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Professor Devendra P. Garg, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

School of Engineering
Duke University
Durham, NC 27708-0300

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13. ABSTRACT (Maximum 200 words)

The major aim of this research project is to study the dynamics and control problems related to open and closed chain robotic systems. The research effort investigates aspects of load sharing and internal force control in case of closed chain manipulation which has been generally ignored thus far in current literature. This research demonstrates a practical solution to dual-arm continuous control problem for heavy link industrial manipulators such as IBM 7540. Integration of vision and force sensors in dual-arm workcells is also described. Analytical and empirical solutions using pseudo-inverse and back error propagation are developed. Insightful study of back error propagation indicates the relationship of neural algorithms to nonlinear least squares fit and established notions in estimation theory. A novel approach to camera-calibration and vision guided robot path-tracking is also advanced. Detailed results and discussions are included in the publications cited in the report.

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PARAMETER IDENTIFICATION AND ADAPTIVE CONTROL OF COOPERATIVE ROBOTS

Final Report

Devendra P. Garg, Ph.D.

Professor of Mechanical Engineering

September 1992

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Durham, NC 27708-0300

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FOREWARD

The research interest in developing new and improved control algorithms for manipulators has been steadily growing over the last few years. The primary reasons can be attributed to the various tasks that the present generation of robots are required to perform. Simplified control algorithms which were considered adequate earlier to perform pick and place operations exhibit severe limitations when applied to trajectory following operations like welding. In this research project the advancement in the control algorithms of robots have been studied with special emphasis on model-based adaptive and non-adaptive strategies. The last few years have also witnessed a considerable interest in the complex problem of multiple arm coordination and control. Although some of the problems encountered in multiple arm coordination are similar to those related to single arm, the problem gets extremely challenging when kinematic and dynamic coupling of the manipulators via the common load is considered in case of continuous cooperation. This research effort addresses the problems of load sharing and internal force control of cooperating manipulators, and discusses the issues of parameter identification, vision and force/torque sensor integration, and adaptive and neural net control associated with multiple robots.

PARAMETER IDENTIFICATION AND ADAPTIVE CONTROL OF COOPERATIVE ROBOTS

Introduction

This research effort has been motivated by various benefits that can be derived from dual-arm robotic systems. Whereas a great deal of effort is currently underway in dual-arm robotics research at several universities and research institutions, a truly versatile and efficient approach is yet to be obtained. Dual arm operation is heavily dependent on the trajectory adherence capabilities of the individual arms as well as a proper understanding of issues such as load sharing and internal force control of the common object manipulated by the robots. As such, the research efforts in this project were directed to develop control algorithms for dual-arm as well as single arms. The associated problems of sensor-integration and sensor calibration were also researched. Load sharing and internal force control of the common object handled by the cooperating robots were analyzed.

Listed in this report are the research publications that resulted from the theoretical and experimental work that were conducted at the Duke University's Robotics and Manufacturing Automation Laboratory with financial support from the U.S. Army Research Office. A brief overview of the research areas investigated is given, which is followed by a list of appropriate research publications based upon this project.

This research deals with dual-arm coordination and control. The primary research objectives encompass the following associated objectives which are listed below, and are subsequently discussed briefly in this report.

a. Single Arm or Open Chain Dynamics and Control
b. Closed-Chain Dynamics
c. Sensor-Integration in a Robotic Workcell
d. Dual-Arm Cooperative Control.

Motivation

The advantages of multi-arm cooperation in performing complex tasks can be easily appreciated by observing human-beings executing intricate tasks with cooperation and coordination of the left and right arms. A successful integration of dual arms can realize difficult tasks, such as handling of objects which exceed the carrying capacity of individual arms and, also in performing intricate assemblies without the use of relatively expensive custom made fixtures. Some of the benefits that can be derived from dual-arm systems are as follows:

(i) Dual-arms can be used to manipulate loads beyond the carrying capacity of a single arm.

(ii) Dual-arms can be used to carry long and slender payloads safely and efficiently.

(iii) Dual-arms can be used in the outer space environment to track and hold a rotating subassembly, and thereafter, to assemble it at an appropriate location, such as in a space station.

(iv) Dual-arms can be used in underwater explorations.

(v) Dual-arms can be used in flexible automation workcells with one of the arms working as a flexible fixture, thereby minimizing rigidity of the workcell and also the time of assembly.

(vi) Dual arms can be used in manufacturing operations such as welding where the weld line extends beyond the workspace of a single arm.

