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Dr. Hawkins:

Please find enclosed our response to your report request of 14 September 1994. The following material is divided into three sections: a brief overview of the scientific progress on our ONR-funded work over the past twelve months, descriptions of two significant accomplishments emerging over the past year, and a standard yearly productivity report.

If you have any questions regarding this information, please contact me either by telephone or electronic mail.

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Sincerely,

Dean Chang

Enclosures

ONR Annual Review 1994

Tactile Sensing and Information for Man and Machine Systems

Grant #N00014-92-J-1887
6/1/92 to 5/31/95

Principal Investigator:
Prof. M. R. Cutkosky
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Co-Investigators:
Prof. Gregory Kovacs
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Prof. Robert Howe
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1. Scientific Progress Overview

The project on Tactile Sensing and Information for Man and Machine Systems recently completed its second year. Accomplishments for 9.15.93-9.15.94 fall into three categories: development of new tactile sensor and display systems with high spatial resolution and dynamic response; development of new controllers and control languages for event-based dextrous manipulation; and development of new models of human mechanoreception and grasp impedance in response to dynamic stimuli for improved teleoperation control.

A slightly more detailed listing of the specific accomplishments in each area follows:

1. Tactile sensor and display systems

- A fluid-supported membrane finger has been developed that employs an optical method to measure skin deflections with an unprecedented resolution of 32,000 array elements at a sampling rate of 10Hz.

- Tactile displays have been developed for relaying vibrations and local shape information to human operators in teleoperation. Experiments with subjects have demonstrated that both types of feedback improve performance in such tasks as precise part mating.

- Second-generation micromachined tactile arrays and individual force sensing probes have been developed and are being tested on a specially designed apparatus. A new CMOS-compatible fabrication process has been developed for the on-chip signal processing circuitry needed to provide fast response and a wide dynamic range for large arrays.

2. Control systems for dextrous manipulation

- A new controller has been developed for accurate and independent tracking of a grasped object's motion and internal force trajectories -- a prerequisite for precise manipulation with rolling and sliding. The method accommodates finger compliance and constraints on internal forces and friction. The method has been tested successfully at high speeds and in the presence of disturbances.

- A general-purpose object-oriented control language has been developed based on a phase/event/transition paradigm that recognizes the importance of contact events in manipulation. The language forms a bridge between a high-level discrete-event view of manipulation and low-level trajectory control. The language is being tested in manipulation tasks and extended to account for the role of context in detecting events.

3. Modeling human mechanoreception for teleoperation

- New models of human mechanoreceptors have been developed. It has been found that the mean firing rate, a standard measure used to describe nerve response, is not suffcient to encode a time-varying stimulus. Improved models are being developed to predict human response to dynamic stimulation.

- The impedance of human hands has been measured for subjects gripping an object and subjected to disturbances. Average stiffness varies between 240 and 1190 N/m with damping between 3.6 and 7.4 Ns/m depending on muscle activation. Knowledge of these parameters is useful for tuning teleoperator controllers for maximum performance.

2. Significant Accomplishment - Stanford

A MICROFABRICATED TACTILE SENSOR

a. Description

The importance of tactile information during robotic manipulation has long been recognized. A high resolution tactile imager would be of significant help in object recognition and the management of state transitions, including the making and breaking of contacts. In particular, the ability to measure applied shear stresses as well as normal stresses would allow direct determination of insipient sliding and rolling. Researchers have been successful in developing high resolution tactile imagers capable of determining the normal stress (pressure) profile produced at the interface between a robotic gripper and a grasped object. Two teams have successfully tested tactile sensors capable of sensing the shear as well as the normal components of a surface traction stress profile.

We have developed a microfabricated tactile sensing element capable of measuring all three components of an applied traction stress profile. The sensor is a redundantly constrained silicon dioxide (SiO_2) structure with embedded polycrystalline silicon (polysilicon) piezoresistors. It is coated with an elastomeric rubber such that, as stresses are applied to the rubber surface through contact, the stresses are transmitted to the underlying structure. Deformation of the structure causes a change in resistance of the piezoresistors. Through simple amplification circuitry, these changes in resistance may be recorded as voltage changes which correspond to the shear and normal stress signals.

Initial characterization data indicates that the sensor is capable of measuring independently the applied shear stresses up to 30 kPa at a resolution of less than 0.9 kPa with virtually no hysteretic error (< 1%). Signal cross-talk between the three signal modes is also minimal (< 0.5 kPa). The sensor is, in its current form, insensitive to applied normal stresses. The mechanism causing this insensitivity is well understood; and steps to eliminate it are being taken.

b. Significance

Utilizing microfabrication technology allows the construction of a very high resolution tactile sensing array. SiO_2 structures as small as 200 x 200 µm have been tested. These dimensions are comparable with the spacing of the papillary ridges of the human dermis. The spatial measurement density allowed by these devices is much higher than that achieved in prior triaxial traction stress imagers.

