Active

Project #: E-25-M22　Cost share #:　Rev #: 10
Center # : R6353-0A0　Center shr #:　OCA file #:
Work type : RES
Contract#: DDM-8657599　Mod #: AMENDMENT 05　Document : GRANT
Prime #:　Contract entity: GTRC

Subprojects ? : N　CFDA: 47.041
Main project #:　PE #: N/A

Project unit: MECH ENGR　Unit code: 02.010.126
Project director(s):
LIPKIN H　MECH ENGR　(404)894-7410

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 870701 to 921231 (performance) 930331 (reports)

Sponsor amount	New this change	Total to date
Contract value	25,000.00	201,125.00
Funded	25,000.00	201,125.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: PRESIDENTAL YOUNG INVESTIGATOR AWARD: "HYBRID CONTROL FOR ROBOTICS."

PROJECT ADMINISTRATION DATA

OCA contact: Mildred S. Heyser 894-4820

Sponsor technical contact	Sponsor issuing office
LOUIS A. MARTIN-VEGA (202)357-5167	DIANE WASHINGTON (202)357-9626
NATIONAL SCIENCE FOUNDATION 1800 G STREET, NW WASHINGTON, DC 20550	NATIONAL SCIENCE FOUNDATION 1800 G STREET, NW WASHINGTON, DC 20550

Security class (U,C,S,TS) : U　ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A　NSF supplemental sheet
Equipment title vests with: Sponsor　GIT X
FORCE/TORQUE SENSOR, APPLE MAC II, LASER PRINTER.
Administrative comments -
AMENDMENT 5 ADDS $25,000 FOR 5TH YEAR BASE FUNDING.

5R426

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 03/30/93

Project No. E-25-M22 Center No. R6353-0A0

Project Director LIPKIN H School/Lab MECH ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-8657599 Contract Entity GTRC

Prime Contract No.

Title PRESIDENTAL YOUNG INVESTIGATOR AWARD: "HYBRID CONTROL FOR ROBOTICS."

Effective Completion Date 921231 (Performance) 930331 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsEFFECTIVE DATE 7-1-87. CONTRACT VALUE $201,125.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other HARRY VANN-FMD	Y
FRED CAIN-OOD	Y

E-25-M22

PROGRESS REPORT

NSF 1987 Presidential Young Investigator Award

July, 1987 - September, 1988

BY

Harvey Lipkin

Assistant Professor

George W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332-0405

FOR

Dr. Tony Woo

Program Director

Automation & Systems Integration

National Science Foundation

Design, Manufacturing and Computer-Integrated Engineering

Room 1107

1800 G Street, NW

Washington, DC 20550

Grant No. DMC-8657599

September 1988

SUMMARY

This report documents the work performed under base funding for the first year of DMC-8657599, 1987 Presidential Investigator Award.

Digital Equipment Corporation has agreed to provide first year matching funds in the form of new equipment.

Five areas of research investigation are documented including work performed under a Research Experiences for Undergraduates Supplement. Due to sponsor interest, two areas are specifically targeted for continued research in the second base year.

A bibliography lists the publications produced during the covered period.

INDUSTRIAL SPONSOR MATCHING FUNDS

In order to attract industrial matching funds, the initial year of funding was used to explore several areas of robot technology. This has resulted in the Digital Equipment Corporation (DEC) External Research Group making a $37,500 grant for new equipment.

The sponsored research focuses on sensor-based robots in automated manufacturing systems. The topic is the outcome of technical discussions with DEC representatives in which their needs were matched with the capabilities and interests of the investigator. A fundamental aspect of the arrangement is technology transfer, for which compatible equipment is advantageous. Although this work has potential applications for the sponsor, it is specifically basic research which is relevant to an advanced manufacturing capability.

TECHNICAL SUMMARY

The research performed for the initial year is grouped into five topics along with the associated publications. A brief description is given on the topic, results, and the relevance of the research.

• Sensor-Based Robots in Automated Manufacturing Systems [1] - New manufacturing systems are using off-line CAD generated data bases for the control of workcell robots. The off-line data bases provide nominal geometric models. Due to unmodelled effects, coarse CAD resolutions, and other system errors, these discrepancies may seriously impede or preclude the intended system function. The goal of this work is to use robot sensors to modify on-line, data base generated commands for the compensation of sensed discrepancies.

The basic method is to use the data base to create a nominal local model of the task using screw theory. This model is then modified using position, velocity and end-effector force/torque sensing. Robot commands are then altered to ensure that they are consistent with the task model. As far as the investigator is aware, this work is entirely new. It has the potential to enhance automated transfer of CAD to CAM by compensating for modelling and workcell discrepancies.

• Automated Robot and Workcell Calibration [2] - This work is an outgrowth of the above research on sensor-based robots. A large amount of work has been done on the calibration of robots. Most calibration techniques involve using expensive and labor-intensive equipment such as theodolites for accurate yet time-consuming results. A new algorithm has been developed which compensates simultaneously for both errors in the geometrical parameters of the robot as well as any displacement of the workpiece. A unique aspect of the algorithm is that the workpiece displacements are not limited to small motions. Further, it has been determined changes in various robot dimensions are equivalent to rigid body motions and thus cannot be separated from the workpiece motion. However, since the algorithm simultaneously compensates for these phenomena, their delineation is not necessary for improved robot performance. A proposed calibration procedure uses a force/torque sensor to collect calibration data. This is a simple routine that can be automatically performed before each piece is processed.

• Root-Locus Analysis of Robot Kinematics [3,4,5] - Given a specified position and orientation of the robot end-effector, the inverse kinematic solution yields the necessary joint angles to configure the manipulator. Using the tangent of half joint angles, it is possible to describe the solution in terms of roots of polynomial equations. By varying the end-effector location, the polynomial roots change and describe a pattern in configuration space. This technique is widely used in the field of automatic controls where it is known as the root-locus. It is used for examining the stability and response of transfer functions by analyzing the characteristic polynomial equation. The technique is facilitated by utilizing the open-loop poles and zeros.

A new analysis of manipulator kinematics is developed by transferring the root-locus method from control theory. Since inverse kinematics is highly nonlinear, it is somewhat of a challenge to select linear variable parameters which are required by the root-locus method. However, this enables the use of standard computer application programs for controls to be utilized for kinematics.

An important result is that root-locus breakpoints correspond to singular configurations of the robot. By adjusting the open-loop poles and zeros it is possible to change the location of manipulator singularities which create difficulties in robot control. Thus the root-locus provides an alternative method for robot design and analysis. It is believed the method may be successfully extended to robots with complex designs which are not easily analyzed by traditional means.

