13:56:41 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 07/18/94

Active

Project #: E-25-644 Cost share #: Rev #: 11
Center # : 10/24-6-R6806-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: DDM-8958383 Mod #: OPAS Document : GRANT
Prime #: Contract entity: GTRC

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

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
LEE K-M MECH ENGR (404)894-7402

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

Award period: 890901 to 950831 (performance) 951130 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	322,000.00
Funded	0.00	322,000.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: PYI AWARDS

PROJECT ADMINISTRATION DATA

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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
COMPUTER SYS. & MULTI-CHANNEL AMPLIFIER
Administrative comments -
ISSUED TO EXTEND PROJECT TERMINATION DATE TO AUGUST 31, 1995. FINAL PROJECT REPORT DUE NOVEMBER 30, 1995.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

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SR 31

Closeout Notice Date 12/05/95

Project No. E-25-644 Center No. 10/24-6-R6806-0A0

Project Director LEE K-M School/Lab MECH ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-8958383 Contract Entity GTRC

Prime Contract No.

Title PYI AWARDS

Effective Completion Date 950831 (Performance) 951130 (Reports)

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

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REQUIREMENT.

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	N
	N

1

E-25-644

PROGRESS REPORT

The current research has two major thrusts. The first focuses on the modeling and experimental investigation of an innovative spherical wrist actuator. The second attempts to establish a rational basis of flexible part-feeding applicable to a broad class of flexible manufacturing systems (FMS).

1. Spherical Wrist Actuator

The objective is to create an innovative prototype spherical wrist actuator which presents some attractive possibilities by combining pitch, roll, and yaw motion in a single joint. In addition to the compact design without the use of a speed reducer, the spherical wrist actuator results in relatively simple joint kinematics and has singularities only at the boundaries of the workspace. The proposed wrist actuator has potential applications where high-speed, precision, and isotropic manipulation of end-effector orientation is required continuously in all directions.

The current research fund has been directed towards the prototype design and development, which will serve as experimental testbeds. Two testbeds have been designed: (1) a preliminary three degrees-of-freedom (DOF) planar actuator and (2) a three DOF spherical joint actuator. The first testbed is to provide the verification of analytical models and to aid control algorithm development and implementation. The second testbed will be developed to provide performance evaluation and demonstration to prove concept feasibility of the complete spherical joint actuator. The current research fund has provided the support of a graduate student in conducting the prototype development and to provide material supplies, and equipment needed for the development of the first experimental testbed. A Post-Doctoral Associate will be involved in this research in developing the optimal control algorithm.

The projected activities for the twelve month period of the second year PYIA funding will be directed towards the experimental investigation and developing the control algorithm. The objectives of the research are to identify the optimal design parameters, to verify the analytical prediction, and to provide physical insights and rational basis of dynamic modeling. The research funding be requested will be to support the PI for two summer months, and two Ph. D. students in performing the research. It is expected that the second experimental testbed will be developed with the industrial funds from the E. I. DuPont de Nemours & Co.

2. Generic Part-presentation

A recent survey on part-feeding methods applicable to a broad class of flexible manufacturing systems has indicated that the flexibility of the overall flexible automated factory cannot be fully exploited due to a lack of flexible part-feeding sub-systems, which may comprise two-thirds of the overall investment and are usually the source of a large percentage of work stoppage and defects. A list of quotations in TABLE I which highlights the problems encountered worldwide in FMS provides evidences of this concern and the research needs.

A research project has been initiated with the industrial funds from Ford Motor Company and General Motor Corporation and the NSF PYIA first year industrial matching fund. The objective is to establish the basic engineering science needed in the area of peripheral to create generic part-presentation system that is flexible, programmable, reliable, and cost-effective. The current research has led to an innovative concept of giving retroreflective material an integral role in sensing for generic part-presentation [8] [9]. The investigation has shown that the retroreflective vision sensing has significant potentials in improving the vision reliability, reducing computation time, and lower the cost in implementation.

The research findings present several new challanges in part-presentation and feeding: high-speed intelligent computation of part's location and orientation, which is less sensitive to environmental effects, establishment of guidelines for generic part-presentation equipment standardization, formulation of part-design and part-packaging guidelines for effective part-feeding. The projected activities for the twelve month period of the second year PYIA funding will address some of these research issues. It is expected that an experimental testbed will be developed to demonstrate the concept feasibility for flexible part-feeding for sub-assembly applications. The Cincinnati Milacron T3 786 industrial robot donated by the R. R. Donnelly and Sons Company will be dedicated to this purpose. Part of the requested NSF second year PYIA matching fund will support a Ph D. student in this project.

TABLE I Problems in Flexible Part-feeding

Year	Country	Quotation
1983	Japan	"Vibratory feeders are most commonly used to feed and orient mechanical parts, but they are far from flexible. Feeder track and orienting devices should be matched to a specific workpiece configuration. Still more, some workpieces cause jamming at the fine toolings of the track." S. Hara, K. Azuma, and K. Hironaka [1] Mitsubishi Electric Corporation
1986	Switzerland	"In a flexible automated installation feeding systems are often entirely inflexible and yet they may constitute 2/3 of the overall investment costs of the installation. They are also generally the source of the very large majority of defects and stoppage." L. S. Horvath [2] Cybro SA.
1986	West Germany	"The problem of fully automatic flexible assembly cells lies in the presentation of parts." "The weakness lies in the peripherals design and in the current price of freely-programmable handling devices." B. Lotter [3] E. G. O. Elektro - Geratebau
1986	UK	"In general purpose assembly, the cost of associated with peripheral equipment is usually prohibitive and this is particularly true if automatic parts feeders cannot be used and reliance has to be on magazines." A. H. Redford [4] University of Salford
1987	USA	"Conventional part-presentation methods (tape feeders, vibratory feeders, stick feeders, etc.) prove time-consuming and are not cost-effective for the high-mix environment." Michael R. Oquist [5] Control Data Corp., Minneapolis
1987	Sweden	"For complex objects the image processing time itself can be up to 4 s. This is for too long a time." A. Arnstrom and P. Grondahl [6] Swedish Institute for Production Engineering Research
1988	USA	"Experience so far has shown, ... it is the feeder that fails in the workstation, not the robot." Linda Decelle [7] AT&T's Merrimack Valley Works, North Andover MA