The fabrication process required to realize this sensor is fully compatible with standard complimentary metal-oxide-silicon (CMOS) circuit foundry processes. Because of this compatibility, it is possible to develop a triaxial tactile system with relatively sophisticated local signal processing circuitry on the same chip as the sensors. Most tactile imaging elements published to date are highly incompatible with standard CMOS fabrication processes. In addition to CMOS compatibility the sensor fabrication process will, with further development, allow the construction of a conformable tactile imaging array.

c,d. Figures and Article on following pages

3. Productivity Report

(a) papers published in refereed journals

J. M. Hyde and M. R. Cutkosky, “Controlling Contact Transition,” *IEEE Control Systems Magazine*, Vol. 14., No. 1., February, 1994, pp. 25-30.

R. D. Howe, "Tactile sensing and control of robotic manipulation," *Journal of Advanced Robotics*, 8(3):245-261, 1994.

(b) papers accepted for publication in refereed journals

(none)

(c) technical reports

D. Kontarinis and R. D. Howe, "Tactile display of contact shape in dextrous manipulation," Harvard Robot Sensors Laboratory, Nov. 1993

A. Z. Hajian and R. D. Howe, "Identification of the mechanical impedance of human fingers," Harvard Robot Sensors Laboratory, June 1994.

R. W. Brockett, Harvard Robotics Laboratory, Language Driven Hybrid Syatems.

(d) books or book chapters

R. W. Brockett, Dynamical Systems and their Associated Automata, in *Systems and Networks, Mathematical Theory and Applications*, Academie Verlag, Berlin, 1994.

(e) books or book chapters in press

(none)

(f) patents filed or granted

B. Kane and G. Kovacs, A Redundently Constrained Traction Stress Sensor for Robotic Tactile Determination, to be submitted 10/25/94.

B. Kane and G. Kovacs, An Elasomer Nib Structure for Robotic Tactile Determination, to be submitted 10/25/94.

(g) invited presentations

"Tactile Sensing and Display in Teleoperated Manipulation," Massachusetts Institute of Technology Leg Lab, Cambridge, Massachusetts, Nov. 15, 1993.

Dimitri A. Kontarinis and Robert D. Howe, "Display of high-frequency information to teleoperators," 1993 SPIE Conference on Telemanipulator Technology, SPIE vol. 2057, Boston, Sept. 1993.

M. R. Cutkosky and J. Hyde, “Manipulation Control with Dynamic tactile Sensing,” Proceedings of the *Sixth International Symposium on Robotics Research*, Heavenly Valley, PA, Oct., 1993, T. Kanade, ed., M.I.T. Press.

"Remote Palpation for Minimally-Invasive Surgery," IBM T.J. Watson Research Center, Yorktown Heights, New York, Aug. 12, 1994

Robert D. Howe and Dimitri A. Kontarinis, "High-frequency force information in teleoperated manipulation," International Symposium on Experimental Robotics, Kyoto, Japan, Oct., 1993.

Dimitri A. Kontarinis and Robert D. Howe, Tactile Display of Contact Shape in Dextrous Manipulation, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME Winter Annual Meeting, Nov. 28-Dec. 3, 1993.

R. W. Brockett, "Representation of Data for Sensing, Communication , and Control" ARO-NASA Workshop on Formal Models for Intelligent Control. Sept. 30, 1993.

R. W. Brockett, "Qualitative and Computional Aspects of Differential Equations", International Conference on Control Theory, Jerusalem, October 19, 1993.

R. W. Brockett, Pattern Generation and Feedback Control of Nonholonomic Systems. IEEE Conference on Decision on control, San Antonio, December, 14, 1993.

R. W. Brockett, Models for Hybrid Control Systems, Hong Kong University of Science and Technology, Jan 13, 1994.

R. W. Brockett, Pattern Generation and Feedback Control, Department of Electrical Engineering, UC Irvine, Feb. 17, 1994.

R. W. Brockett, Formal Models for Motion Control, Institute for Research in Cognitative Science, University of Penn., March 29-April 1, (Three Talks).

R. W. Brockett, Motion Control and Geometry, National Academy of Sciences, Board on Mathematical Sciences, Washington DC, April12, 1994.

R. W. Brockett, Systems with Hysterises, McGill University, May 7, 1994.

(h) contributed presentations

Y. Yamada and M. R. Cutkosky, "Tactile Sensor with 3-Axis Force and Vibration Sensing Functions and its Application to Detect Rotational Sip," Proceedings of the *1994 IEEE International Conference on Robotics and Automation,* May 10-15, San Diego, CA, pp. 3550-3556.