• Singularity Analysis of Manipulators [6,7] - This research focuses on obtaining insight into the design of robot manipulators by examining their singular properties. The long term goal is to design robot geometries by placing singularities at specified locations in the joint configuration space. This is highly analogous to methods used in automatic control system design. There the singularities of the closed-loop transfer functions, i.e. the system eigenvalues, are manipulated to produce a desired response.

The initial investigation has made an exhaustive enumeration of singularities and their simultaneous occurrence for several representative industrial robots. Although much has been published on singularities, this line of investigation appears new. The enumeration of singularities is performed by a novel recursive method where primary singular configurations yield the possible secondary and ternary cases. The interpretation of the resulting conditions is simplified by developing expressions in terms of cartesian vectors. A numerical technique is also presented which enables the identification of a special class of singularities known as stationary configurations.

- Manual Controller Development (REU) [8] - This research was performed under the NSF Research Experience for Undergraduates Supplement. The basic goal is to simplify the programming of industrial robots. This is done by using the natural manual motion capabilities of the human for a teach-by-showing capacity.

To implement this activity a general six degree-of-freedom manual controller (i.e. joystick) was fabricated. The position of the handgrip is sensed by potentiometers at the controller joints. A Motorola M68HC11 Evaluation Board is used to provide a stand-alone interface and computational capability. It contains an 8-bit CPU, A/D converters, EEPROM, and serial and parallel I/O ports. The board is used to sample the potentiometer voltages using the A/D converters, filter the data, and output the data to an IBM XT PC via a RS233 serial interface.

Due to the computational limitations of the Evaluation Board, the PC is used to convert potentiometer voltages into joint angles and the controller handgrip location. The system runs at approximately 70 Hz. This is sufficiently fast for future interface with a PUMA robot which requires updates at only a 37 Hz rate.

SUMMARY OF WORK TO BE PERFORMED

In the second year of this grant the Investigator is focussing on the two areas of interest supported by the Sponsor.

For Sensor-Base Robots in Manufacturing, basic research will be performed developing and evaluating algorithms to implement on-line model and robot command modification. Work will also be started in the generation of local models from CAD based data.

The work in Automated Robot and Workcell Calibration will be extended and developed algorithmatically. A demonstration of the techniques will be initiated using a PUMA robot and an end-effector force/torque cell. The results are expected to be transferrable directly to the industrial sponsor.

BIBLIOGRAPHY

[1] Lipkin, H., "Sensor-Based Modification of Local Models for Robot Manipulation," NATO Advanced Research Workshop on CAD Based Programming for Sensor Based Robots, Il Ciocco, Italy, July 4-6, 1988. To be published by Springer-Verlag.

[2] Duggan, M. S. and Lipkin, H., "Automatic Correction of Robot Programs Based on Sensor Calibration Data," Final Report, Georgia Tech, August 1988.

[3] Lipkin, H. and Park, Y.S., "A Root-Locus Investigation of Robot Kinematics," 1988 ASME Design Technology Conferences, Sept. 25-18, Orlando. Under review for publication in <u>ASME Journal of Mechanisms, Transmissions, and Automation in Design</u>.

[4] Lipkin, H. and Park, Y.S., "Investigation of Robot Kinematics via the Tan-Half Angle Root-Locus," Proceedings of the 1988 Computers-in-Engineering Conference, San Francisco, July 31 - August 4.

[5] Park, Y.S. and Lipkin, H., "Robot-Locus Techniques for Robotic Manipulator Kinematics," Final Report, Georgia Tech, May 1988.

[6] Lipkin, H. and Pohl, E., "Enumeration of Singular Configurations for Robotic Manipulators," 1988 ASME Design Technology Conferences, Sept. 25-18, Orlando. Accepted for publication in <u>ASME Journal of Mechanisms, Transmissions and Automation in Design</u>.

[7] Pohl, E. and Lipkin, H., "Analysis of Singular Configurations for Robotic Manipulators," Final Report, Georgia Tech, June 1988.

[8] Rice, M. and Njaka, C., "Development of a Six Degree-of-Freedom Manual Controller," Final Report, Georgia Tech, 1988.

PROGRESS REPORT

NSF 1987 Presidential Young Investigator Award
October 1, 1988 - September 31, 1989

BY

Harvey Lipkin
Assistant Professor
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Georgia Institute of Technology
Atlanta, Georgia 30332-0405

FOR

Dr. Tony Woo
Program Director
Automation & Systems Integration
National Science Foundation
Design, Manufacturing and Computer-Integrated Engineering
Room 1107
1800 G Street, NW
Washington, DC 20550

Grant No. DMC-8657599

SUMMARY

This report documents the work performed under base funding for the second year of DMC-8657599, 1987 Presidential Investigator Award.

Digital Equipment Corporation has agreed to provide second year matching funds in the form of new equipment.

Three areas of research investigation are documented, force/torque control of parallel mechanisms, design of fourth order manipulators, and design of sensor-based placement machines for surface mount technology.

INDUSTRIAL SPONSOR MATCHING FUNDS

The exploratory research in the previous year, was used to solicit a grant from Digital Equipment Corporation (DEC) External Research Group. The $37,500 grant is for new equipment and is subjected to the university 17% discount in determining the matching funding.

The sponsored research focuses on sensor-based pick-and-place machines in the electronics industry. The topic is the outcome of technical discussions with DEC representatives in which their needs were matched with the capabilities and interests of the investigator. This represents a new area of research for the investigator. A fundamental aspect of the arrangement is technology transfer. Although this work has potential applications for the sponsor, it is specifically basic research which is relevant to an advanced manufacturing capability.

TECHNICAL SUMMARY

The research performed for the second year is grouped into three topics. A brief description is given on the topic, results, relevance of the research, and future directions.

- Force/Torque Control of Parallel Mechanisms - This work builds upon the results of the hybrid control research in the previous year. Newer robotic devices include a large degree of parallelism in the geometric design. These include dexterous hands, walking machines, and multiple serial manipulators grasping a single rigid body. In the control of these devices, forces and torques are transmitted between the component active systems as well as to the external system. The control of forces and torques leads to the formulation of an underconstrained set of equations since the problem is generally statically indeterminate. Previous researchers have suggested various approaches using a pseudoinverse solution. A unified framework has been developed in which the various techniques can be compared and evaluated. The basis of this has been to formulate the problem into a constrained optimization problem and identify the physical significance of the Lagrangian multipliers. These represent the axis coordinates of a single screw quantity. The screw fully characterizes the force/torque distribution of the particular solution and leads to efficient methods of calculation. The cases of point contact (force transmission of fingers), full constraint (rigid grasping by cooperating robots), and generalized contact are all analyzed on a common basis. In particular, it has been shown that some popular solutions do not yield invariant solutions when the units of length are altered. This is a very serious shortcoming. Future work will integrate the homogeneous solution into the screw description. The work in this research area currently constitutes the thesis topic for a Ph.D. student.