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7. L. S. Decelle, "Design of a Robotic Workstation for Component Insertions," AT&T Technical Journal, March/April 1988, Volume 67, Issue 2. pp 15-22.

8. K-M. Lee and D-R. Li, "Retroreflective Vision Sensing for Generic Part-Presentation," Conference Record of the 1990 IEEE SouthCon/90, Orlando, Florida, March 20-22.

9. K-M. Lee and D-R. Li, "Principle and Applications of Retroreflective Vision Sensing for Discrete Part-Presentation," 1990 Japan-USA on Flexible Automation, July 9 - 13, 1990, Kyoto, Japan.

ABSTRACT

The current research has two major thrusts. The first focuses on the modeling and experimental investigation of an innovative spherical wrist actuator. The current research has been directed towards the prototype design and development of a spherical wrist actuator. The projected activities for the twelve month period of the second year PYIA funding will be directed towards the experimental investigation and developing the control algorithm of the spherical joint actuator. The second research project has been initiated with the industrial funds from Ford Motor Company and General Motor Corporation and the NSF PYIA first year industrial matching fund to establish the basic engineering science needed in the area of peripheral to create generic part-presentation system that is flexible, programmable, reliable, and cost-efficient. The current research has led to an innovative concept of giving retroreflective material an integral role in sensing for generic part-presentation. An experimental testbed will be developed to demonstrate the concept feasibility for flexible part-feeding for sub-assembly applications.

E-25-644

ANNUAL PROGRESS REPORT on PYI Awards (NSF Grant DDM-8958383)

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Current research has been continued on two major thrusts. The first thrust focuses on the experimental investigation of an innovative wrist actuator. The second thrust has been directed towards establishing a rational basis of flexible part-feeding applicable to a board class of flexible manufacturing systems (FMS).

1. Spherical wrist actuator

The objective is to create an innovative prototype spherical wrist actuator [1] which presents some attractive possibilities by combining pitch, roll, and yaw motion in a single joint. In addition to the compact design without the use of a speed reducer, the spherical wrist actuator results in relatively simple joint kinematics and has singularities only at the boundaries of the workspace. The proposed wrist actuator has potential applications where high-speed and precision isotropic manipulation of the end-effector orientation is required in all directions.

Past research efforts have been directed towards the design and development of a prototype variable reluctance (VR) spherical motor, which serves as experimental testbed. Two experimental testbeds have been developed. As discussed in [2], the validity of the permeance model is essential to the success of control algorithm development and implementation. The first testbed, a three degrees-of-freedom (DOF) planar actuator, has been developed to provide the verification of permeance model [3] upon which the analytical model of the spherical motor was built. The identification of optimal design parameters on the three DOF VR planar motor and the theoretical framework presented in [4] have provided the basis for the design and development of the second testbed, a prototype three DOF VR spherical motor.

The projected activities for the third year funding period will be directed towards motion control law development and implementation of the three DOF spherical motor. The VR spherical motor is characterized by the ability to control a relatively large number of distributed actuating coils individually to achieve smooth orientation control. The research on motion control of the spherical wrist will be performed in two tasks. The first task will determine analytically the optimal input torque vector for any specified conditions. Upon that, the second task will be conducted to develop motion control law based on the feedback of the orientation measurement. The second testbed will be used to prove concept feasibility of motion control law.

Vision-guided flexible part-feeding

The research objective is to develop a flexible computer-controlled system for feeding parts into machine tools or assembly processes that combines maximum flexibility and reliability with minimum cost and cycle-time.

Although it has been well recognized in the past decade that computer vision can add considerably to flexibility by simplifying grippers, component feeders, and location tooling, and can reduce the engineering time required to implement it, research in practical part-feeding automation has concluded that current computer vision techniques have been significantly limited by the following factors [5]:

1. Many vision systems of todays are integrated using off-the-shelf cameras such as entertainment and surveillance type cameras, which are created for human eyes and brains rather than for machine perception. Biological vision tends to be insensitive to absolute light intensity and spatial accuracy. Video camera tends to suffer the same biases as humans do. Moderate location inaccuracies pose no difficulty for human operators since they use vision, hand-eye coordination, sense of touch to locate and correctly load the parts. The attempt to duplicate human perception often for for time-consuming computation and does not necessarily determine the location and orientation of a given part with the accuracy required for successful part-acquisition by the robot.

2. Conventional vision systems often built upon off-the-shelf components. In general, the system includes a video camera which outputs a standard RS170 video signal, a frame grabber board which converts the RS170 video signal into a series of n bit brightness values (grey levels) and stores them in fast memory components, and a micro-computer which computes the location and orientation of the part. In addition to error resulting from the timing mis-match between the image acquisition and the computer hardware, the RS170 video signal limits the read out of a complete frame at a rate of 30 fps (frame per second).

3. Apart from the lack of appropriate hardware and the high equipment cost, two other major problems often associated with the conventional video system are poor reliability and excessive image processing time, both of which depend on illumination techniques, the complexity of the geometry, and the surface reflectance of both the background and the objects to be handled. In addition, system specifications for illumination are often vague or may be left to the final user.

