Robust Control of Multi-Jointed Robot Arm with a Decentralized Autonomous Control Mechanism

N95- 23710

Shinichi Kimura, Ken Miyazaki and Yoshiaki Suzuki
Communications Research Laboratory,
Ministry of Posts and Telecommunications,
4-2-1, Nukui-Kitamachi, Koganei-shi, Tokyo 184, Japan
TEL (0423)27-7514 FAX (0423)27-6699
E-mail shin@crl.go.jp

KEY WORDS AND PHASES

Decentralized autonomous control mechanism, robust to partial damage.

ABSTRACT

This paper presents a decentralized autonomous control mechanism applied to the control of three dimensional manipulators, and its robustness to partial damage was assessed by computer simulation. Decentralized control structures are believed to be quite robust to time delay between the operator and the target system. A 10-jointed manipulator based on our control mechanism was able to continue its positioning task in three-dimensional space without revision of the control program, even after some of its joints were damaged. These results suggest that this control mechanism can be effectively applied to space telerobots, which are associated with serious time delay, between the operator and the target system, and which cannot be easily repaired after they have been partially damaged.

INTRODUCTION

Teleoperating space robots presents two essential problems for the current control theory because of the long distance between the operator and the target system.

Since the target and the operator are separated by a great distance, not only physically but also within the telecommunication network, there is a serious transmission delay between operational commands and feedback information. The transmission delay in the communication link between a ground station and a space telerobot in low Earth orbit is expected to be as long as 2 to 8 s. System operation is quite difficult with a transmission delay in the order of several seconds. Although some attempts have been made to apply approximation techniques to the control mechanism [1,2], such techniques are limited when the target system is rapidly changed and under uncertain conditions, occurring when the transmission delay is much larger than several hundred milliseconds. Therefore, the space telerobots should be intelligent in order to produce operational information from limited teleoperation commands.

Since the target system is far from its earth base, it will incur high cost and present a danger when repairing space robots after they have been partially damaged. Therefore, telerobots in space should be able to work even when they have been partially damaged. To ensure that the telerobot system can adapt to partial damages, it should have redundant degrees of freedom. On the other hand, space robots are limited in weight, size, and cost limiting the ability to give space robots a redundant degree of freedom. Under normal conditions, space robots that can effectively use this redundant degree of freedom, will be highly adaptable. Even though some efforts have been made to solve automatically the inverse-kinematics of redundant manipulators using a pseudoinverse matrix [3-7] or quadratic programming [8,9], these manipulators will have problems in time performance where the degree of freedom is much larger.

The control mechanisms of motion in living organisms were previously studied [10,11], and it has been proposed that the decentralized autonomous control mechanisms found in biological control systems may be effective in dealing with the problems associated with the teleoperation of space robots. [12] Namely, biological control systems produce rapid and appropriate adaptation according to various external conditions. They are also quite robust in response to partial damage. In these studies it is found that a decentralized autonomous control mechanism is essential for biological adaptation and robustness. Since these control systems are constructed in a hierarchical manner on a foundation of decentralized control, they can adapt to changes in external conditions much more rapidly than if the adaptations had been determined one at a time in the higher center. Furthermore, since the operational information in biological control systems is generated in real time using autonomous control elements according to local and global information in a decentralized manner, the systems are robust to changes in their architecture due to partial damage.

This paper presents a decentralized autonomous control mechanism into a three-dimensional manipulator. It has been successfully demonstrated that the manipulator using the robustness of our control mechanism was able to continue its positioning task in two-dimensional space without revision of the control program, even after 2 (non-adjacent) of its 5 joints were damaged. This paper also describes how this control mechanism can be easily extended to a three-dimensional multi-jointed manipulator.