- Design and Analysis of Fourth Order Robots - Most industrial manipulators are based on one or two simple kinematic designs. They enable the inverse kinematic position equations to be solved using quadratic equations. It is important to have a simple solution for real-time planning and control. These robots have been well studied. The next most simple manipulator requires the solution of a fourth order equation in its inverse kinematic solution. Almost no information is known about these robots. This is a very important class of robots since a fourth order polynomial is the maximum degree which can be calculated using a closed-form algebraic solution. A new technique for analyzing robots with fourth order inverse kinematics has been discovered. This technique restates the solution of the inverse kinematics problem as a pencil of conics. The four solutions correspond to the four common points to all of the conics in the pencil. Fourth order robots can be classified using the well known invariants of conics. In the conic representation, the order of the solution reduces when one of the conics in the pencil becomes degenerate and noncentral and thus includes second order kinematics solutions as a special case. The conics technique holds great promise for introducing new classes of robots along with the ability to analyze them using elementary geometry. Future research is directed to extending the technique to higher order robots. The conics method research forms the basis for a Ph.D. thesis.

- Design of Sensor-Based Pick-and-Place Machines for Surface Mount Technology - The pick-and-place assembly machine is one of the most expensive and critical pieces of equipment in a surface mount technology (SMT) manufacturing line. Typically, SM pick-and-place equipment constitutes about 50% of the total capital investment required for a medium volume SM line. A basic factor in determining true assembly machine efficiency is the yield, the number of SM components accurately placed. Without guiding leads of holes, yield depends almost entirely on machine placement reliability, which in turns depends on machine repeatability. SM assembly machines vary widely in capabilities. Equipment capable of high speed placement usually has low accuracy and flexibility capabilities. For fine-pitch assembly the machines have lower cycle times but are typically more flexible in the types of components that can be handled. The research in this area addresses the particular needs of the industrial sponsor and represents a new research direction for the investigator. Initial work has been to assess the technology state-of-the-art. Surprisingly, there has been relatively little material published in scholarly journals on placement machine technology. Several reasons are suggested for this. First, most of the placement machines are now made in Japan and thus does not promote English language publication. Second, most of the companies involved consider their research as entirely proprietary, even though it may contain substantial generic issues. Third, this is an area which has not yet attracted researchers in the academic field, even though electronics manufacturing is an important area of wealth generation for a country. The current assessment shows that there are only three basic designs for

SM placement machines, gantry, split axis, and turret head. All of these use dual cameras for placement accuracy. In order to address the more demanding needs of fine-pitch components, the trend appears to be to fine tune these existing arrangements. In this research, new placement machine systems are being investigated to address the requirements of increased placement accuracy and the capability of handling varied chip packages. Two basic issues are being examined, the machine structure and the sensing integration. While direct sensing of the chip leads on the printed circuit board pads provides a manner of increasing accuracy, it severely limits component variety. Future work will investigate a hybrid type of design which uses a vision system to track the chip tooling and provide increased flexibility and accuracy over currents machines. This work currently forms the basis for an M.S. thesis.

E-25-M22

Georgia Tech

THE GEORGE W. WOODRUFF SCHOOL OF
MECHANICAL ENGINEERING

Georgia Institute of Technology
Atlanta, Georgia 30332-0405

Dr. Louis A. Martin-Vega
Program Director
Production Systems
National Science Foundation
Design, Manufacturing and Computer-Integrated Engineering
Room 1107
1800 G Street, NW
Washington, DC 20550

18 February 1991

Dear Dr. Martin-Vega:

Please find enclosed a Progress Report for Year Three of the PYIA DMC-8657599.

Also enclosed is a request for Year Four base funding. Although the delayed submission should expectedly preclude fulfillment, it is nonetheless being forwarded for consideration.

I regret any possible inconvience that may result from this matter and appreciate whatever help can be offered.

Sincerely,

Harvey Lipkin
Assistant Professor

PRESIDENTIAL YOUNG INVESTIGATOR AWARDS
REQUEST FOR NSF BASE AWARD AND/OR MATCHING FUNDS

Note: See reverse for instructions and definitions
Submit one form for each activity year

PYI Name: Harvey Lipkin   Date of Request: 18 February 1991

NSF Award #: DMC-8657599   Year PYI Awarded: 1987

NSF BASE AWARD REQUEST   Yes x   No ___   (Check one)

Amount: $ 25,000

Activity Year: 1 2 3 (4) 5 (Circle only one)
From month 7 year 90 to month 6 year 91

MATCHING FUNDS REQUEST   Yes ___   No x   (Check one)

Amount: $ ______________ (Maximum $37,500 per activity year)

Activity Year: 1 2 3 4 5 (Circle only one)

Sources (List Individually)	Inst. Address (City, State, Zip)	Inst. Prefix	Cash Donation ($)	Equipment Donation ($)
(See sample on reverse side)				
1.				
2.				
3.				
4.				
5.				
6.				

EE INSTRUCTIONS ON
EVERSE BEFORE
OMPLETING)

SUMMARY PROPOSAL BUDGET

APPENDIX IV

ORGANIZATION	FOR NSF USE ONLY		
Georgia Tech Research Corporation	PROPOSAL NO. DMC-8657599	DURATION (MONTHS) Proposed	Granted
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR: Harvey Lipkin	AWARD NO.	12	

Item	NSF FUNDED PERSON-MOS CAL.	ACAD	SUMR	FUNDS REQUESTED BY PROPOSER	FUNDS GRANTED BY NSF (IF DIFFERENT)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.6. show number in brackets)					
1. H.Lipkin		0	2	$ 10,149	$
2.					
3.					
4.					
5. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
6. ( ) TOTAL SENIOR PERSONNEL (1-5)					
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. ( ) POST DOCTORAL ASSOCIATES					
2. ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)					
3. (1) GRADUATE STUDENTS				9,000	
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL-CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				19,149	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				2,669	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				21,818	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				600	
2. FOREIGN					
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $					
2. TRAVEL					
3. SUBSISTENCE					
4. OTHER					
TOTAL PARTICIPANT COSTS					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				309	
2. PUBLICATION COSTS/PAGE CHARGES					
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				309	
H. TOTAL DIRECT COSTS (A THROUGH G)				22,727	
I. INDIRECT COSTS (SPECIFY) 10% of A+B+C+E+G (22,727)					
TOTAL INDIRECT COSTS				2,273	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				25,000	
K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)					
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 25,000	$

PI/PD TYPED NAME & SIGNATURE*	DATE	FOR NSF USE ONLY		
Harvey Lipkin	2/18/91	INDIRECT COST RATE VERIFICATION		
INST. REP. TYPED NAME & SIGNATURE*	DATE	Date Checked	Date of Rate Sheet	Initials - DGC
David B. Bridges	2/25/91			Program

Form 1030 (1-87) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED

PROGRESS REPORT

NSF 1987 Presidential Young Investigator Award
June 1989 - May 1990

BY

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Assistant Professor
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Georgia Institute of Technology
Atlanta, Georgia 30332-0405

FOR

Dr. Louis A. Martin-Vega
Program Director
Production Systems
National Science Foundation
Design, Manufacturing and Computer-Integrated Engineering
Room 1107
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Washington, DC 20550

Grant No. DMC-8657599

Summary

This report documents the work performed under base funding for the third year of DMC-8657599, 1987 Presidential Investigator Award. Five areas of research investigation are documented: fourth order robot kinematics, complex number robot kinematics, force/torque control of robotic mechanisms, elastic robots, and surface mount placement machines. The last topic addresses the interests of the industrial sponsor, Digital Equipment Corporation.

