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FINAL REPORT

ROBOTIC TACTILE SENSING

DARPA Contract N00014-84K-0098

Submitted to:
Defense Advanced Research Products Agency

by

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Case Western Reserve University

and

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Pr.

June 8, 1988

CASE WESTERN RESERVE UNIVERSITY

Executive Summary

This report describes research activities in the area of robotic tactile sensing, supported by DARPA contract N00014-84K-0098, over the period 12-1-83 to 5-31-88. This research activity was a cooperative effort between Case Western Reserve University, the prime contractor, and The Lord Corporation, a subcontractor. The Center for Automation and Intelligent Systems at Case Western Reserve University provided experimental facilities and additional research funds to supplement the DARPA funding.

The report is organized into two main sections which provide the technical details of the work performed under this contract by CWRU and the Lord Corporation. The work of CWRU is summarized next.

The overall goal of the research program was to investigate the utility of tactile sensing in the control of manipulation. For the most part, the work at Case Western Reserve University was oriented toward the theoretical and conceptual issues related to the problem domain; the Lord Corporation took a more pragmatic approach in attempting to develop a working experimental system which could demonstrate dexterous manipulation in a robotic assembly task. The scope of work can generally be divided into two areas: control and sensing. The control work can further be divided into lower level servo control and higher level "intelligent" control. These concepts can be effectively integrated within a multilayer hierarchical control structure; this idea has formed the basis of much of our theoretical and experimental work.

The work in the synthesis of lower level control strategies for multifingered articulated hands focused on the development of nonlinear tracking control algorithms. The M.S. thesis by Xirostilidis developed a nonlinear tracking controller based on a set of linearized decoupled regulators and proportional plus derivative control to improve velocity tracking. In this work, the linear tracking control is implemented through the realization of a casual (approximate) linear inverse model. In the work by Vakalis, the tracking control problem is formulated in the context of a quadratic

regulator problem. Linearization about the desired trajectory is accomplished using a uniform grid in the configuration space (workspace). This allows for off-line computation of the controller parameters through the solution of a system of matrix differential equations. Excellent tracking performance was obtained in the configuration space, velocity tracking in the nonlinear system requires further improvement.

The Ph.D. thesis by T. H. Speeter represents a major contribution to this research effort. This work integrates concepts from kinematics and dynamics of articulated mechanisms, continuum mechanics models for touch sensing, parameters estimation and nonlinear adaptive control, and the use of tactile feedback in object manipulation.

Manipulation and control of multifingered mechanical grippers are analyzed. First, the functions of the human hand, its sensors and control are discussed. Following this discussion, a formal kinematic and dynamic analysis of a representative multifingered gripper is developed to address the fundamental properties of multifingered grippers as actuators for controlling manipulation. The ability to identify parameters of the gripper's dynamic model is explored to evaluate the feasibility of model based control of the mechanism.

The effect of the choice of variables that are controlled during manipulation is investigated by evaluating the ability of the gripper to exert forces and to impart motion on an object. These abilities, called facility and mobility, respectively, are quantified and compared over the workspace of a multifingered articulated gripper. A model based, state space controller is developed to control motion of the fingers. This method provides parameterized, variable stiffnesses and damping of the fingers. The ability to modulate the dynamics of the fingers provides a mechanism for regulating forces while the positions of the fingers are controlled. The responses of tactile sensors on the finger are modeled using a continuum mechanics model of an elastic medium. The model is a reasonable representation of the transduction mechanism used in the Lord tactile sensor LTS 200A/V. The stress and strain profiles in the medium are analyzed during contact with an object and the extraction of control related variables from the responses of receptors is discussed. From the responses of tactile receptors, control for the regulation of contact forces is developed. An important problem is that of maintaining a stable grasp during a manipulation task. A detailed solution would require the development of new modelling, sensing and control methodologies; some initial results are discussed in the section describing ongoing research. In Speeter's work a simplified simulation model was developed and it was assumed that slip occurred when the ratio of tangential to normal force of contact exceeded a threshold; this is a simple model of frictional contact. A method using only normal stresses at two depths in the elastomeric touch surface was developed to accurately assess the status of the grasp. Two feedback control structures for modulating the contact forces were derived and tested in simulation to validate the results. These ideas are currently being implemented at AT&T Bell Laboratories on the UTAH/MIT hand; this work is being directed by Dr. Speeter.