DECENTRALIZED CONTROL MECHANISM FOR A MULTI-JOINTED MANIPULATOR

Using our theory, the following control mechanism was applied to a two-dimensional 10-jointed manipulator (Fig. 1). The control mechanism proposed here can be easily extended to a three-dimensional manipulator. (1) Each of the joints contains an Elemental Information Processor. (2) The Operator, which corresponds to a remote operator, such as in a control center on Earth, sends information about the target location. (3) Each of the Elemental Information processors calculates a set of possible joint angles based on the two strategies for pointing at the object described below. (Feed forward) (4) The Elemental Information processors exchange these sets of possible joint angles with each other through a Global Information Bus, and select the best set based on a particular cost function. (Consensus-making) (5) Each Elemental Information Processor then applies this Consensus set to itself by sending torque information to its own actuator according to the magnitude of the desired angle change. (Motion) (6) The processes of Feed forward-Consensus-making - Motion are looped until the manipulator points the desired object.

The following benefits can be achieved using this control mechanism: (1) Once the object-related commands are given by the operator, the operational information can be autonomously generated in a decentralized (on-board) system using real-time feed-forward and feed-back information. Therefore, the entire system will be robust to the transmission delay between the target system and the operator. (2) Since all of the elemental processors calculate their own strategies in parallel, and exchange this information with each other, if some of these elements are damaged, the manipulator will still be able to point at the object employing the strategy generated using the undamaged elements (particularly using the following Non-Redundant Strategy).

The 2 two-dimensional strategies can simply be extended to a three-dimensional system in the following manner. [12] The "Equally Shared" strategy, which is based on constraints that depend upon the number of joint angles that can bend simultaneously, can be applied to a three-dimensional system by supposing that the base joint and the objective lie within the same imaginary plane. Namely the needed angle is equally shared by the pitch and/or yaw angles of joints on the plane which is parallel to the pitch or yaw axis.

For the "Non-Redundant" strategy, the non-redundant degrees of freedom are simply extended from two to three. Namely one pitch and two yaw angles, or one yaw and two pitch angles are adjusted to solve inverse kinematics as if it were nonredundant manipulator.

Cost Functions for Selecting from Among Possible Joint Angles

Various cost functions can be used to select a set of joint angles from among the possible solutions calculated using the previous strategies, according to desired performances of the manipulator. For example, if the manipulator is to move in the most energy-efficient manner, a cost function is used that measures energy consumption, which may correspond to the sum of the changes of all of the joint angles.

A simple cost function that selects the set in which the maximum change of all of the joint angles is less than those in the other sets. This cost function is believed to select the solution which enables the manipulator to point at the target location in the shortest amount of time.

To prevent the system from attempting a particular set of joint angles that cannot be achieved because of damage, a valuation scheme is introduced. In this scheme, a set of joint angles is considered invalid if the torque values of all of the joint angles are less than a certain value and the manipulator cannot access the target location.

In the next report, a comparative study of this cost function will be done.

RESULTS FROM COMPUTER SIMULATION

Computer simulation was used to verify the merits of our decentralized autonomous control of a 10-jointed manipulator. The arm lengths between the joints are identical.

Accessing Path According to Initial Condition

A cost function was selected which will achieve the fastest positioning. Therefore, the time required to point at each target location was expected to be optimized under various conditions. As shown in Fig. 1, the manipulator changed its accessing path according to its initial position. This result indicates that decentralized control mechanism effectively uses a redundant system parameter for time performance. In this decentralized control