Past research efforts have demonstrated that the potential flexibility and reliability of machine vision can be achieved by means of retroreflective vision sensing technique [6] [7]. The concept of retroreflective vision sensing for flexible part-feeding was demonstrated using two prototype systems, a breadboard configuration integrated using off-the-shelf hardware [8] and an integrated vision system (IVS) [9]. The latter has led to the concept development of GRIPPS (Generic Retroreflective Integrated Part-Presentation System) [9][10]. Practical implementation issues of the low-cost integrated vision system for flexible part-feeding were addressed [11].

Current research efforts have been directed towards performance analysis, algorithm development for model-based vision sensing, and overall system integration for cost-effective flexible part-feeding.

The projected activities for the third year PYIA funding period will be directed towards two major thrusts: The first is to establish analytical design tools for vision-guided part-presentation and assembly. In particular, the research will focus on system characterization, illumination simulation, and performance prediction for effective vision-guided part-presentation. The second thrust will be directed towards the investigation of model based retroreflective vision sensing for part kitting based on an integrated vision system. The performance analysis would result in an assessment of the system calibration, cycle-time distribution, and sensor physical parameters. Upon that the system integration is based which adequately deals with the critical points emerged from the analysis. The Factory-of-the-Future Kitting Cell donated by General Motors Corporation will serve as a testbed in a real world environment in the proposed research.

References:

1. Lee, K-M., and Kwan, C-K., "Design Concept Development of a Spherical Wrist Stepper," IEEE Journal of Robotics and Automation, Vol. 7, No.1, p.175-180, February 1991.
2. Lee, K-M., Pei, J-F and Gilboa, U., "On the Development of a spherical Wrist Actuator," Proceedings of the 16th NSF Conference on Manufacturing Systems Research, Tempe AZ, January 8-12, 1990.
3. Pei, J-F., "Methodology of Design and Analysis of Variable-Reluctance Spherical Motors," Ph.D. Thesis, (ME) Georgia Institute of Technology, October 1990.
4. Lee, K-M. and Pei, J-F., "Kinematic Analysis of a Three Degrees-of-Freedom Spherical Motor," Proc. of the 5th Int'l. Conference on Advanced Robotics, Pisa, Italy, June 20-22, 1991.
5. K-M. Lee, "Flexible Part-feeding system for Machine Loading and Assembly, Part I: A State-of-art Survey and Part II: A cost-effective Solution, " Submitted to the International Journal of Production Economics.
6. K-M. Lee and D-R. Li, "Retroreflective Vision Sensing for Generic Part-Presentation," MHRC Technical Report MHRC-TR-89-06. Presented at 1990 IEEE SouthCon/90, Orlando, Florida, March 20-22. Also in Journal of Robotic Systems, February 1991, Vol. 7, Number 1.
7. K-M. Lee, "A Low-cost Flexible Part-Feeding System For Assembly Automation," Proceedings of the ICARCV International Conference on Automation, Robotics and Computer Vision, 18-21 September 1990, Singapore.
8. S. Yutkowitz, "A Practical Vision-Guided Part Feeding Algorithm for Flexible Manufacturing," MS Thesis (ME), MHRC Report TD-90-10.
9. K-M. Lee, S. Dickerson and J. Mercurio, "Generic Retroreflective Integrated Part Pickup System (GRIPPS)," Proceedings of the 1991 NSF Conference on Design and manufacturing, Jan. 9-11, Austin, Texas.
10. K-M. Lee, R. Blenis, S. Yutkowitz, and P. Motaghedi, "Software GRIPPS," January 1991 (Version 1.0 Draft)

11. K-M. Lee, R. Blenis, S. Yutkowitz, D-R. Li, and P. Motaghedi, "A Low-cost Flexible Part-feeding System for Machine Loading and assembly," MHRC Final Report (Draft), April 1991.

Abstract

The current research has two major thrusts. The first thrust focuses on the experimental investigation and motion control of an innovative spherical wrist actuator. Two prototype testbeds have been developed to aid verification of permeance model, upon which the analytical model of the spherical motor was built. The projected activities for the proposal twelve month funding period will be directed toward motion control law development and implementation. The second research thrust is to establish the basic engineering science needed for flexible part-feeding. The investigation has led to the concept of GRIPPS (Generic Retroreflective Integrated Part-Pickup System). The projected activities in the proposed funding period will focus on the establishment of analytical design tools and performance analysis for part kitting.

ANNUAL PROGRESS REPORT ON PYI AWARDS (NSF Grant DDM-8958383)

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During the reporting period (October 1, 1989 - April 30, 1992), the grant's activities have focused on two areas: The first thrust has been directed towards the experimental verification of an innovative spherical wrist actuator. The second thrust addressed the problem of feeding components parts for machine loading and assembly.

1. Spherical wrist actuator

The objective is to create an innovative prototype spherical wrist actuator which presents some attractive possibilities by combining pitch, roll, and yaw motion in a single joint. In addition to the compact design without the use of a speed reducer, the spherical wrist actuator results in relatively simple joint kinematics and has singularities only at the boundaries of the workspace. The proposed wrist actuator has potential applications where high-speed and precision isotropic manipulation of the end-effector orientation is required in all directions.

Past research efforts have been directed towards the design and development of a prototype variable reluctance (VR) spherical motor. Specific findings and contributions are listed as follows:

- The design concept of a VR spherical motor, which allows a few but evenly spaced ferromagnetic poles to be used for three DOF actuation, has been further developed. The design concept allows high positioning resolution of the VR spherical motor to be achieved by using continuous-amplitude current control instead of by increasing the number of poles with constant-amplitude current switching. As a result, the mechanical structure and the control circuitry of a VR spherical motor are much simplified for manufacturing.