The Ph.D. thesis by Shen addresses the problem of object recognition using only tactile sensing. Here it is assumed that the objects are significantly larger than the touch surface of the sensor so that object identification requires active exploration of the object under investigation. The approach developed is based on a continuum model of the sensor's elastomeric touch surface; again directly relating to the actual sensor used in our experimental studies, the LTS 200A/V sensor. The problem is decomposed into local surface identification using cutaneous data from the array sensor and global surface reconstruction using kinesthetic data provided by the robot which is guiding the exploration tas.. A set of local surface primitives are identified, i.e., flat plane, spherical surface, conic surface, cylindrical surface, vertex, and edge. Each object in a prescribed object domain of finite cardinality is represented as a graph: the nodes represent local surface features and the branches correspond to the spatial (geometric) relationships between the features. The exploration of an object is guided by a simple rule based (expert) system which maps the current state of information, i.e., ordered pairs of surface features and geometrical relationships, into a next move which corresponds to the next surface feature to search for. Local surface features are identified using a feature matching technique on an interpolated tactile image. The discrete spatially oriented touch data is smoothed using a model based interpolation scheme which describes the bending of a thin plate under loading. This appears to be a good model for the deflection of the elastomeric touch surface of the Lord pad.

Object recognition is obtained using a graph matching procedure and object reconstruction is obtained using a procedure developed by Grimson for visual image data; kinesthetic (position) data from the robotic system is used here to orient the local surface features. A graphical representation of the object, including orientation, is presented for possible correlation with other sensory information, e.g., vision data.

Additional studies were also conducted which address the following problem areas: the physiology of tactile sensing and tactile image processing, a decision theoretic framework for robot assembly, the application of transform techniques to tactile data processing, the development of an algebraic system theoretic framework for planning, and experimental work which demonstrates the utility of touch data in a robotic assembly task. This work is described in a series of reports/papers which are included in the report.

Because of our affiliation with the Center for Automation and Intelligent Systems, we were able to significantly broaden our research scope at no additional cost to DARPA. A number of theses and reports which describe this work is included. The Ph.D. thesis by D. Raviv discusses the development, implementation, and experimental evaluation of a new method for the reconstruction of 3D images from 2D vision data and for segmentation of visual images. The Ph.D. thesis by Woo discusses the development of new techniques for adaptive grasping using tactile sensing and object determination using a 2D vision system. Some preliminary work by Vakalis discusses the problem of modeling and control of manipulation. In this work, new mathematically rigorous problem formulation is developed using techniques from differential geometry which describes the dynamics of contact between two possibly controlled, inelastic objects. In the M.S. thesis by Hassibi a hierarchical software system for multi-sensory integration is described; this system has been implemented in the robotics laboratory of the Center for Automation and Intelligent Systems at CWRU.

Case Western Reserve University

List of Theses, Reports and Papers

I. Primary source of support from DARPA

A. "A Nonlinear Tracking Controller for Robotic Systems," K.N. Xirostilidis, M.S. Thesis

B. "A Nonlinear Tracking Control Scheme for a 3-Degree of Freedom Mechanical Finger," J.S. Vakalis, M.S. Thesis

C. "Analysis and Control of Robotic Manipulation," T.H. Speeter, Ph.D. Thesis

D. "Object Recognition Using Tactile Data," J.T. Shen, Ph.D Thesis

E. "A Decision Theoretic Approach for Robot Assembly," J.S. Vakalis, A. Kandil, Technical Report

F. "Tactile Sensation," T.H. Speeter, Technical Report

G. "Tactile Image Processing: Lessons from Human Psychology and Physiology," D. Kazdan, Technical Report

H. "Digital Image Processing: Edge Detection in a Tactile Array," S. Friedman, Technical Report

I. "Mathematical Transforms and Correlation Techniques for Object Recognition Using Tactile Data," J. Jurczyk and K. Loparo, to appear in *IEEE Journal on Robotics and Automation*, 1988

J. "An Active Touch Processing System," J.T. Shen, K.A. Loparo, and C.W. Thomas, *Sensors '86*, paper No. MS86-940, Nov. 11-16, 1986, Detroit, MI

K. "An Integrated Robotic System for Assembly," C. Linville, J. Sydir, K. Loparo, and F. Merat, submitted for publication, 1988

L. "On Planning Under Uncertainty," W. Hafez and K. Loparo, IASTED Conference on Industrial Applications of Computers, Cairo, Egypt, Feb. 2-5, 1988