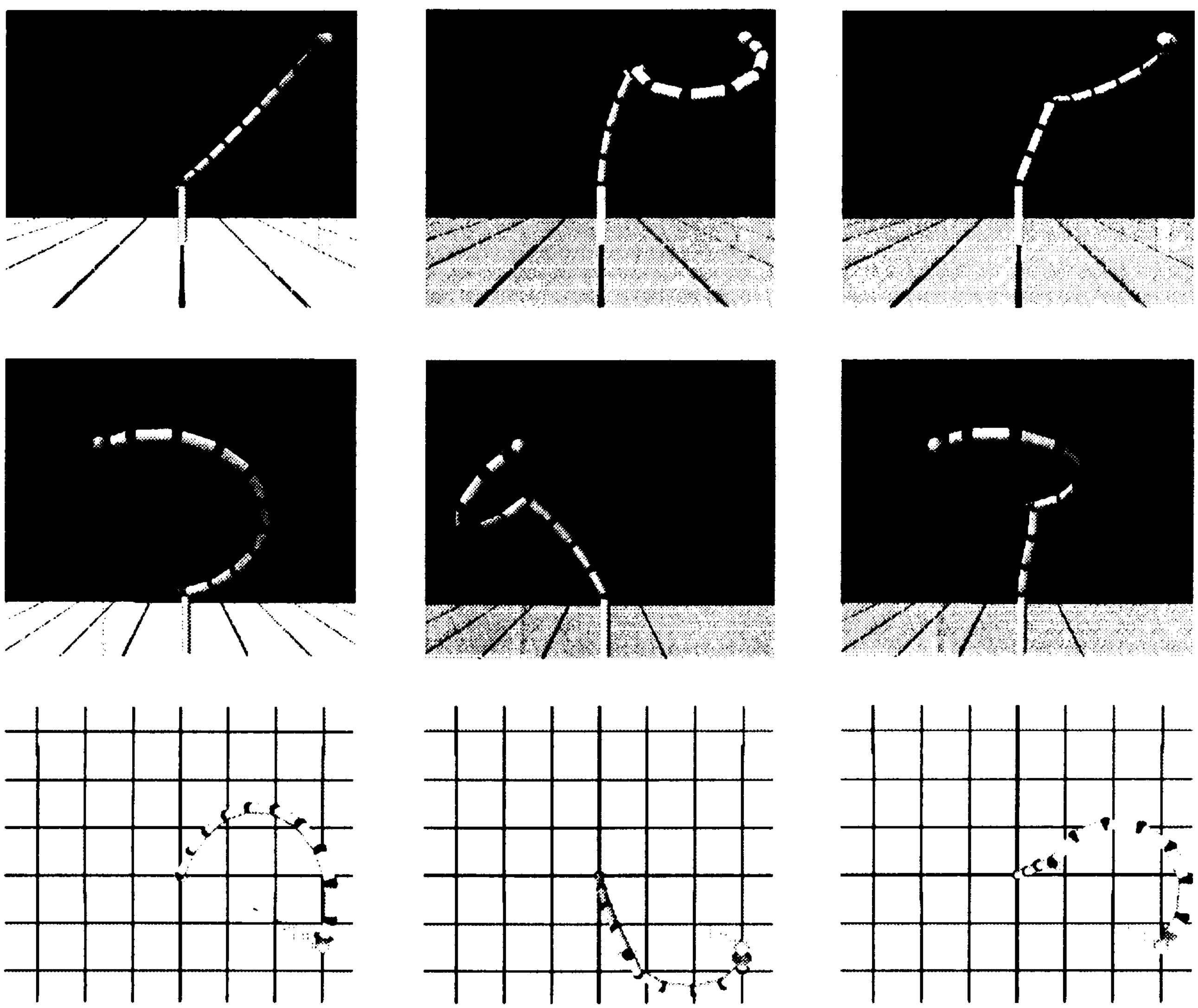

Fig. 1: Kinematic views of the access path of a 10-jointed manipulator based on its initial position. The target location is all identical.

mechanism, the number of joints hardly affects the control performance, since calculations are performed in local processors. Therefore, this result suggests that, under this control mechanism, as the number of joints in the manipulator is increased, the manipulator becomes more dexterous and faster, if permitted by the constraints of the hardware and the communication within the Global Information Bus.

Robustness to Partial Damage

The robustness of this redundant manipulator to partial damage is assessed by fixing one or two joints at a certain angle. Even after one of the ten joints was frozen at a certain angle while the manipulator was accessing the target location, the manipulator successfully pointed at the target location by autonomously changing its strategy without any external assistance or additional information. Figure 2 shows how this manipulator accesses to the target after the fifth joint was frozen when the manipulator was at its initial position. The percent of the dead area is not increased when one of the ten joints is frozen at an angle of 0°. These results show that the manipulator can solve the inverse-kinematics of every location it can physically. As shown in Figure 3, this manipulator can autonomously adapt to the condition when some joints are simultaneously damaged. (The other conditions are the same as Figure 2.) These results show that the manipulator based on our control mechanism has high adaptability to its partial damage.