- The kinematic model of the VR spherical motor has been derived, which is essential to the dynamic modeling, design optimization, and motion control of a VR spherical motor. The kinematic model of a VR spherical motor is a function of the derivative of the overlapping area between the stator and rotor poles in a three-dimensional space. It represents the first detailed study of the kinematic analysis of a three DOF VR spherical motor. Yet, the model permits a spectrum of design, and provides the basis for designing a practical spherical motor operated on the principle of variable-reluctance (VR) motor.

- Two experimental testbeds have been developed. The validity of the permeance model is essential to the success of control algorithm development and implementation. The first testbed, a three DOF planar actuator, has been developed to provide the verification of permeance model upon which the analytical model of the spherical motor was built. The identification and modeling of the optimal design parameters have provided the basis for the design and development of the second testbed which represents the first unique, potentially useful design of a three DOF VR spherical motor. It offers some interesting insights to the design, manufacturing, modeling, and motion feasibility study of a VR spherical motor.

- An analytical dynamic model and the control strategy of an unique, potentially useful design of a three DOF ball-joint-like VR spherical motor has been developed. The model represents the first detailed study on both the forward and the inverse dynamics of a VR spherical motor, which permits a spectrum of design configurations to be analyzed. The analysis offers some interesting insights to the design and control of VR spherical motors.

  The inverse model of a VR spherical motor, which determines the coil excitations for a specified torque, is characterized by its infinite solutions. It has been shown that for a current controlled spherical motor, the relationship between the output torque and the input currents are algebraic and quadratic. The torque prediction model of a current controlled VR spherical motor is decoupled from the dynamic equations of the system, and therefore allows the determination of the optimal electrical inputs to be separated from the motion control of the spherical rotor.

  For motion control of the VR spherical motor, both the forward dynamics which determine the motion as a result of activating the motor coils and the inverse model which determines the coil excitations required to obtain the desired torques are needed. The solution to the inverse model has multiple solutions and allows an optimal control vector to be chosen to minimize a specified cost function. The distributed multi-inputs allows a greater flexibility in controller designs. This characteristic significantly differs from that of a popular three-consecutive-rotational-joint wrist based on the traditional single-axis motor or spherical motors of other types which typically have unique solutions to both the forward and inverse dynamics.

  Along with the formulation of the input vector optimization, the method of designing a lookup table for the practical implementation of the optimal solution in real-time has also been addressed. It has been shown that the memory size of the lookup table can be effectively reduced by parameter elimination and by making use of the symmetry property of the pole configuration. Research efforts are being directed towards the experimental verification of the inverse model, and the development of real-time algorithms for input vector optimization and implementation.

- The development of the ball-joint-like VR spherical motors has motivated the investigation of an alternative wrist sensor for direct measurement of three degrees-of-freedom (DOF) orientation. Single-axis encoders are often used in measuring three DOF orientation of a ball-joint-like device. The use of these single-axis encoders for measuring multi-DOF orientation requires a mechanism to house the encoders. This moving mechanism which

constrains the rotor for orientation measurement by using single-axis encoders introduces friction, stiction, and inertia.

A three DOF vision-based orientation sensor has been conceptualized. The vision-based orientation sensor provides a means for direct measurement of the pitch, roll, and yaw motion. In addition to the compact design, the vision-based wrist orientation sensor is essentially a non-contact measurement system and thus, eliminates friction and stiction, and has low inertia. It is expected that this design concept would offer a potential solution to overcome the problems associated with the conventional three-consecutive-joint-measurement using single-axis encoders. Research efforts are being directed towards design and experimental testing of a prototype imaging system.

2. Vision-guided flexible part-feeding

The research addressed the problem of and a potential solution to cost-effective feeding of parts. The problem is to precisely locate known objects, which are supplied in separate, regularly-spaced locations in totes, pallets, or kit. The investigation has led to the development of a prototype system called GRIPPS (Generic Retroreflective Integrated Part Pick-up System) as peripheral equipment of robots. Specifically, the research has addressed the following issues: 1) a state-of-the-art survey on current part-feeding approaches and part-presentation techniques, 2) the fundamental principles of the optics used for effective collocated illumination, 3) an algorithm for cost-effective part-presentation, and 4) the development and evaluation of two prototype systems. Specific findings and contributions are listed as follows:

- Traditional part-feeding methods rely primarily on part-specific tooling. These traditional approaches have severely limited the flexibility of the overall flexible automation from being fully exploited, which may two-thirds of the overall investment and are usually the source of a large percentage of work stoppages and defects.

- Although it has been well recognized in the past decade that computer vision can add considerably to flexibility by simplifying grippers, component feeders, and location tooling, and can reduce the engineering time required to implement it, current computer vision techniques have several limitations for uses in real-time part-presentation.

  Computer vision systems of today are largely based on video TV standards. These systems, though well developed and available widely in commercial markets, are more suitable for human perception than machine vision for manufacturing applications, where relatively short cycle-time, reliability, and precision are required at low cost.

  Apart from a lack of appropriate hardware for real-time part-presentation, there does not exist a systematic design methodology to aid designers and process planners for developing a cost-effective vision-guided part-presentation.

- A technique of giving retroreflective materials an integral role in vision-guided part-presentation has been conceptualized. The technique does not rely on the knowledge of a detailed object geometry or the surface reflectance of the object and its background. This technique has potential applications for locating quasi two-dimensional objects the

orientation of which can be characterized by its silhouette, outline, or structured "engineered landmarks." It has been proven to have significant potentials in improving reliability, reducing the computational load/time, and lowering the cost of implementation for part-feeding.