(vii) Use of more than one arm is desirable for working on assemblies that extend beyond the workspace of a single arm.

(viii) More than one arm can be used in the efficient design of a flexible workcell, drawing concepts from queuing theory for improving throughput.

(ix) Dual-arms can be used in combat in place of human beings for loading and firing artilleries and for retrieving wounded soldiers.

(x) Dual-arms are essential for building an android which could be useful in unmanned space vehicles .

Several researchers have contributed to the development of dual-arm coordination and control. However, all of the benefits listed above have not been fully realized as yet in practice. This research makes an effort to solve some of the problems associated with this challenging research area. An overview of the contributions made by this research is presented below. Detailed discussions, a comprehensive bibliography, and research results are included in the doctoral dissertation* which was based upon this project.

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* Nagchaudhuri, A., "Coordination and Control of Open and Closed Chain Robotic Manipulators", Ph.D. Dissertation, Deparmtent of Mechanical Engineering and Materials Science, Duke University, Durham, NC, 1992.

Single Arm or Open Chain Dynamics and Control

A two-arm single object system of manipulators can be considered to consist of two separate arms and a common object (payload) with the appropriate interaction forces. This approach was utilized to develop closed chain dynamics . A study of the dynamics and control of the individual open chains and their dynamic interaction with the common object leads to an understanding of dual arm coordination and control.

Among several control approaches that can be used to control a complex dynamic system, this research investigated both model based and performance based adaptive control. Model Reference Adaptive Control (MRAC) is an efficient way to change the behavior of a dynamic system. However, MRAC suffers from the uncertainty in the dynamic parameters, especially in the nonlinearities such as friction, backlash, and joint compliance. Although this creates a problem with the analytical development of parameter identification and convergence the trajectory tracking is quite satisfactory, with a priori approximate identification of parameters. These approximately identified parameters are used in the feedforward path, and a simple proportional and derivative feedback signal closes the control loop.

The dynamic interaction of the manipulator with the environment presents difficult control problems. In dual-arm manipulation, both manipulators simultaneously interact with the common object. The control efforts used in single-arm manipulation provide insights for developing dual-arm control strategy.

Associated Publications

[1] Garg, D.P., " Nonlinear Dynamic Characteristics in Mechanical Manipulators," *Proceedings of the Twentieth Annual Modeling and Simulation Conference*, Volume 20, Part 5, May, 1989, pp. 2125-2129.

[2] Garg, D.P., Nagchaudhuri, A., and Ma, Y., "Adaptive Identification and Control of Robotic Manipulators," *Proceedings of the 21st Modeling and Simulation Conference*, Pittsburgh, PA, Vol. 21, Pt. 5, May 1990, pp. 2093-2096.

[3] Garg, D.P., Ma, Y., and Nagchaudhuri, A., "Nonlinear Dynamic Analysis and Control of SCARA Robots, " *Proceedings of the 21st Modeling and Simulation Conference*, Pittsburgh, PA, Vol. 31, Pt. 5, May 1990, pp. 2099-2103.

[4] Ananthraman, S., Nagchaudhuri, A., and Garg, D.P. , "Control of a Robotic Manipulator using a Neural Controller," *Proceedings of the 22nd Modeling and Simulation Conference*, Vol. 22, Pt. 5, May 1991, pp. 1846-1853.

[5] Johnson, C. B., and Garg, D.P., "Parameter Selection For Smoothed Variable Structure Controllers in Robotic Applications," To appear in the *Proceedings of the 23rd Modeling and Simulation Conference*, 1992.

[6] Ananthraman, S., and Garg, D.P., " Robot Manipulator Control Using a CMAC Based Real-Time Neural Controller," To appear in the *Proceedings of the 23rd Modeling and Simulation Conference*, 1992.

Closed Chain Dynamics

The dual-arm system with the common object forms a "closed-kinematic chain" via the inertial frame or any other reference frame with respect to which kinematics of the manipulators is described. The development of complete dynamic equation for a system of manipulators with a common load involving both the "forward" and "inverse" dynamics is defined as closed chain dynamics in literature.

The common object constrains the total number of degrees of freedom of the manipulators, resulting in a redundant system of actuation. Several optimization possibilities exist which take advantage of the redundancy. The distribution of the load among the coordinating manipulators due to the common object, and keeping internal forces in the object at an optimum level are inherent to the development of a complete closed chain dynamic model.