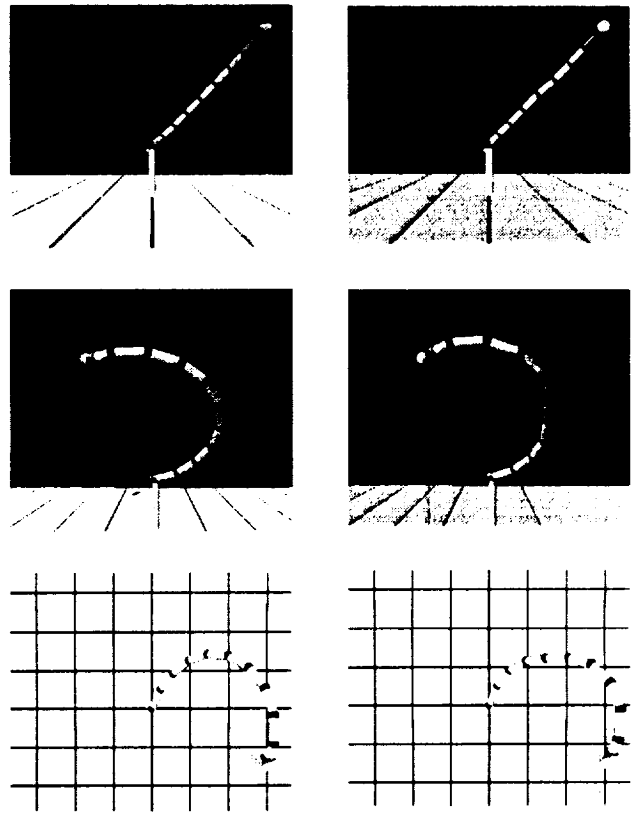

Fig. 2: Kinematic views of the access path after the fifth joint was frozen.

DISCUSSION

This section discusses how to design a control system based on our control mechanism from a generalized viewpoint. The designing principle can be summarized using the following five points.

The first is to give "local processors" to each element of the system. The "local processor" discussed in our scheme can be imaginarily achieved using a single processor employing a program module. Of course it is better for performance and robustness if a small and independent processor for each joint is used to construct a control system.

The second is to provide an information path so that these local processors can communicate with each other. If an independent processor is used for each joint, an information path must be given between local processors. Especially for space robots, wireless communication will be advantageous since wireless communication is less sensitive to structural constraints and can broadcast information.

The third is to have algorithms show how the local processors calculate an operational-information candidate independently of one another (Strategy 1 and 2, in the case of this manipulator).

The fourth is a cost function regarding how to select the operational information from the candidates (a cost function which selects the set in which the maximum change of all of the joint angles is less than those in the other sets, as in the case of this manipulator).

Points (3) and (4) are the most important points for designing a control system. These algorithms should be created according to the function of plant. For example the cost function that selects a candidate to minimize energy consumption may suit one plant, another cost function that selects the candidate which

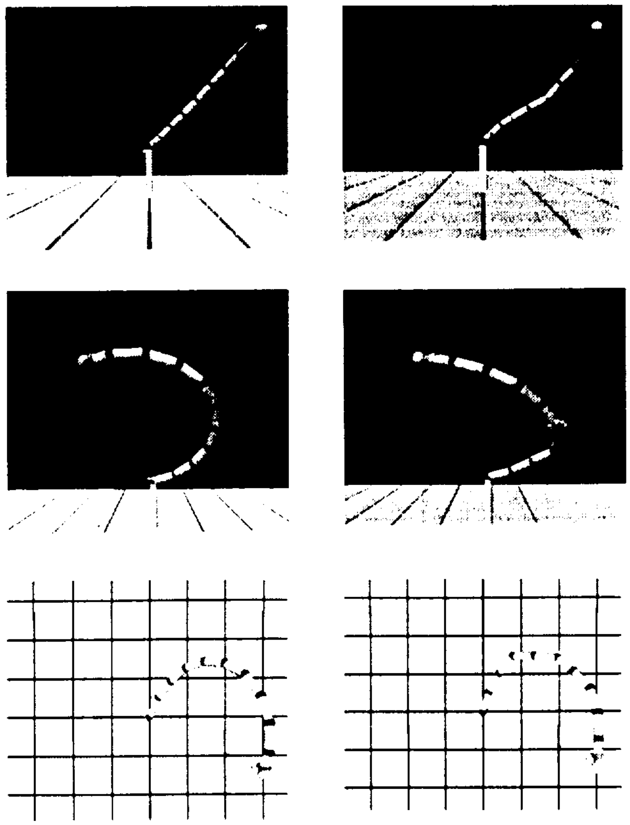

Fig. 3: Kinematic views of the access path after the third, fifth, seventh and tenth joints were simultaneously frozen.