M. "Robot Planning Under Uncertainty," W. Hafez, Technical Report

II. Partial Support from DARPA: Research supervision by K. Loparo

A. "Moving Shadows Methods for Inferring Three Dimensional Surfaces," D. Raviv, Ph.D. Thesis

B. "Robotic Adaptive Grasping Based on Vision and Tactile Sensor Data," D.M. Woo, Ph.D. Thesis

C. "A Software and Hardware Structure for Object Recognition and Manipulation Using Multiple Sensors," K.M. Hassibi, M.S. Thesis

D. "Object Manipulation, Dynamics, and Control," J. Vakalis, Technical Report

E. Reconstruction of Three Dimensional Surfaces for 2D Binary Data," D. Raviv, Y.H. Pao, and K. Loparo, IEEE Conference on Vision, Madrid, Spain, Sep. 30-Oct. 1, 1987

F. "3D Surface Reconstruction from 2D Binary Images," D. Raviv, Y.H. Pao, and K. Loparo, SPIE, Nov. 1987

G. "Segmentation Between Overlapping Parts: The Moving Shadows Approach," D. Raviv, Y.H. Pao, and K. Loparo, submitted for publication, 1988

H. "A Multi-Sensor Robotic system for Object Recognition and Manipulation," K.M. Hassibi, K.A. Loparo, F.L. Merat, Technical Report TR-126, 1987

I. "A Software and Hardware Structure for Object Recognition and Manipulation Using Multiple Sensors," K.M. Hassibi, K.A. Loparo, and F.L. Merat, Technical Report TR 127, 1987

J. "An Algorithm for Object Recognition and Manipulation Using Multiple Sensors," K.M. Hassibi, K.A. Loparo, and F.L. Merat, Technical Report, TR-128, 1987

K. "Application of Fourier Descriptor to Object Recognition and Orientation Determination," D.M. Woo, K.A. Loparo, and Y.H. Pao, submitted for publication, 1988

FINAL REPORT

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May 14, 1988

Executive Summary

The following is a summary description of research conducted at Lord Corporation on Robotic Tactile Sensing while under three years of financial support from DARPA. As stated in the contract proposal, the objectives of the work were to "gain knowledge and understanding of flexible and adaptable manipulation systems which include multi-mode, multi-domain tactile sensing and decoupled control systems." To accomplish this objective, several advances is effector and sensor hardware were made over that time period. These advances represent a parallel effort within Lord to develop tools through internal funding which can be made available to the academic community. The milestones set forth for applications requiring advances in sensors, effectors, and control, over each of the three years, follow. The intent was to start with applications that could be tackled with simple systems and build toward increasing complexity.

Year 1

Taction	-- Separate, non-integral with effector
Effector	-- Simple, special
Control	-- Classical
Intelligence	-- Concentrated, ad hoc algorithms
Simulation	-- Basic design, mechanism and actuation

Year 2

Taction	-- Integral with effector
Effector	-- Simple, dexterous
Control	-- Distributed
Intelligence	-- Distributed, parallel and peripheral
Simulation	-- Full design and operational, taction and control

Year 3

Taction	-- Multi-location array and vector
Effector	-- Complex, dexterous
Control	-- Hierarchical
Intelligence	-- Hierarchical, distributed, coordinated
Simulation	-- Full operations, system studies

Internal technical reports and journal publications referenced in this Summary are contained in the Appendices. Full copies of theses have not been included but, of course, are available if requested. The work was conducted by the equivalent of two full-time personnel over the three year period, leveraged with summer student and university thesis support. The list of personnel who contributed, in varying levels of effort, is shown in Appendix A.

1. Development of sensor technology.

Several styles of tactile sensors have been applied in this work. They include integrated spatial array and force/torque sensors for use in parallel jaw grippers (LTS-200) and large-field, table-mounted array sensors (LTS-300). In addition work has begun on high resolution array sensors in complex geometries. Along with Lord's wrist-mounted force/torque (f/t) sensors, these sensors are the most widely used of their type in research and academic institutions throughout the world. Appendix B contains contains a description of the LTS-200, 300, and f/t sensors.

2. Development of end-effector technology.

In 1984, there was a distinct lack of end-effectors suitable for experimentation in haptic sensing and simple manipulation. There existed complex hands such as the Stanford-JPL Hand designed to investigate the kinematic and stability issues relating to dexterous manipulation, but no simple parallel jaw device suitable for mounting array and f/t sensors with easily-programmable servos.