Associated Publications

[8] Nagchaudhuri, A., Ananthraman, S., and Garg, D.P., " Kinematics, Dynamics, and Control of Closed Chain Manipulators," *Proceedings of the Twenty-Second Modeling and Simulation Conference,* Part 4, Vol. 22, May 1991, pp. 1835-1840.

[9] Garg, D.P, and Ruengcharungpong, C., " Force Balance and Energy Optimization in Cooperating Manipulation," To appear in the *Proceedings of the 23rd Modeling and Simulation Conference,* 1992.

[10] Nagchaudhuri, A. and Garg, D.P., " Load Sharing and Internal Forces in Multiple Cooperating Manipulators : A New Perspective," To appear in the *Proceedings of the 23rd Modeling and Simulation Conference,* 1992.

Sensor Integration

Since forces need to be controlled with most applications involving dual-arms (for example, dual-arm assembly and dual-arm coordinated control), it is imperative to integrate a force sensor in a dual-arm workcell. Moreover, one of the primary motivations in dual-arm systems is to eliminate rigid fixtures from automation workcells and develop a completely flexible automation unit. The integration of vision sensors into a manufacturing workcell provides versatility and flexibility with respect to different components handled in the cell without expensive re-tooling or developing specific rigid fixtures.

Associated Publications

[11] Nagchaudhuri, A., Thint, M., and Garg, D.P., " Vision Guided Tracking of a SCARA Type of Robot,"*Proceedings of the Twenty-Second Modeling and Simulation Conference*, Pittsburgh, PA, Part 3, Vol. 22, May 1991, pp. 1536-1543.

[12] Nagchaudhuri, A., Ananthraman, S., and Garg, D.P., " Vision Integration in a Multi-Robot Workcell,"*Proceedings of the Twenty-Second Modeling and Simulation Conference*, Pittsburgh, PA, Part 4, Vol. 22, May 1991, pp. 1841-1845.

[13] Garg, D.P., Ananathraman, S., and Nagchaudhuri, A., " Sensor Integration For Payload Weight Estimation in a Robotic Work Cell," *Advances in Instrumentation*, DSC-Vol. 30, ASME 1991, pp. 25-29.

[14] Nagchaudhuri, A., Thint, M., and Garg, D.P., " Camera-Robot Transform for Vision-Guided Tracking in a Manufacturing Workcell," *Journal of Intelligent and Robotic Systems: Theory and Applications* , Vol. 5, No. 3, June 1992, pp. 283-298.

Dual-Arm Cooperative Control

In this research, dual-arm control has been analyzed and solved from two different perspectives; a) dual arm manipulation with two industrial robots moving at relatively low speeds, and b) dual arm manipulation in a demanding dynamic environment. In the first approach, a dual-arm coordinated control and assembly problem is solved practically using tight sensor integration and a simple decentralized high speed Proportional plus Integral plus Derivative (PID) control scheme. For the more dynamically demanding environment simulation, studies are performed to evaluate performance of dual-MRAC scheme as well as model reference adaptive proportional plus integral plus derivative control.

The controllers in the two IBM 7540 SCARA robots, that were originally equipped with independent Z-80 microprocessors, were replaced by Motorola 68020 microprocessor based controllers. In addition, to facilitate communication, both motion control boards of the two robots were plugged on a common VME bus. A six-axis force/torque sensor and a vision sensor, both having independent Motorola 68020 microprocessor based boards, were integrated into the dual-arm workcell. The vision and force sensors help to close the feedback loop around the robot end-effectors to provide efficient control in the task or operational space. The encoders and tachometers provide the joint space feedback control. The encoder signals are re-directed from the IBM-controllers to the new VME-bus based controller (acquired from Adept Technology, Inc.). Appropriate proportional, integral, and derivative control gains were used after comparison with the reference signals to direct proper motion. The power amplifier circuitry of the IBM 7540 robots was kept the same. A provision has been made while interfacing to switch between the original IBM 7540 controller and the new controller if so desired.

Each axis of the IBM 7540 robots has been fine-tuned independently by manually adjusting the PID control gains off-line, while the joint link system is subjected to high amplitude and low time period square waves. The amplitude of the square waves is increased and the time period is decreased successively, and at each stage the feedback gains are adjusted to achieve the desired performance. The feedback gains that yield good performance for the worst case are used as the controller gains for the joints. Robustness to bounded disturbances is assured since the gains are used for the worst case, a situation which is seldom encountered in practice. Improved trajectory adherence of the robots using the new controller, combined with the vision and force feedback, has enabled specific complex dual-arm load carrying and assembly tasks that were performed in the Robotics and Manufacturing Automation Laboratory at Duke University.