optimizes fluency may suit another plant. The system function should be implemented into algorithms from the viewpoint of the local processor.

Point five is to give time constant for the calculation-process calculation process loop. In this control mechanism, it is essential to loop locally and globally real time. If the time constant is small, precise control is attainable and if the time constant is large, control systems have good time performance. Therefore, optimum time constants should be given according to the function of the plant.

According to the generalization of the designing principle of control systems, our control system can be extended for various plants, and an adaptive decentralized autonomous control system can be achieved.

CONCLUSION

This paper presents our decentralized autonomous control mechanism applied to the control of three-dimensional manipulators and its robustness to partial damage was assessed by computer simulation. Decentralized control structures are believed to be quite robust to time delays between the operator and the target system. A 10-jointed manipulator based on our control mechanism was able to continue its positioning task in three-dimensional space without revision of the control program, even after some of its joints were damaged. These results suggest that this control mechanism can be effectively applied to space telerobots, which are associated with serious time delays between the operator and the target system, and which cannot be easily repaired after they have been partially damaged.

REFERENCES

[1] Vemuri B. C.; and Skofteland G., 1990, Motion Estimation from Multi-Sensor Data for Tele-Robotics, In *IEEE Workshop on Intelligent Motion Control*, 20-22.

[2] Hirzinger G.; Heindl J.; and Landzettel K., 1989, Predictive and Knowledge-Based Telerobotic Control Concepts, In *IEEE Conference on Robotics and Automation*, 14-19.

[3] Liegeois A., 1977. Automatic Supervisory Control for the Configuration and Behavior of Multibody Mechanisms, *IEEE Trans. Sys. Man Cyber.* 7:868-871.

[4] Hollerbach J. J.; and Suh K. C., 1985, Redundancy Resolution of Manipulators through Torque Optimization, In *Proc. 1985 IEEE Int. Conf. Robotics Automation.*, 1016-1022.

[5] Salisbury J. K.; and Abramowitz J. D., 1985, Design and Control of a Redundant Mechanism for Small Motion, In *Proc. IEEE Int. Conf. Robotics Automation*, 323-328.

[6] Maciejewski A. A.; and Klein C. A., 1985, Obstacle Avoidance for Kinematically Redundant Manipulators in Dynamically Varying Environments, *Int. J. Robotics Res.* 4,: 109-117.

[7] Kelin C. A.; and Blaho B. E., 1987, Dexterity Measures for the Design and Control of Kinematically Redundant Manipulators, *Int. J. Robotics Res.* 6: 72-83.

[8] Cheng F. T.; and Orin D. E., 1990, Efficient Algorithm for Optimal Force Distribution - The Compact-Dual LP Method, *IEEE Trans. Robotics Automat.* 6: 178-187.

[9] Cheng F. T.; Chen T. H.; and Sun Y. Y., 1994, Resolving Manipulator Redundancy under Inequality Constraints, *IEEE Trans. Robotics Automat.* 10: 65-71.

[10] Kimura S.; Yano M.; and Shimizu H., 1993, A Self-Organizing Model of Walking Patterns of Insect, *Biol. Cybern.* 69: 183-193.

[11] Kimura S.; Yano M.; and Shimizu H., 1994, A Self-Organizing Model of Walking Patterns of Insect, (II) The Loading Effect and Leg Amputation, *Biol. Cybern.* 70: 505-512.

[12] Kimura S.; Miyazaki K.; and Suzuki Y., 1994, Application of a Decentralized Autonomous Control Mechanism for Space Robotics, In *Proceedings of 19th International Symposium on Space Technology and Science*, in press, Yokohama, Japan.