- Two prototypes were experimentally investigated in order to provide a rational basis for future development of a vision hardware for flexible part-feeding. The first prototype, a breadboard configuration, has been built by using off-the-shelf components: a video camera, a frame-grabber, a standard IBM PC/AT, and a separate illumination configuration. The second prototype, an integrated vision system, has been built upon an electronic framework of a landmark tracking system originally designed to track well-defined circular landmarks in the navigation of an AGV.

  The system performance of the off-the-shelf breadboard configuration are found to be limited by both the video format specified by the TV standard and the data bus of the host computer. Consequently, significant overhead cost to support memory, clock synchronization, system bus, data communication, and power supply.

  The method by which an on-board microprocessor of the integrated vision system exercises direct control of the imaging sensor, illumination, and computation results in improved speed and accuracy. The ability to integrate the functional control (CCD array scanning, integrating time, illumination intensity, image processing, and data communication) into a single unit presents a potential compact design cost saving.

- Along with a software GRIPPS, three system geometrical calibration algorithms were developed and experimentally tested; namely, camera, gripper-camera relationship, and pallet calibrations. Tsai's two-stage RAC calibration techniques were found to be quite robust and good for the camera and the gripper-camera calibrations. However, the second stage of the Tsai's RAC-based calibration results in a homogeneous system of linear equations if the optical axis is in parallel with the normal of the calibration board, which yields a trivial solution for an over-determined system. In order that the silhouette of each part can be obtained with the observation axis perpendicular to a plane on which the part is to be characterized, a pallet calibration algorithm has been developed to calibrate the extrinsic parameters of the camera given that the intrinsic parameters are known a priori. The pallet calibration is not limited, as Tsai's method was, by the board being constrained to form an angle of less than 45 degrees with the camera optical axis.

- The research efforts have led to the concept of a flexible integrated vision system (FIVS), which significantly reduces the image processing time and cost without sacrificing system performance. The FIVS offers performance and cost advantages by combining the imaging sensor, control, illumination, direct digitization, computation, and data communication in a single unit. Research efforts will be towards the performance evaluation and experimental investigation of the FIVS in the complete factory of the future kitting cell donated by General Motor Corporation.

Contribution to the development of human resources

Several graduate and undergraduate students have been advised in the reporting research. A list of recent publications (in the subsection List of publication) resulting from the students' contribution provides evidence of their involvement. The graduate students working on this reporting research as parts of M.S. and Ph. D. Theses are listed as follows:

Ph.D. Student Supervised

Jianfa Pei Ph.D. Thesis:	Graduated (December 1990) Methodology of design and analysis of a spherical wrist motor"
Ronald Roth Ph. D. Thesis:	Expected to graduate by June 1992 Design optimization of a three degree-of-freedom variable-reluctance spherical motor.
Xioa-An Wang Ph. D. Thesis:	In progress Dynamic modeling and control of a high-speed wrist motor.
Shankar Janakiraman Ph. D. Thesis:	In progress Object refelectance based lighting design for rapid extraction of features and active ranging.
Blenis, Robert Ph. D. Thesis	In progress An analytical and experimental modeling of an integrated stereo-vision for direct three DOF orientation measurement of a spherical VR motor.
Qian, Yifei Ph. D.Thesis:	In progress Development of an Intelligent Diagnoser for Failure-Free Operation of a Flexible Robot Assembly System
Parker, Johne' Ph. D. Thesis:	In progress Physically Accurate Synthetic Images for Machine Vision Applications
Zhou, Zhi Ph. D. Thesis:	In progress Intelligent control of a three degrees-of-freedom VR spherical motor

Master Thesis Students

- Yutkowitz, S., "A Practical Vision-Guided Part Feeding Algorithm for Flexible Manufacturing," M. S. Thesis, The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, March 1991. Also available in MHRC Report TD-90-10.

- Parker J. M., "A Methodology for Generating Physically Accurate Synthetic Images for Machine Vision Applications," M. S. Thesis, The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, March 1992. Co-advised by Dr. Rushmeier and the PI. Ms. Joene' Parker is continuously pursuing a Ph.D. degree in the Woodruff School of Mechanical Engineering. Her Ph. D. Thesis will be on the modelling and simulation of physically-accurate images. The PI and Dr. Rushmeier are serving as a research advisor and co-advisor for Ms. Parker's Ph.D work.

- McCullough J. P., "Concept Development of a Product Design Algorithm: An aid to increase designer's productivity," M. S. Thesis, The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, March 1992. The PI has served as a M. S. Thesis advisor.

Undergraduate Students

- Pejmum Motaghedia and James Shepherd have been trained to work on debugging and operational manual documentation of the software under the supervision of the PI.

List of publication

1. Lee, K.-M., and Kwan, C.-K., "Design Concept Development of a Spherical Wrist Stepper," IEEE Transaction on Robotics and Automation, Vol. 7, No.1, p.175-180, February 1991.

2. Lee, K.-M., Pei, J., and R. Roth, "Kinematic Analysis of a Three-Degrees-of-Freedom Spherical Stepper Motor," Proceedings of the Fifth International Conference on Advanced Robotics, June 20-22, 1991, Pisa, Italy. Also sumbitted to IEEE Trans. on Robotics and Automation.

3. Lee, K.-M. and Gilboa, U., "Reluctance Force Characterization of a Three Degrees-of-freedom VR Spherical Motor," IFAC Symposium on Intelligent Components and Instruments for Control Applications, Malaga, Spain, May 20-22, 1992.