Significant progress has been made in the analytical and computational areas. It must be remarked that whereas an adequate performance can be obtained using conventional control algorithms for heavy link industrial manipulators which are predominantly linear, the performance begins to deteriorate when link systems become lighter, payloads become heavier, and speed of manipulation becomes faster. Such a behavior becomes evident since the nonlinear components in the robot dynamics begin to dominate the overall dynamics. The high speed manipulators of the future would need to incorporate as far as practicable, the entire dynamics of the manipulators in the feedforward path to generate the required control torques. The model mismatch due to imperfect identification and payload variations can be compensated on-line via adaptive control.

Computer simulation studies based on model reference adaptive control have been conducted in the laboratory for dual robots manipulating a common load. The desired object trajectory is first decomposed into end-effector trajectories for the two robots. An inverse map based on inverse kinematics of the manipulators converts these trajectories to desired joint trajectories of the two manipulators. Model reference adaptive control is applied to the two manipulators in parallel. The manipulators are assumed to be equipped with force-torque sensors. These force torque sensors identify the object mass approximately during grasping. The manipulator torques are updated with the loads due to the object after dividing this load symmetrically amongst the two cooperating manipulators. The force-torque sensors also monitor the internal forces on the common object and maintain appropriate level of desired internal forces with suitable feedback action from the Cartesian space. Excellent trajectory adherence is obtained using the model reference adaptive control strategy applied to the closed-chain dynamic system .

Associated Publications

[15] Garg, D. P. " Coordination of Multiple Robots Via Supervisory Control," *Proceedings of the 1991 IEEE International Symposium on Intelligent Control,* Reston, VA, Aug 13-15, 1991, pp. 19-24.

[16] Garg, D.P., Nagchaudhuri, A., Ananthraman, S. and Johnson, C. " Multiple Robot Coordination Using Vision and Force Sensors", To be presented at the *Intelligent Control Session at ASME, WAM*, in Annaheim, CA, in November 1992.

[17] Nagchaudhuri, A., Garg, D.P., Ananthraman, S., and Johnson, C., " Vision and Force Sensing for Cooperative Control in a Multiple-Robot Work Cell," Submitted for publication to the *Journal of Robotics and Autonomous Systems*, 1992.

[18] Nagchaudhuri, A., "Coordination and Control of Open and Closed Chain Robotic Manipulators," Ph. D. Dissertation, Department of Mechanical Engineering and Materials Science, Duke University, 1992.

Significant Results

In this research the various salient aspects of open chain and closed chain manipulation have been investigated. With increasing demands on the flexibility and dexterity of manipulators in robotic workcells and robotic applications in hazardous environments, research efforts are being specifically directed towards developing new and improved control algorithms. Sensor integration has also become a key element in robotic workcells for added dexterity and flexibility.

The main results of this research can be summarized as follows:

(i) For lightweight high speed manipulators of the future, centrifugal and Coriolis effects will dominate the dynamics of manipulators rather than the inertial effects. Hence, the nonlinear components that the control algorithm would handle will become significant. Thus a feedforward component which has enough dynamic information will need to be incorporated in the control law. This feedforward component will have to refine itself with the passage of time. This adaptive learning ability can be built into the controller in several different ways. A model based adaptive scheme has been studied in this research. It has been shown, that the MRAC scheme not only has the ability to identify the dynamic parameters of the robot, but can also adjust to payload variations. For parameter convergence, only trajectories that are sufficiently rich can be used. It has been confirmed by simulation studies that convergence of parameter estimates is not essential for accurate trajectory tracking. This trajectory following capability under conditions of parameter mismatch and insufficiently rich inputs leads the manipulators controlled by model reference adaptive control to be extremely flexible with changes in task specification.

It was also observed as a part of this research that by using diagonal terms in the manipulator mass matrix, Coriolis and centrifugal effects, frictional effects and high feedback gains, accurate trajectory following can be obtained in a non-adaptive fashion.

(ii) In this research the dynamic effects of the object and the interaction of two manipulators involved in dual-arm manipulation have been studied. The differences between multiple finger manipulation and multiple arm manipulation have been pointed out. The kinematic coupling and dynamic coupling have been elaborated. A new insightful look from a very fundamental viewpoint has been laid out, which enables a clear understanding of internal forces and motion inducing forces.