Technical Summaries:

1. ***Design and Analysis of Fourth Order Robots (with D. Smith).*** The inverse kinematic solution for a robot is the most fundamental problem for control. Almost all industrial robots are designed to have the most simple inverse kinematic solution which is solvable by a series of quadratic polynomial equations. This makes up a rather limited class of robots. The next higher class solves fourth order polynomial equations. The first analysis of these robots is over twenty years old. Due to its complexity, no significant research has been performed since. For example, each polynomial coefficient may contain hundreds of terms which are functions of the robot dimensions. This class of robots is particularly significant since a fourth degree equation is the highest polynomial that can be solved algebraically in closed form. Such solutions are important to guarantee real-time control. A new technique has been developed to analyze fourth degree robots and by extension, fourth degree polynomials. Using a form natural to robot kinematics, the problem is transformed

into the investigation of a linear pencil of conics. Using the well-known invariants of conics, all such robots can be given a unique classification. Because of the complexity of the problem, it is necessary to use a symbolic manipulation program (Mathematica). Two important applications have been made. First, it has been discovered that degenerate conic pencils, which always contain a pair of straight lines, yields the criteria for fourth order robots to degenerate into the simpler second order robots. For robots which contain a wrist (the most common), seven second order robots have been found, five of which are previously unknown and have potential industrial application. Second, the conic representation has been used to evaluate the workspace properties of fourth order robots. This includes the indentification of workspace singularities which must always be considered in robot control. The current work in this area is essentially complete. It is believed that the method of studying invariants can be applied to the study of more complex robots.

2. *Complex Number Kinematics of Manipulators (with E. Pohl).* The inverse kinematic procedure determines the joint angles that position a robot at a specified location. If the robot can reach the location then the joint angles are all real. This work is the first to consider the case of complex joint angles. These occur if the specified location is outside of the robot workspace. Thus, it requires complex joint angles to move the robot to a physically unattainable location. While this may seem purely academic, there are actually some very useful applications. Since complex angles cannot be actuated, it is necessary to map them into real angles. The most fundamental mapping is simply to drop the imaginary part of the angle. This is also used in developing other mappings. The result is that even though the robot cannot

execute the originally specified motion, it executes an alternative one given by the mapping. In some sense this approximates the motion. For several types of industrial robots, it has been shown that it provides the closest robot position. Importantly, the computational expense can be almost negligible, depending on the selected algorithm. There are two basic algorithms. In the first, as soon as a complex angle is encountered, it is transformed into a real angle and then used to compute the remaining angles. This is the most efficient computationally since it can be done using all real functions. The second method is to use complex arithmetic throughout the calculations until the final step where the complex angles are mapped into real ones. While there is virtually no increase in programming difficultly over the real case, all variables and functions must be computed using the complex forms. A useful application is to the control of teleoperator systems where a human directly controls a robot using a joystick or a button box. It is relatively easy to specify locations outside of the robot workspace. Ordinarily, the system would stop the robot once an impossible location is specified. This significantly degrades performance. Using the complex angle mapping provides a graceful means of recovery which in many cases provides an optimal alternative motion. Another application is to task planning for the interception of an object coming into the workspace, often placed there by another robot. While still unreachable, the robot can be commanded to grasp the object and it will respond with some alternative motion. When the object first enters into the workspace, the robot will be precisely located at the boundary to intercept it. Since this form of task planning requires so little computational overhead, it can be computed in real time. Further applications of the complex method extend to the dynamics and control of mechanical systems.

3. ***Analysis of Cooperating Robotic Mechanisms (with J. Joh).*** Cooperating robotic mechanisms include: dexterous hands, walking machines, and multiple arm robots. Typically, these are underconstrained systems which are statically indeterminate. The control of forces and torques in these systems is an important and fundamental issue. Most previous work has utilized the pseudoinverse solution yielding a minimum norm solution. By approaching the problem as a constrained optimization problem, a unified method has been developed in which many previous results are included and several new ones appear. Central to the problem is the interpretation of the Lagrangian multipliers as a physical quantity. Geometrically, they represent the coordinates of a screw quantity. It fully specifies the distribution of forces and torques in the system and leads to efficient calculation methods. By adding an additional quadratic constraint, a unique kinematic eigenvalue problem has been identified, the properties of which are under study. The overall formulation is also being extended to another class of underdetermined robots, redundant manipulators (containing more than six independent joints). The results are dualistic to the ones obtained for the force distribution of cooperating mechanisms.

4. ***Elastic Robotic Systems (with T. Patterson).*** The inherent compliance of a manipulator effects its control and performance. Most investigators have concentrated efforts on compensating for the effects of compliance in manipulation. There are relatively limited previous investigations into the structure of robot compliance. The investigation focusses on the eigensystem of a six by six compliance matrix which similtaneously transforms forces and torques into linear and

rotational deformations. The problem is not straightforward due to the fact that the action and the displacements are actually in two different types of screw coordinates. A proper eigenvalue problem can only be developed by introducing a coordinate transformation which changes the positive definite compliance matrix into an indefinite matrix. A similar result applies to the stiffness matrix. By themselves, the eigenvectors do not seem to convey useful information, but can be used to develop some important properties. The foremost result is the classification of robot compliance according to the number of existing compliant axes. A compliant axis is a central concept in robotics. It has the properties that a force along the axis produces a parallel linear displacement and a rotation about the axis creates a parallel reaction couple. These axes are useful since they greatly simplify the understanding of spatial compliance. A necessary and sufficient condition has been determined for their existence in terms of the eigensystem. A second eigenvalue problem has been developed whose solution generalizes the concept of compliant axes. This allows a further refinement in classification and is applicable to systems which other have no ordinary compliant axes. Further work will explore the extremal properties of these solutions and extend the results to kinematically constrained models.