4. Lee, K.-M., and Wang, X., "Dynamic Modeling and Control of a Ball-joint-like Variable Reluctance Spherical Motor," As a REGULAR paper in Proceedings of American Control Conference, June 24-26, 1992. A revised version will be submitted to IEEE Trans. on Robotics and Automation.

5. Lee, K.-M. and Blenis, R., "Design Concept and Prototype Development of a Flexible Integrated Vision System," Applied Machine Vision Conference'92, June 1-4, 1992 Atlanta, Georgia.

6. Lee, K.-M. and Meyouhas, G., "A Machine-Vision-Based Wrist Sensor for Direct Measurement of Three Degrees-of-Freedom Orientation," Applied Machine Vision Conference'92, June 1-4, 1992 Atlanta, Georgia.

7. Lee K.-M. and D-R. Li, "Retroreflective Vision Sensing for Generic Part-Presentation," MHRC Technical Report MHRC-TR-89-06. Presented at 1990 IEEE SouthCon/90,

Orlando, Florida, March 20-22. Also in Journal of Robotic Systems, February 1991, Vol. 7, Number 1.

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10. Lee, K.-M., "Design Concept of an Integrated Vision System for Cost-Effective Part-presentation," 1991 ASME WAM Symp. on Sensors, Controls, Quality Issues in Manufacturing, Atlanta, GA. A revised version is being reviewed for possible publication in ASME Trans. Journal of Engineering in Indutry.

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14. Rushmeier, H., J. Parker, and K.-M. Lee, "Physically Accurate Synthetic Images for Machine Vision System Design," Georgia Tech GVUC Technical Report GIT-GVU-91-25, 1991. A revised version is to be presented at the Applied Machine Vision Conference '92, June 1-4, 1992, Atlanta, Georgia.

15. Lee, K.-M. and S. Janakiraman, "A Model-based Vision Algorithm for Real-time Flexible Part-feeding and Assembly," Applied Machine Vision Conference '92, June 1-4, 1992, Atlanta, Georgia.

Brief description of available data, sample, physical collections, and other research products not described elsewhere.

1. Dickerson S. L. and K.-M. Lee, "Image Reading System," U.S. Patent filed on June 1991 (to be issued).

2. Lee, K.-M., R. Blenis, S. Yutkowitz, and P. Motaghedi, "Software GRIPPS and Operational Manual," MHRC software documentation, Georgia Tech, 1992.

3. A preliminary prototype Flexible Integrated Vision System (FIVS) which has been designed for gray-scale imaging will be used in the proposed research.

OMB Number 345-0058

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PI/PD Name and Address

Kok-Meng Lee
School of Mechanical Eng.
DATA NOT AVAILABLE
Atlanta GA 30332

NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Karen R. Lebries - DMI

2. Program Name MANUFACTURING PROCESSES & EQUIPMENT PROG

3. Award Dates (MM/YY) From: 05/89 To: 08/93

4. Institution and Address
GA Tech Res Corp - GIT
Administration Building
Atlanta GA 30332

5. Award Number 8958383

6. Project Title
Presidential Young Investigator Award: High Performance Precision Motion Control

This Packet Contains
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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

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.

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PART II - SUMMARY OF COMPLETED PROJECT (for public use)
(Kok-Meng Lee, NSF Award Number 8958383)

The objective of this research is to create an innovative three degree-of-freedom (DOF) spherical wrist actuator based on the principle of variable reluctance (VR) for motion control, robotics, and manufacturing automation. The ball-joint-like VR spherical motor which presents some attractive possibilities by combining pitch, roll, and yaw motion in a single joint has significant potentials in applications such as coordinate-measuring, high-speed plasma, laser and water cutting where the end-effector is required to orient quickly, continuously, and isotropically.

Unlike the popular three-consecutive-rotational-joints wrist or spherical motors of other types where the solutions to the forward and inverse kinematics are unique, the VR spherical motor is characterized by its multiple independent inputs and the direction-varying and orientation dependent torque output. Research results on the forward and inverse torque models in quadratic form, as a function of coil excitations and a permeance model in terms of the relative position between the rotor and the stator, are the first to provide a rational basis for design, modeling, and control of the VR wrist motor as well as the first showing the important differences between the VR spherical motor and the popular three-consecutive-joint wrist and spherical wrist motor of a different kind. Analytical techniques for modeling and control have been verified experimentally.

Along with a prototype ball-joint-like spherical motor, this research has led to the creation of a spherical encoder for non-contact sensing of roll, yaw, and pitch motion in a single joint, and a real-time digital vision system. The development of the digital vision system has provided a rational basis for realizing an alternative method for non-contact direct sensing of three DOF rotational motion and for motion control. The former overcomes several problems (such as friction, inertia, and backlash) associated with the use of single-axis encoders for measuring three DOF orientation. These research efforts are recognized by five US patent awards, two of them involving students in developing the concept. The implementation of digital vision system has been proven to have a major impact in industry, and has resulted in much greater productivity and substantial economic benefits in manufacturing.

PART III TECHNICAL INFORMATION (for program management use)
(Kok-Meng Lee, NSF Award Number 8958383)

This research has two major thrusts. The first thrust is to establish a rational basis for design, dynamic modeling and control of an innovative wrist actuator. The second thrust focuses on the creation of a cost-effective digital vision system for real-time applications such as spherical wrist motion control, robotics, and manufacturing automation.