B. Gillespie and M. R. Cutkosky, "Interactive Dynamics with Haptic Display," *Advances in Robotics, Mechatronics and Haptic Interfaces*, DSC-Vol 49, H. Kazerooni, J. E. Colgate, and B. D. Adelstein, eds., ASME Winter Annual Meeting, New Orleans, Nov 28-Dec 3, 1993, pp. 65-72.

D. Kontarinis and R. D. Howe, "Tactile display of contact shape in dextrous manipulation," in *Advances in Robotics, Mechatronics, and Haptic Interfaces*, DSC-vol. 49, H. Kazerooni, J. E. Colgate, and B. D. Adelstein, eds., ASME Winter Annual Meeting, New Orleans, Nov. 28-Dec 3, 1993, pp. 81-88.

R. D. Howe and D. A. Kontarinis, "High frequency force information in teleoperated manipulation," *Proc. Third International Symposium on Experimental Robotics*, Kyoto, Japan, Oct. 28-30, 1993, Springer-Verlag.

(i) transitions of ideas to industry or military

R.Howe and M.R. Cutkosky: discussions with Tyler Schilling and visits to Schilling Development Inc. Schilling has agreed to work with Howe and Cutkosky to pursue development of dynamic tactile feedback as an addition to bilateral force reflection in their teleoperated arms for hazardous waste and underwater applications. We are currently looking for a small amount of development funding to permit a student to spend the summer at Schilling to assist with the tech. transfer and product development.

R. Howe: meeting with Dr. David Rosen, Medical Products Group Director, Physical Sciences, Inc., Andover, MA, Sept. 30, 1994. Discussion of application of haptic interfaces to control of medical laser surgery systems. *See attached letter.*

M.R. Cutkosky: meetings with Jim Kramer, President & CEO, Virtual Technologies. Discussions of adding dynamic tactile feedback as an addition to low frequency force feedback in their virtual reality glove interface.

M.R. Cutkosky: meetings with Brent Gillespie, Interval, Inc. and Computer Research in Music and Acoustics. Exchange of event-driven manipulation and haptic interface schemes for development of virtual musical instruments, specifically a touch feedback electronic keyboard.

R. Howe: meetings with Lt. Christopher Hasser, USAF, Human Sensory Feedback and Telerobotics Group, Armstrong Laboratories, Wright- Patterson Air Force Base, Nov. 29-30, 1993 and Sept. 23, 1994. Discussions on design and testing of tactile shape displays for haptic interfaces which Armstrong Lab is developing. Provided information about performance advantages of Harvard display developed under ONR sponsorship.

R. Howe: meeting with Dr. Russell Taylor, Director, Medical Robotics Group, IBM T.J. Watson Research Center, Yorktown Heights, New York, Aug. 12, 1994. Discussions on application of tactile sensing technology to surgical robotics.

R. Howe: meeting with Dr. Wolfgang Daum, President, Daum Handy Systems GmbH, Pittsburgh, PA, Sept. 24, 1994. Discussed application of tactile array sensor technology to surgical instruments. Planned follow-up meeting in Boston in December.

D. Chang: correspondence with Capt. Paul Whalen, USAF, Human Sensory Feedback and Telerobotics Group, Armstrong Laboratories, Wright-Patterson Air Force Base, June 1993. Discussions of possible collaboration to perform mutually interesting dextrous manipulation experiments using Armstrong Lab's Bonneville Scientific ultrasonic tactile array sensors.

(j) training data

Stanford:

- Undergraduates: 1 (1 minority)
- Graduate students: 3 (1 non-US citizen)
- Post Docs: 0

Harvard:

- Undergraduates: 1 (1 minority)
- Graduate Students: 4 (2 non-US citizen, 1 minority)
- Post Docs: 0

(k) awards and honors

M. R. Cutkosky appointed to the Charles M. Pigott Professorship at Stanford.

M. R. Cutkosky, Program Committee, 1994 IEEE International Conference on Robotics and Automation, San Diego, CA, May 1994.

R.D. Howe, Associate editor, IEEE Transactions on Robotics and Automation.

R.D. Howe, Program Committee, 1994 IEEE International Conference on Robotics and Automation, San Diego, CA, May 1994.

R.D. Howe, Program Committee, First International Symposium on Medical Robotics and Computer Assisted Surgery, Pittsburgh, PA, September 22-24, 1994.

G. Kovacs, National Young Investigator Award.

G. Kovacs appointed Terman Fellow.

Dean Chang, graduate research assistant, Air Force Office of Scientific Research Graduate Fellowship, renewed for 1993-1994.

Marc Tremblay, graduate research assistant, NCERC (Canadian) Graduate Fellowship, renewed for 1993-1994.

(l) cost and descriptions of items exceeding $1000

Stanford: Zeos Pantera-90 Personal Computer, $4000.

Harvard: 486 PC Clone, for hosting the video board, $1300