5. ***Assembly Machines for Fine-Pitch Surface Mount Technology (with M. Shartouny).*** Circuit board assembly with fine pitch surface mount components requires accurate micropositioning. Current placement machines use gantry style geometries with integrated vision systems to increase their placement accuracy. For most systems, vision is used prior to placement to inspect the component and locate it relative to the printed wiring board. In some systems, increased precision is obtained

by actively tracking the component during placement using a specially aimed camera mounted to the placement arm. This method requires camera realignment for each type of component, and is thus limited in application. An alternative is to have fixed cameras focussing on targets affixed to the placement arm to direct component alignment. All assembly needs to be done at approximately the same location so it is necessary to shuttle the board on an X-Y table. It is also necessary for the arm to position the tooling accurately enough to be within the fields of view. The current work is to develop a model of the placement machine. Since most precision assembly is done at low speeds, a static deflection model is appropriate. This will provide basic information to determine the practicallity of using fixed camera locations for placement arm tracking. If deflections are large compared to the required placement accuracies, then frequent recalibration may be necessary. This is undesireable for a production system. The model will also be used to suggest improvements in the basic machine structure to increase accuracy. These will be summarized into a set of design guidelines.

Publications and Presentations:

1. Pohl, E. and Lipkin, H., "Real and Extended Workspaces of Robotic Manipulators," *ASME Transactions, Journal of Mechanical Design,* (Accepted for publication).

2. Patterson, T. and Lipkin, H., "Structure of Robot Compliance," *ASME Transactions, Journal of Mechanical Design,* (Accepted for publication).

3. Patterson, T. and Lipkin, H., "A Classification of Robot Compliance," *ASME Transactions, Journal of Mechanical Design,* (Accepted for publication).

4. Pohl, E. and Lipkin, H., "Kinematics of Complex Joint Angles in Robotics," *Proceedings 1990 IEEE International Conference on Robotics and Automation,* Cleveland, May 14-18.

5. Smith, D. and Lipkin, H., "Analysis of Fourth Order Manipulator Kinematics Using Conic Sections," *Proceedings 1990 IEEE International Conference on Robotics and Automation,* Cleveland, May 14-18.

6. Lipkin, H., "Invariant Properties of the Pseudoinverse in Robotics," *Proceedings 16th Conference on Production Research and Technology,* Tempe, January 8-12, 1990.

Ph.D. Students:

1. David Smith, Started - Fall 1988, Passed Comprehensive Exam - Spring 1988, Graduation - Spring 1990 (Expected). "Design of 6R Solvable Manipulators."

2. Eric Pohl, Started - Fall 1988, Passed Comprehensive Exam - Fall 1988, Graduation - Spring 1991 (Expected). "On Mappings of Complex Inverse Kinematic Solutions."

3. Joongseon Joh, Started - Fall 1988, Passed Comprehensive Exam - Spring 1988, Graduation - Spring 1991 (Expected). "Geometrical Analysis of Cooperating Robotic Mechanisms."

4. Timothy Patterson, Started - Fall 1988, Passed Comprehensive Exam - Fall 1989, Graduation - Spring 1991 (Expected). "Reduction of Compliance in Space-Based Manipulators."

5. D. Clay Ardoin, Started - Fall 1989.

6. Syed Jaffar, Started - Winter 1989.

PROGRESS REPORT

NSF 1987 Presidential Young Investigator Award
June 1990 - May 1991

BY

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FOR

Dr. Louis A. Martin-Vega
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National Science Foundation
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Grant No. DMC-8657599

Summary

This report documents the work performed under base funding for the fourth year of DMC-8657599, 1987 Presidential Investigator Award. In the past year, research has concentrated on four areas of investigation: complex number robot kinematics, force/torque control of robotic mechanisms, elastic robots, and surface mount placement machines. Work in these areas is essentially complete with two Ph.D.s to graduate this June and one to graduate in August. Additionally, one Ph.D. graduated in June 1990 with the corresponding research detailed in the previous annual report. Upcoming work will concentrate on the design of robotic bracing systems for manufacturing processes. This will make extensive use of our work on elastic robotic systems.

Technical Summaries:

1. ***Complex Number Kinematics of Manipulators (with E. Pohl).*** This work continues the research of the previous year. The inverse kinematic procedure determines the joint angles that position a robot at a specified location. If the robot can reach the location then the joint angles are all real. This work is the first to consider the case of complex joint angles. These occur if the specified location is outside of the robot workspace. Since complex angles cannot be actuated, it is necessary to map them into real angles. The result is that the robot executes an alternative motion. For several types of industrial robots, it has been shown that it provides the closest robot position. Importantly, the computational expense

can be almost negligible. A useful application is to teleoperator systems where a human directly controls a robot using a joystick or a button box. Ordinarily, the system would stop the robot once an impossible location is specified. The complex angle mapping provides a graceful means of recovery which in many cases provides an optimal alternative motion. The principal contributions of this year's research has been the discovery of new complex-to-real mappings, an analysis of their properties, and the extension of the technique to velocity control. The velocity control work also incorporates a new method of robot control near singularities, which currently plague all robots. Essentially, the mapping method approximates the velocity control using a second order approximation of the motion. While this requires the solution of a system of polynomial equations, the multi-dimensional Newton-Raphson technique has proven efficient. This is because the previous robot position provides a good initial guess for the new joint angles.

2. ***Analysis of Cooperating Robotic Mechanisms (with J. Joh).*** This work continues research on cooperating robotic mechanisms e.g., dexterous hands, walking machines, multiple arm robots, and redundantly actuated robots. These are underconstrained systems which are statically indeterminate. The control of forces and torques in these systems is an important and fundamental issue. Using a constrained optimization approach, a unified method has been developed. Many previous results are included and several new ones appear. Central to the problem is the interpretation of the Lagrangian multipliers as a physical quantity. Geometrically, they fully specify the distribution of forces and

torques in the system and lead to efficient calculation methods. By adding an additional kinematic quadratic constraint, directions of optimal loadings have been identified. This year, the loading properties been investigated and the overall analysis has been extended to systems encountering an environmental constraint. This has led to a new geometrical interpretation of the corresponding Lagrangian multipliers as projections of the unconstrained ones. When combined with some type of constitutive property such as mass, damping, or stiffness, the results yield loadings for which the expended energy is minimal.