1. Spherical Wrist Actuator

The objective is to create an innovative prototype spherical wrist actuator which presents some attractive possibilities by combining pitch, roll, and yaw motion in a single joint.[1] [2]. In addition to the compact design without the use of a speed reducer, the spherical wrist actuator results in relatively simple joint kinematics and has singularities only at the boundaries of the workspace. The proposed wrist actuator has potential applications where high-speed and precision isotropic manipulation of the end-effector orientation is required in all directions.

Efforts have been directed towards the design and development of a prototype variable reluctance (VR) spherical motor, which serves as experimental testbed. As discussed in [3] [4] [5], the validity of the permeance model is essential to the success of control algorithm development and implementation. The three degrees-of-freedom (DOF) actuator has been developed which provides the verification of permeance model upon which the analytical model of the spherical motor was built [6] [7] [8]. The identification of optimal design parameters [9] [10] on the three DOF VR planar motor and the theoretical framework presented in [11] have provided the basis for the method of controlling a three DOF self-levitated VR spherical motor [13] [14] [15].

Paper [4] presents the modeling and control of a practical, yet potentially useful, spherical motor which offers the possibility to combine roll, yaw, pitch motions in a single joint. The ball-joint-like spherical motor has significant potentials in applications such as coordinate-measuring, high-speed plasma, laser and water cutting where the end-effector is required to orient quickly, continuously, and isotropically. In [4], the engineering basis for modeling and control strategy of a three degrees-of-freedom (DOF) variable-reluctance (VR) spherical motor is described. This paper represents the first detailed study of such a three DOF VR spherical motor. Yet, it permits a spectrum of design configurations to be analyzed.

Unlike the popular three-consecutive-rotational-joints wrist or spherical motors of other types where the solutions to the forward and inverse kinematics are unique, the VR spherical motor is characterized by its multiple independent inputs and the direction-varying and orientation dependent torque output. In order to characterize the torque specifications of the three DOF VR spherical motor which is significantly different from the traditional one DOF actuators, paper [12] derives the maximum torque-to-input power ratio to describe explicitly the relationship between the torque and the power input. This relationship provides an effective means to characterize and optimize three DOF spherical motors. The paper further explores the use of this relationship to estimate the maximum payload, and to determine the characteristic orientation where a global design optimization can be accomplished. (Zhi Zhou, on whose thesis this paper was based, won

a SAIC best paper award for a paper entitled: "Integrated design and characterization of a three DOF VR spherical Motor.")

2. Digital Vision System

Although it has been well recognized in the past decade that computer vision can add considerably to flexibility by simplifying grippers, component feeders, and location tooling, and can reduce the engineering time required to implement it, research in practical part-feeding automation has concluded that current computer vision techniques have been significantly limited by the following factors:

1. Many vision systems of today are integrated using off-the-shelf cameras such as entertainment and surveillance-type cameras, which are created for human eyes and brains rather than for machine perception. Biological vision tends to be insensitive to absolute light intensity and spatial accuracy. Video camera tends to suffer the same biases as humans do. Moderate location inaccuracies pose no difficulty for human operators since they use vision, hand-eye coordination, and sense of touch to locate and correctly load the parts. The attempt to duplicate human perception often for time-consuming computation and does not necessarily determine the location and orientation of a given part with the accuracy required for successful part-acquisition by the robot.

2. Conventional vision systems which often build upon off-the-shelf components. In general, the system includes a video camera which outputs a standard RS170 video signal, a frame grabber board which converts the RS170 video signal into a series of n bit brightness values (gray levels) and stores them in fast memory components, and a micro-computer which computes the location and orientation of the part. In addition to error resulting from the timing mis-match between the image acquisition and the computer hardware, the RS170 video signal limits the read-out of a complete frame at a rate of 30 fps (frame per second).

3. Apart from the lack of appropriate hardware and the high equipment cost, two other major problems often associated with the conventional video system are poor reliability and excessive image processing time, both of which depend on illumination techniques, the complexity of the geometry, and the surface reflectance of both the background and the objects to be handled. In addition, system specifications for illumination are often vague or may be left to the final user.

This research has demonstrated that the potential flexibility and reliability of machine vision can be achieved by means of retroreflective vision sensing technique. The concept of retroreflective vision sensing for flexible part-feeding was demonstrated using two prototype systems, a breadboard configuration integrated using off-the-shelf hardware and an integrated vision system (IVS). The latter has led to the concept development of GRIPPS (Generic Retroreflective Integrated Part-Presentation System). Practical implementation issues of the low-cost integrated vision system for flexible part-feeding were addressed.

Papers [16] [17] discusses the problems associated with conventional vision systems for motion control applications, and offer a unique solution to overcome these problems. The paper describes in detail the design concept and system architecture of a cost-effective vision system, which provides a means to process pixel data without the limitation of the TV video standard and without having to pre-store the image [18]. The system architecture has also provided a basis for realizing an alternative method for non-contact direct sensing of three DOF rotational motion and for vision-based motion control. The former overcomes several problems associated with the use of single-axis encoders for measuring three DOF orientation [19]. In addition, the results have been extensively appied to wrist orientation sensor [20], manufacturing automation applications [21] [22] [23] and in classroom [24].

Papers [25] contributes to the design methodology and the analytical modeling to aid design of practical illumination for retroreflective vision sensing, the concept of giving retroreflective materials an integral role in machine vision. His results on the use of low-cost, low power LED's with pin-hole optics are among the first showing importance of optical effects and collocated illumination on cost-effective, reliable vision sensing. The paper demonstrates several practical methods of collocated illumination for cost-effective flexible part-presentation, the implementation of which has been proven to have a major impact in industry, and has resulted in much greater productivity and substantial economic benefits in manufacturing.