The Lord Experimental Gripper System (LEGS) was developed to fill this void. The gripper was designed to facilitate the type of simple tasks in mechanical assembly anticipated to be tackled under this contract. The intent was to start with a simple design and incrementally increase the complexity and sophistication with each new stage of the application. A detailed description of the system can be found in Appendix C.

In addition to the gripper system at Lord Corporation, complete systems have been delivered, at cost, to Case Western Reserve, Columbia , Carnegie-Mellon, and Clemson Universities, and the University of Pennsylvania. Several other research institutions are currently considering the LEGS system for use in experimental research.

3. Development of feature extraction algorithms for spatial array sensors.

Object recognition and shape analysis are required in robotic systems for part location and identification. Although the development of feature extraction algorithms for vision has received considerable attention, less work has been performed on the development of feature extraction algorithms for tactile array sensors.

As opposed to vision, tactile information is inherently three dimensional. As a result, Lord's approach was to investigate the application of feature extractors employed in three-dimensional vision systems, such as laser range finders, to tactile array feature extraction. Experimental studies were conducted using the LTS-200 to determine the applicability of vision feature extractors to tactile arrays. The studies are described in two reports in Appendix D. To facilitate the interpretation of the sensor data, a graphical simulator for the Macintosh was developed. The software package on which the simulator was based is described in Section 5. Median filtering, thresholding, and gradient operators were found to be successful in identifying straight edges. The results were applied to the object identification demonstration described in Section 6 below.

4. Integration of multiple sensory modalities into robot systems.

It is difficult to effectively integrate sensor data into commercial robot controllers. Even if the I/O capability exists to interface the sensors to the controller, the programming environment and processor speeds do not permit effective implementation of sensor data processing algorithms. In addition, the controller structure is fixed and cannot be configured to act on the sensor input in a timely fashion.

As a result, a custom-built controller was constructed and interfaced to the commercial controller. A Motorola 68010-based single board computer on a VME bus coordinates the control of the manipulator, the end-effector, and the data collection from the sensors. Either position/orientation (pose) or force/torque goal points for the robot can be specified. The task plan is decomposed into the required goal points for both the robot and the end-effector. The desired Cartesian pose or force goal points for the robot are passed over a 16 bit bidirectional interface to the robot controller. The servos for the fingers are also implemented on the 68010 processor.

The robot controller consists of an LSI-11 residing on a Q-bus in which the trajectory and kinematic calculations are performed. If pose control is requested by the host computer, a simple trajectory plan is formulated to move the robot from its current position along a straight line to the goal pose, subject to velocity and acceleration constraints. If force/torque control is requested, small differential displacements and rotations are added to the current pose trajectory of the robot in the directions required to produce the required forces.

Work is continuing with internal funding to develop a distributed processor implementation of the system based on the NASREM architecture which will entirely supplant the manufacturer's controller.

5. Development of a modelling system for graphical display.

A software package was developed to implement three-dimensional coordinate transformations for graphic display systems and robot control. Since the computational tools required for controlling robots in three-space and manipulating three-dimensional pictures are similar, the package can be applied to both applications. The system is written in C++ and is easily portable.

The control package supports assignment of and linear transformations on vectors and matrices. The g. ·phics system is based upon polyhedral objects. Polyhedrons are defined as ordered sets of vectors (or points in space) and sets of surfaces defined as arrays of pointers to the vectors. Thus, a cube is defined by eight vectors (or eight corners) and six surfaces, where each surface is an ordered array of pointers to four of the vectors. The polyhedrons are in turn grouped into objects called links that can move relative to each other. As an example, the hand demonstration program shown in Appendix E has five fingers, each with two links, and a palm which is linked to the fingers. If the palm is moved, the fingers follow; however, if the proximal finger link is moved, the distal link follows, but the palm is unaffected. Note that the polyhedrons and links work with the transformation package just as the vectors do.

Details of the software package are contained in Appendix E. Additional examples of the graphic output are shown in the application paper on "Object Recognition ..." in Appendix F. This package will serve as the programming environment in which the distributed processor version of the robot controller mentioned in Section 4 will oe implemented.

6. Demonstration of complex automatic mechanical assembly.

The integration of sensors, end-effector, and programmable controller result in a system with which applications involving object recognition, object manipulation, and parts mating using autonomous machines can be investigated. The system, methods, and algorithms approximate a system with haptic capabilities.