3. ***Elastic Robotic Systems (with T. Patterson).*** There are relatively limited previous investigations into the structure of robot compliance. The investigation focusses on the eigensystem of a six by six compliance matrix which similtaneously transforms forces and torques into linear and rotational deformations. The problem is not straightforward due to the fact that the action and the displacements are actually in two different types of coordinates. A proper eigenvalue problem is developed by introducing a coordinate transformation which changes the positive definite compliance matrix into an indefinite matrix. The eigenvectors are used to develop important properties such as the classification of robot compliance according to the existence of compliant axes. A force along the axis produces a parallel linear displacement and a rotation about the axis creates a parallel reaction couple. These axes are a central concept in robotics since they greatly simplify the understanding of spatial compliance. A second eigenvalue problem has been developed which generalizes the concept of compliant axes. Work this year has demonstrated that these are

the most significant since all compliance matrices have a full set of them. Analysis of their properties show that they yield both the maximum and minimum stiffnesses of the elastic system. This considerably simplifies what is otherwise a very complicated system. Analysis of singular elastic systems leads to a generalized eigenvalue problem with singular matrices. In this case the eigenvalues may become infinite and indeterminate. Initial work has been performed in synthesizing a singular system from a nonsingular system in order to have desired properties. This forms the basis for the design of robotic bracing mechanisms.

4. ***Assembly Machines for Fine-Pitch Surface Mount Technology (with M. Shartouny).*** Circuit board assembly with fine pitch surface mount components requires accurate micropositioning. Current placement machines use gantry style geometries with integrated vision systems to increase their placement accuracy. This year, in order to analyze the current mechanical state-of-the-art, a previous static model was refined. Since most precision assembly is done at low speeds, a static deflection model is appropriate. It provides basic information on the accuracy of placement machines. Results of the analysis were used to develop a set of design guidelines for improvements in the machine structure to increase accuracy. For example, many assembly machines use a single overhead rail with the tooling and vision system asymmetrically overhung. Using realistic beam and bearing stiffnesses, it was found that this arrangement made the most significant contribution to unwanted deflections. Based on simulations, a simple redesign effectively eliminated this source of errors without additional cost. A conceptual

prototype was designed to maximize accuracy with minimize maintenance requirements to ensure continued precision.

Publications and Presentations:

1. Pohl, E. and Lipkin, H., "A New Method of Robotic Rate Control Near Singularities," *Proceedings 1991 IEEE International Conference on Robotics and Automation,* Sacramento, April 7-12.

2. Patterson, T. and Lipkin, H., "Duality of Constrained Elastic Manipulation," *Proceedings 1991 IEEE International Conference on Robotics and Automation,* Sacramento, April 7-12.

3. Joh, J. and Lipkin, H., "Lagrangian Wrench Distribution for Cooperating Robotic Mechanisms," *Proceedings 1991 IEEE International Conference on Robotics and Automation,* Sacramento, April 7-12.

4. Smith, D. and Lipkin, H., "A Summary of the Theory and Application of the Conics Method in Robot Kinematics," *Advances in Robot Kinematics,* Springer-Verlag, To Appear.

Ph.D. Students:

1. David Smith, Started - Fall 1988, Passed Comprehensive Exam - Spring 1988, Graduation - June 1990. "Design of 6R Solvable Manipulators."

2. Timothy Patterson, Started - Fall 1988, Passed Comprehensive Exam - Fall 1989, Graduation - June 1991 (Expected). "Reduction of Compliance in Space-Based Manipulators."

3. Joongseon Joh, Started - Fall 1988, Passed Comprehensive Exam - Spring 1988, Graduation - June 1991 (Expected). "Geometrical Analysis of Cooperating Robotic Mechanisms."

4. Eric Pohl, Started - Fall 1988, Passed Comprehensive Exam - Fall 1988,

Graduation - August 1991 (Expected). "On Mappings of Complex Inverse Kinematic Solutions."

5. Syed Jaffar, Started - Winter 1989.

6. Namik Ciblak, Started - Fall 1990.

OMB Number 345-0058

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NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. F. Hank Grant / DDM

2. Program Name Production Systems

3. Award Dates (MM/YY) **From:** 1 July 87 **To:** 31 Dec 92

4. Institution and Address

Georgia Tech Research Corp. / GTRI
Atlanta, GA 30332

5. Award Number DDM-8657599

6. Project Title

Presidential Investigator Award:
Hybrid Control for Robotics

**This Packet Contains
NSF Form 98A
And 1 Return Envelope**

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days alter the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

(See page 4)

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	19 March 93
Principal Investigator/Project Director Signature	Date

IMPORTANT:
MAILING INSTRUCTIONS
Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

PART IV -- FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1				6		2			
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]: American Indian or Alaskan Native										
Asian.										
Black, Not of Hispanic Origin.							2			
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin	1				6					
C. Total, Other Non-U.S. Citizens										
Specify Country 1. Korea					2					
2. Lebanon					1					
3.										
D. Total, All participants (A + B + C)	1				9		2			
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the orignal peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

NSF Form 98A (Rev. 10/90)

SUMMARY

Advances in nine areas of robotics and automation are reported: structure of Cartesian-modelled elasticity, complex number kinematics, design and analysis of manipulators with 4th order kinematics, analysis of underconstrained robotic mechanisms, design of a fully dexterous robotic wrist, design of fine-pitch placement machines, automatic robotic workcell calibration, root-locus analysis of manipulator kinematics, and singularity analysis of manipulators.

Key findings include: identification of extremal properties of elastic systems based on six by six stiffness matrices and screw theory; the physical properties of complex joint angles in manipulators due to violation of kinematic constraints; the kinematic design of five new robot geometrics suitable for industrial applications; a geometric characterization of properties for underconstrained robotic mechanisms such as walking machines, cooperative robots, and dexterous hands; and the design and implementation of the first robotic wrist that can attain every possible orientation.

DESCRIPTION OF RESULTS

Nine basic areas of research are summarized. The first four areas correspond to Ph.D. theses and are given the greatest detail. The remaining five areas correspond to M.S. theses and are presented much more concisely.

1. **Structure of Cartesian-Modelled Elasticity (with T. Patterson, Ph.D.).** There have been relatively limited previous investigations into the geometrical structure of generalized Hooke's Law for an elastically suspended rigid body. This work focusses on 6×6 stiffness and compliance matrices modelling stable systems about an equilibrium. The matrices relate applied forces and torques (wrenches) to the resulting linear and angular deformations (deformation twists). Both positive definite and semi-positive definite matrices are analyzed. Two generalized eigenvalue problems have been investigated in detail.

   The first eigenvalue problem was introduced by Ball (1900). Contributions include the identification of new properties which are used to classify elastic systems based on the existence of *compliant axes.* A force along a compliant axes creates a parallel linear deformation and an angular deformation about a compliant axis creates a reaction couple. Essentially, it represents decoupled linear and torsional springs about and axis. When compliant axes exist, they considerably simplify the understanding of elastic suspensions. For singular elastic systems, a new and important result shows that a complete set of eigenvectors does not exist when the null space of the matrix contains an isotropic (self-reciprocal) subspace. In practice this is very common and makes the delineation of physical properties difficult.