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1. Lee, K.-M., "An Analytical Development Of A Spherical Wrist Motor," Proceedings Of International Conference On Automation, Robotics, And Computer Vision, 18-21 September, 1990, Singapore, pp. 1325-1329.

2. Lee, K.-M. and Kwan, C.-K., "Design Concept Development Of A Spherical Wrist Stepper," IEEE Transaction On Robotics And Automation, Vol. 7, No.1, pp. 175-180, February 1991.

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4 Lee, K.-M., "Design, Modeling, And Control Strategies Of A Three Degrees-Of-Freedom VR Spherical Motor, Part I: Reluctance Force Characterization And Part II: Dynamic Modeling And Control," in Precision Sensors, Actuators and Systems, edited by H.S. Tzou and T. Fukuda, Kluwer Academic Publishers, pp. 73-132. (1992).

5. Lee, K.-M., Pei, J., and Roth, R., "Kinematic Analysis Of A Three-Degrees-Of-Freedom Variable Reluctance Spherical Motor," Mechatronics, Vol. 4, No. 6, pp. 581-605, (1994). A preliminary version has been presented in Proceedings Of The Fifth International Conference On Advanced Robotics, June 20-22, 1991, Pisa, Italy.

6. Lee, K-M. and Wang, X., "Dynamic Modeling And Control Of A Ball-Joint-Like Variable Reluctance Spherical Motor," Proceedings Of American Control Conference, Chicago, Illinois, June 24-26, 1992, pp.2463-2469.

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15. Zhou, Z. and Lee, K.-M., "Real-time Motion Control of a Multi-degree-of-freedom Variable Reluctance Spherical Motor," Submiteed to 1996 IEEE Robotics and Automation Conference.

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25. Lee, K.-M., "Design Concept Of An Integrated Vision System For Cost-Effective Flexible Part-Feeding Applications," ASME Trans. Journal Of Engineering For Industry, Vol. 116, pp. 421-428, November 1994. Also presented at the 1991 ASME Winter Annual Meeting,

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III.2 NSF Grantees Conference Proceedings

1. Lee, K.-M., Pei, J., and Gilboa, U., "On The Development Of A Spherical Wrist Actuator," Proceedings Of The 16th NSF Conference On Manufacturing Systems Research, Tempe Arizona, January 8-12, 1990, pp. 295-300.

2. Lee, K.-M., Dickerson, S., and Mercurio, J., "Generic Retroreflective Integrated Parts Pick-Up System (GRIPPS)," Proceedings Of The 1991 NSF Design And Manufacturing System Grantees Conference, Austin, Texas, January 9-11, 1991, pp. 857-864.

3. Lee, K.-M., and Wang, X., "Dynamic Modeling And Control Of A Ball-Joint-Like Variable Reluctance Spherical Motor," Proceedings Of The 1992 NSF Design And Manufacturing System Grantees Conference, Atlanta, Georgia, January 8-10, 1992, pp. 1051-1057.

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III.3 Patents

1. Dickerson, S. and Lee, K.-M., Image Reading And Processing Apparatus, US Patent 5,146,340. (September 8, 1992)

2. Lee, K.-M., Orientation Sensing System And Method For A Spherical Body, US Patent 5,319,577. (June 7, 1994)

3. Lee, K.-M., Blenis R., and Pao, T.-L, System And Method For Controlling A Variable-Reluctance Spherical Motor, US Patent 5,402,049. (March 28, 1995)

4. Lee, K.-M., Spherical Motor And Methods, US patent 5,410, 232. (April 15, 1995)

5. Lee, K.-M., Blenis, R. and Pao, T.-L., Real-Time Vision System And Control Algorithm For A Spherical Motor, US Patent 5,416,392. (May16, 1995)

III.4 NSF Invention disclosures.

1. Lee, K.-M., "Three DOF Ball-joint-like Spherical Motor,' NSF Invention Disclosure 93-11.

2. Lee, K.-M., "Three DOF Optical orientation Sensor," NSF Invention Disclosure 93-12.

3. Lee, K.-M., Blenis, R. and Pao, T.-L., "A real-time DSP-based Intelligent Image Processor for Vision based Control Systems Applications," NSF Invention Disclosure 93-13.

III.5 Software

1. Lee, K-M, Blenis, R., Yutkuwitz, S., and Motagogh, P., "Software: GRIPPS Version 1.0", May 1990.

III.6 Thesis

.Students	Degree	Date Graduated	Thesis
Pei, Jianfa	Ph.D.	December 1990	Methodology Of Design And Analysis Of A Variable Reluctance Spherical Motor
Roth, Ronald	Ph.D.	December 1992	An Experimental Investigation And Optimization Of A Variable Reluctance Spherical Motor
Qian, Yifei	Ph.D.	June 1995	A Study Of Dynamic Pursuit Of Moving Objects With Hand-Eye Coordination
Zhou, Zhi	Ph.D.	June 1995	Real-Time Control And Characterization Of A Variable Reluctance Spherical Motor
Yukowitz, Steven	M.S.	March 1990	A Practical Vision-Guided Part-Feeding Algorithm For Flexible Manufacturing Automation

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.

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	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	0				8	1	3	1	0	
B. Total, Permanent Residents	1				1				1	
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native					1					
Asian	1								1	
Black, Not of Hispanic Origin					1	1		1		
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin					1		3			
C. Total, Other Non-U.S. Citizens					2		1		2	1
Specify Country										
1. TAIWAN							1			
2. CHINA					2				1	1
3. ISRAEL									1	
D. Total, All participants (A + B + C)	1				11	1	4	1	3	1
Disabled[3]										

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[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.)*

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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.

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PACIFIC ISLANDER: A person having origins in any of the original 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.

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