The first application paper in Appendix F, "Integrating Tactile Sensors with Robot Work Cells," describes the assembly of a small nylon bushing into a throttle lever. The application is representative of the first year objectives of using sensors physically nonintegral with the eff·-tor, special-purpose end-effectors, classical, non-distributed control, and ad-hoc algorithms.

The PUMA is equipped with a 6-axis f/t sensor and a spring-mounted electromagnet. Single levers are acquired from a bin using the electromagnet and f/t sensor. The sensor is used to detect contact with the pile and to weigh the acquired parts to determine quantity. If more than one part is acquired, they are dropped back into the bin and reacquisition is initiated. When a single lever is found, it is then dropped on an LTS-300 large-field array sensor. The 'footprint' of the lever on the sensor can be used to determine the position and orientation of the part. The grasp point is then determined and the part reacquired and placed into an assembly nest. A pre-taught, point-to-point sequence is executed to maneuver the lever into the nest and over the bushing, and for final mating.

The second application paper, "Object Recognition Through End-Effector Force/Torque Sensing," is representative of the second year objectives of using sensors integral with the effector, simple general purpose end-effectors, distributed control, and generic algorithms.

A real-time modelling, planning, and control system was developed to facilitate the integration of a variety of sensory modalities for use in assembly-type tasks. Manipulation functions were developed based on a pseudo-force control scheme which integrated both force/torque and tactile array data into the control loop. The system employing selected manipulation primitives was used to develop an object recognition demonstration based on edge tracking of polyhedral objects. The only pre-taught positions were two points which defined a line along which the objects were initially placed. The objects were then located, identified, acquired, and stacked in a corner defined by two rails whose positions were unknown to the system.

Towards the third year objectives of using multi-location sensors, complex, dexterous end-effectors, and hierarchical control, the paper "An Initial Experimental Study of Robotic Manipulation" is included. A simple instrumented two-arm 'stick-ball' robot was developed to study coordinated manipulation. Each arm consists of an aluminum rod with a spherical ball at the free end. Each stick-ball is mounted in an assembly which allows four degrees-of-freedom, three in rotation and one in translation. Force data was collected for each arm as selected manipulation tasks were performed. It was found that each distinct manipulation produces a distinct force signature. These signatures are potentially useful in the development of control schemes employing force feedback to achieve intelligent dexterous manipulation.

7. Investigation of incipient slip conditions with the LTS-200.

The constraints on grasping without dropping or damaging can fall within narrow limits, particularly for fragile objects being manipulated. An attempt was made to determine if precursors of slip could be detected using several forms of taction.

A hypothesis was proposed that strain energy is stored in the touch surface of the sensor as shear fores tending to cause slip are increased. In general, it is considered that when the shear force at the touch surface exceeds the restraining friction force, slip occurs. For a real surface of some area, it might be expected that this is still true but not uniformly over the entire surface. Realistic differences from one local area in the contacting surface to another would suggest that such changes from no-slip to slip would occur at random localities throughout the surface. The population of those localities would increase with increasing forces which drive the tendency to slip. At a given time, some localities would be slipping and others would not. If those not slipping are sufficient in number to restrain the driving force, the situation might still be considered stable.

Once a given locality did slip, the energy stored by it would be released and distributed among the other non-slipping localities. Since the clamping or normal force at the locality which slipped would still be present, that locality would again begin to store strain energy. It would have gone through a stick-slip-stick cycle.

The result of this occurrence at some number of localities on the entire surface would be an incremental movement or creep. As the population of the localities which slip grows with higher driving forces, creeping movement would accelerate. Finally, when the non-slipping population is insufficient to restrain the driving forces, gross slip or free movement occurs.

From experimental results, this creeping phase was clearly evident. Also, what appeared to be stick-slip disturbances were present in several of the sensor modes. Although these signs of slip were detected, questions remain on how similar measurements could be made and utilized in a practical operating system.

Although the work to date has emphasized assembly tasks in manufacturing operations, the results from the research should have utility in any area involving adaptable dexterous manipulation. Knowledge and technology developed from the work should benefit robotic systems which must depend on current information about its own status and that of the environment in order to operate effectively. This is especially true when the operations to be performed by the robot require information in the geometry domain and the force-moment domain. Besides robots in manufacturing applications, work will continue at Lord on applications involving general purpose robots, teleoperators, and remote autonomous devices in underwater, aerospace, and land operations.