   The second eigenvalue problem was developed by expanding upon the work of Dimentberg (1965). Actually, it consists of a pair of eigenvalue problems. In the opinion of the authors, the investigation of these problems has provided the fundamental tools to investigate generalized compliance and stiffness. They apply equally to the nonsingular and singular cases. Principal results show that there *always exists* three orthogonal *wrench-compliant axes* and three orthogonal *twist-compliant axes.* Together these form the six eigenvectors. A wrench along a wrench-compliant axis produces a (pure) parallel linear deformation of the body. A twist along a twist-compliant axis produces a (pure) parallel reaction couple. These are proper generalizations of the compliant axis notion. All stiffness and compliance matrices have full sets of these elements. They are used in a congruence transformation to *diagonalize* the stiffness and compliance matrices. The diagonal elements are the eigenvalues representing the *stationary values* of linear compliance and angular stiffness. The eigenvectors are then used to define a *center-of-elasticity* whose properties are investigated. By analogy, the six eigenvectors can be used to generalize the concept of principal axes of inertia to six dimensions.

2. **Complex Number Kinematics (with E. Pohl, Ph.D.).** It is believed that this is the first comprehensive work to investigate the kinematics of complex joint angles. While complex number representations have been used to represent *real* joint angles of mechanisms, e.g. Sandor (1959), typically the angles themselves are not considered to be complex. For a manipulator, if a specified position and orientation of the terminal link is outside of the workspace, then the inverse kinematic calculation returns complex joint angles. Since complex joint angles cannot be actuated, for practical applications it is necessary to map them into real joint angles. The result is that an alternative motion is executed. The simplest mapping is to merely use the real part of the joint angle. For several types of manipulators, it is proved that this best approximates the position or orientation. General criteria are developed which delineate additional suitable mappings. A transcendental mapping is examined which also has application to joint angles with finite rotation limits and to prismatic joints.

Importantly, the additional computational expense can be almost negligible if complex joint angles are immediately mapped before they are used to calculate the remaining joint angles. In general this produces different results than mapping the angles after they are all determined. A useful application is to teleoperator systems where a human directly controls a manipulator using a manual control device. Humans routinely specify locations outside of the workspace. The complex angle mapping provides a graceful means of recovery which in many cases provides an optimal and easily predictable alternative motion.

The mapping technique has also been extended to instantaneous kinematics and velocity control. It incorporates a new method of kinematic control near singular configurations. Essentially, the mapping method approximates velocity control using a second order approximation of the motion. While this requires the solution of a system of polynomial equations, the multi-dimensional Newton-Raphson technique has proven efficient in simulations.

3. **Design and Analysis of Manipulators with Fourth Order Kinematics (with D. Smith, Ph.D.).** A new technique has been developed to analyze fourth degree manipulators and by extension, fourth degree polynomials. Currently, almost all industrial manipulators belong to a rather limited class in which the inverse position kinematics may be solved by consecutive quadratic equations. The next level of design requires the solution of quartic polynomials for which the properties are substantially more difficult to analyze. The problem is transformed into the investigation of a linear pencil of conics. Using the well-known invariants of conics, all such manipulators can be given a unique classification. Because the coefficients may contains hundreds of terms with physical dimensions, a symbolic manipulation program facilitates the derivations.

   Two important applications have been made. First, it has been discovered that degenerate conic pencils, which always contain a pair of parallel lines, yields the criteria for fourth order kinematics to degenerate into the simpler second order kinematics. For manipulators which contain a wrist (the most common), seven second order designs have been found, five of which are previously unknown and have potential industrial application. Second, the conic representation has been used to evaluate the workspace properties for fourth order manipulators. This includes the indentification of workspace singularities which must always be considered in control.

4. **Analysis of Underconstrained Robotic Mechanisms (with J. Joh, Ph.D.)** This work focusses on dexterous hands, walking machines, multiple armed and redundantly actuated manipulators. These are underconstrained systems which are statically indeterminate. The control of forces and torques in these systems is an important and fundamental issue. Using a constrained optimization approach, a unified method has been developed. Many previous results are included and several new ones developed.

   Central to the problem is a new interpretation of Lagrangian multipliers as a physical quantity called the Lagrangian screw. Geometrically, they fully specify the distribution of forces and torques in the system. By adding an additional quadratic kinematic constraint, directions of optimal loadings are identified. The overall analysis has been extended to include systems with an environmental constraint. This has led to a new geometrical interpretation of the corresponding Lagrangian multipliers as projections of the unconstrained ones. When combined with a constitutive property such as inertia, damping, or stiffness, the results yield loadings for which the expended energy is minimal.

5. **Design of a Fully Dexterous Robotic Wrist (with S. Coleman, M.S.)** A novel wrist is designed and prototyped which allows continuous rotations of all three joint angles. Based on a spherical linkage, the wrist can orientate an object in any direction with any spin. The hand is located at the wrist center so that any external force load intersects each joint axis. Thus joint torques are unnecessary to maintain static equilbrium. This is especially useful for carrying large gravity loads using light-duty actuation.

6. **Design of Fine-Pitch Surface Mount Placement Machines (with M. Shartouny, M.S.)** Several placement machines are modelled using representative bearing and beam stiffnesses. Based on simulation results, a redesign eliminates a major source of placement errors without increasing cost.

7. **Automated Workcell Calibration (with M. Duggan, M.S.)** A novel positioning cali-

bration procedure for industrial manipulators is developed using a six degree-of-freedom force/torque cell. It is a relatively simple routine and calculation that can be performed daily or before processing a new production batch.

8. **Root-Locus Analysis of Manipulator Kinematics (with Y.S. Park, M.S.)** A new kinematic analysis is developed by transferring the root-locus method from control theory. An important result is that root-locus breakpoints correspond to singular configurations. By adjusting physical dimensions, open-loop poles and zeros change and the locations of the singularities are correspondingly altered.

9. **Singularity Analysis of Manipulators (with E. Pohl, M.S.)** For several industrial manipulators, an exhaustive enumeration of singularities and their simultaneous occurrence is developed. Using a novel recursive formulation and a tree structure, combinations of primary singularities yield the possible secondary and ternary singularities.

STUDENT DEVELOPMENT (Thesis titles are in the following publications list.)

Ph.D. Graduates:

1. David Smith, 1990
2. Timothy Patterson, 1991
3. Joongseon Joh, 1991
4. Eric Pohl, 1991

M.S. Graduates (With Thesis):

1. Daniel Gehrman, 1987
2. Young Soo Park, 1988
3. Eric Pohl, 1988

4. Matthew Duggan, 1988
5. Micheal Shartouny, 1991
6. Scott Coleman, 1991

B.S. Students: Nine undergraduate students have been involved in research projects with final report documents.

Development of Engineering Students from Underrepresented Groups: During 1988-1989, an NSF Research Experience for Undergraduates Supplement was obtained. This supported two students from an underrepresented group to perform laboratory research on robot control and computer interfacing. Final project reports were submitted.