(iii) In this research, techniques have been developed for vision and force sensor calibration. Results obtained from a conventional and a neural algorithm have been compared. The BEP(back error propagation) neural network has been studied and its ability to approximate systems by using input-output observations has been pointed out. It has been observed that neural network is a multi-dimensional empirical iterative data fitting scheme similar to nonlinear least squares fit using a different basis function. In situations where mathematical modeling becomes difficult, it can form an approximate estimate of the underlying functional relationship between the input and the output data.

(iv) Motion, vision, and force sensors have been integrated in a workcell consisting of two IBM 7540 robots, for assembly and coordinated operation to carry a common load. Experiments have been conducted using decentralized robust PID control of the joints. This is the first reported integration of motion, vision, and force in dual-arm workcell. It has been observed that with an increase in speed of manipulation, internal forces developed in the jointly held object also increase.

(v) Conventional control schemes yield accurate trajectory adherence for almost all industrial manipulators due to the presence of heavy linkage systems which are commonly used for industrial manipulators. The Coriolis and centrifugal effects in the manipulator dynamics become dominant when the link weights are reduced, and higher speeds of operation are demanded. Under such circumstances, nonlinear control schemes have to be used for improved performance. In this research project, a model reference adaptive scheme has been described for controlling two manipulators carrying a common heavy load. Partial knowledge of manipulator dynamics is used to formulate the control scheme. Force sensors assumed to be mounted at the wrist of the manipulator, give an approximate estimate of the payload. This estimate is also used in formulating the control strategy. Simulation studies confirm that the scheme is robust to payload variations as well as rapid changes in task or trajectory specification, which is an extremely desirable feature for a flexible automation environment.

(vi) The specified internal force characteristics, which may be required for some specialized dual-arm applications have been generated using a modified adaptive impedance control scheme. Although adaptive impedance control scheme is receiving increased attention for applications involving a single arm operating over a constraint surface, this is the first time that the scheme has been adapted to dual-arm systems. Adaptive impedance schemes are very wide in scope. They consist of an abstraction in the physical domain which helps design control algorithms. The application of impedance control is particularly useful in all contact tasks to be performed by manipulators.

The research areas addressed in this project are rather wide in scope. An effort has been made to address most of the relevant issues. Control of dual-arms is an extremely complex task. Further research needs to be conducted in areas of sensor integration, advanced control algorithms and multi-arm kinematics and dynamics to provide physical insights. Dual-arm systems have wide application possibilities and therefore, further research endeavors should be directed to realize these benefits in practice.

List of Project Participants

Visiting Research Scholar

Mr. Yawei Ma (From People's Republic of China)

Ph.D. Candidates

Mr. Santosh Ananthraman

Mr. Abhijit Nagchaudhuri

M.S. Candidates

Mr. Wajd Almadani

Mr. Thomas Givens

Mr. Zakir Hussain

Mr. Christopher Johnson

Mr. Cartree Ruengcharungpong

Titles and Authors of Ph.D. Dissertations and M.S. Theses Completed During the Project Duration

(Jan. 1989 - June 1992)

Ph.D. Dissertation in Progress:

Santosh Ananthraman	*Neurocontrol of Cooperating Robotic Manipulators*	

Ph.D. Dissertation Completed:

Abhijit Nagchaudhuri	*Coordination and Control of Open and Closed Chain Robotic Systems*	1992

M.S. Theses Completed

Chartree Ruengcharungpong	*Position Control of Multiple Robots Using an Optimization Technique*	1991
Thomas Givens	*Improvement of Cooperative Motion for Multiple Robot Manipulation by Iterative Learning*	1992
Christopher Johnson	*Smoothed Variables Structure Trajectory Control for a Two-Link Manipulator*	1992
Mark Everett	*Grasping Stability of a Two-Fingered End Effector with Rigid and Compliant Semispherical Fingertips*	1992
Wajd Almadani	*Adaptive PID Control of Two Cooperating Robotic Manipulators*	1992
Syed Zakir Hussain	*MuRAL: A Programming Environment for Multiple Robot Application Language.*	1992

List of Papers Published by the Principal Investigator and the Research Team During the Project Duration

Garg, D.: Supervisory Control for Coordination of Multiple Robots, Accepted for Publication in *The International Journal of Systems Science*, to appear in 1992.

Nagchaudhuri, A., Thint, M., and Garg, D.: Camera-Robot Transform for Vision-Guided Tracking in a Manufacturing Work Cell, *Journal of Intelligent and Robotic Systems*, Vol. 5, No. 3, 1992, pp. 283-298.

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