo, R. Francesconi :" A Sensorized Scenario for Basic Investigation of Active Touch", in "Robot Sensors : vol. 2, Tactile and Non-Vision". A. Pugh Ed. , IFS (Publications) Ltd. and Springer Verlag, 1986.

[35]. A. Bicchi, M. Bergamasco, P. Dario, A.S. Fiorillo :"Integrated Tactile Sensing for Gripper Fingers", Proc. of Ro.Vi.SeC. 1988, Zurich, Switzerland, 1988.

Hierarchical Robot Multi-Sensor Data Fusion System

Ren C. Luo and Min-Hsiung Lin

Robotics and Intelligent Systems Laboratory
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC 27695-7911

ABSTRACT

The objective of this paper is to develop a knowledge-based hierarchical paradigm for effective fusion of multiple sensors into the operation of an intelligent system.

A mathematical model is developed to represent the level of confidence measures determining the optimal fused sensor data. The proposed approach permits data to be mer in both a low-level way (to minimize the influence of noisy data) and a high level way (c straints are put on the influence between sensors and the way the data is combined). T work can potentially clear the air on a number of issues such as the usefulness of faulty sen isolation, the accuracy of combined data sources, and the overall cohesiveness of the vari templates for phased sensing.[1]

The investigation is based on a Unimation PUMA 560 robot and various external s sors. These include overhead vision, eye-in-hand vision, proximity, tactile array, positi force/torque, cross-fire, overload and slip sensing devices. The efficient fusion of data fr different sources will enable the machine to respond promptly in dealing with the "r world." Towards this goal, the general paradigm of a sensor data fusion system has be developed, and some simulation results for the concepts of sensor data fusion have b demonstrated.

1. Introduction

There has been increasing interest in recent years in upgrading robot intelligence usi multiple visual and non-visual sensors. For example, Henderson et al. introduced the conc of the Logic Sensor and the Multisensor Kernel system [1,2], and Kak et al.[3] have presen a concept of knowledge-based robotics assembly cells, using multiple sensors. Althou many good individual ideas have been explored, several key issues remain to be resolved make possible a more general multi-sensor system.

Multi-sensor integration, as defined in this paper, refers to the systematic use of the d provided by multiple external sensory devices to assist in the accomplishment of a task b robot or robotic system. An additional distinction is made in this paper between multi-sen integration and the more restricted notion of multi-sensor fusion. Multi-sensor fusion, defined in this paper, refers to those multi-sensor integration techniques that actually combi (or fuse) different sources of sensory data into one representational format. Although this d tinction is not standard in the literature, it serves to separate techniques that attempt t

---

[1] [illegible]