PUBLICATIONS

Coleman, Scott, "Design of a Fully Dexterous Robotic Wrist," M.S. Thesis, Mechanical Engineering, Georgia Institute of Technology, 1991.

Duggan, Matthew "Automatic Correction of Robot Programs Based on Sensor Calibration Data," M.S. Thesis, Mechanical Engineering, Georgia Institute of Technology, 1988.

Gehrman, Daniel, "Utilization of Force Sensing in the Modified Inverse Damping Control of Robot Manipulators," M.S. Thesis, Mechanical Engineering, Georgia Institute of Technology, 1987

Joh, Joongseon, "Geometrical Analysis of Underconstrained Robotic Mechanisms," Ph.D Dissertation, Mechanical Engineering, Georgia Institute of Technology, 1991.

Joh, J. and Lipkin, H., "Lagrangian Wrench Distribution for Cooperating Robotic Mechanisms," 1991 IEEE International Conference on Robotics and Automation, Sacramento, April 7-12, 1991.

Joh, J. and Lipkin, H., "A Unified Framework for Analysis of Cooperating Robotic Mechanisms," Theory of Machines and Mechanisms, 8th World Congress, Prague, August 26-31, 1991.

Lipkin, H., "Sensor-Based Modification of Local Models for Robotic Manipulation," pp. 313-332, CAD Based Programming for Sensory Based Robots, NATO Advanced Science

Institute Series F: Computer and Systems Sciences Vol. 50, (R. Ravani, Ed.), Springer-Verlag, New York, 1988.

Lipkin, H., "Sensor-Based Modification of Trajectories and Local Models for Robotic Manipulation," 15th Conference on Production Research and Technology: Advances in Manufacturing Systems Integration and Processes, Berkeley, pp. 171-178, January 9-13, 1989.

Lipkin, H., "Invariant Properties of the Pseudoinverse in Robotics, "16th Conference on Production Research and Technology, Tempe, January 8-12, 1990.

Lipkin, H. and Park, Y.S., "Investigation of Robot Kinematics Via the Tan-Half Angle Root-Locus," ASME Computers in Engineering, San Francisco, vol. 2, pp. 275-284, July 31 - August 3, 1988.

Lipkin, H. and Park, Y.S., "Root-Locus Analysis of Robot Kinematics," ASME Transactions, Journal of Mechanical Design. (Accepted for publication.)

Lipkin, H. and Patterson, T., "Generalized Center of Compliance and Stiffness," 1992 IEEE International Conference on Robotics and Automation, Nice, May 10-15, 1992.

Lipkin, H. and Patterson, T., "Geometrical Decomposition of Robot Compliance," CSME Forum 1992, Montreal, June 1-5, 1992.

Lipkin, H. and Patterson, T., "Geometrical Decomposition of Robot Elasticity," Theory and Practice of Robots and Manipulators, Proceedings of RoManSy'92: The Ninth CISM-IFToMM Symposium, Udine, Italy, September 1-4 1992.

Lipkin, H. and Patterson, T., "Geometric Properties of Modelled Robot Elasticity: Part I Decomposition," 1992 ASME Design Technical Conferences, Vol. DE 45, pp 179-185, Scottsdale, September 13-16.

Lipkin, H. and Patterson, T., "Geometric Properties of Modelled Robot Elasticity: Part II Center-of-Elasticity," 1992 ASME Design Technical Conferences, Vol. DE 45, pp 179-185, Scottsdale, September 13-16.

Lipkin, H. and Pohl, E., "Enumeration of Singular Configurations for a Robotic Manipulators," ASME Design Technology Conferences - 20th Biennial Mechanisms Conference, Kissimmee, Florida, vol. 3, pp.283-290, September 25-28, 1988.

Lipkin, H. and Pohl, E., "Enumeration of Singular Configurations for a Robotic Manipulators," ASME Transactions, Journal of Mechanical Design, vol. 113, no. 3, pp. 272-285, September 1991.

Park , Young Soo, "Applications of Complex Numbers to Robotic Manipulators," M.S. Thesis, Mechanical Engineering, Georgia Institute of Technology, 1988.

Patterson, Timothy , "Reduction of Compliance in Spaced-Based Manipulators," Ph.D Dissertation, Mechanical Engineering, Georgia Institute of Technology, 1991.

Patterson, T. and Lipkin, H., "Structure of Robot Compliance," ASME Transactions, Journal of Mechanical Design. (Accepted for publication.)

Patterson, T. and Lipkin, H., "A Classification of Robot Compliance," ASME Transactions, Journal of Mechanical Design. (Accepted for publication.)

Patterson, T. and Lipkin, H., "Duality of Kinematically Constrained Elastic Manipulation," International Journal of Laboratory Robotics and Automation, Vol. 4 pp. 77-84, 1992.

Patterson, T. and Lipkin, H., "A Classification of Robot Compliance," ASME Design Technology Conferences - 21th Biennial Mechanisms Conference, DE-Vol. 26, pp.307-314, Chicago, September 17-19, 1990.

Patterson, T. and Lipkin, H., "Structure of Robot Compliance," ASME Design Technology Conferences - 21th Biennial Mechanisms Conference, DE-Vol 26, pp.315-322, Chicago, September 17-19, 1990.

Patterson, T. and Lipkin, H., "Duality of Constrained Elastic Manipulation," 1991 IEEE International Conference on Robotics and Automation, Sacramento, April 7-12, 1991.

Pohl, Eric, "Enumeration of Singular Configurations for Robotic Manipulators," M.S. Thesis, Mechanical Engineering, Georgia Institute of Technology, 1988.

Pohl, Eric, "On Mappings of Complex Inverse Kinematic Solutions," Ph.D Dissertation, Mechanical Engineering, Georgia Institute of Technology, 1991.

Pohl, E. and Lipkin, H., "Kinematics of Complex Joint Angles in Robotics," 1990 IEEE International Conference on Robotics and Automation, pp.86-91, Cleveland, May 14-18, 1990.

Pohl, E. and Lipkin, H., "Kinematic Behavior of Mapped Complex Joint Angles in Robot Manipulators," Theory and Practice of Robots and Manipulators, Proceedings of RoManSy'90: The Eighth CISM-IFToMM Symposium, Cracow, Poland, July 1990 (In press).

Pohl, E. and Lipkin, H., "Real and Extended Workspaces in Robotic Manipulators," ASME Design Technology Conferences - 21th Biennial Mechanisms Conference, DE-Vol. 25, pp.307-314, Chicago, September 17-19, 1990.

Pohl, E. and Lipkin, H., "A New Method of Robotic Rate Control Near Singularities," 1991 IEEE International Conference on Robotics and Automation, Sacramento, April 7-12, 1991.

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