Inverse Kinematics Algorithm based on Fuzzy Control Model

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Abstract - In this paper, we propose a multijoint control reduction method for small self-contained autonomous robots. This method reduces the inverse kinematics operation. Furthermore, this method enables the development of an easy control system, because the use of the fuzzy logic enables the linguistic modeling of the joint angle. By carrying out an experiment on horizontal coplanar points using the arm of a small humanoid robot, we confirmed that the robot can perform the same movements as humans. In addition, we achieved fast information sharing applying the control algorithm of an all-integer arithmetic algorithm in a low-cost and low-power microprocessor.

Keywords - Inverse Kinematics, Reduction algorithm, Reduction control, Fuzzy model, Multijoint control

1. Introduction

Multijoint robots are widely used in households and industries. They are becoming increasingly complex and sophisticated. Their operation and actions have been studied for planning robot paths using dynamics or kinematics.

However, the present path planning techniques are not suitable for small, low-cost, and general-purpose microprocessors, because the use of mathematical functions increases the computational burden, and the little memory space in the small microprocessors are consumed by the generation of a conversion table of trigonometric functions, and so on. However, high-speed operation and high precision are essential for robots used for factory automation. However, for entertainment robots and amusement robots to coexist in daily life, they are not necessarily often requested. In the case of small robots, movement speed and precision, which are otherwise not given importance in the design concept, should be given the top priority. Small robots should be able to perform a wide range of movements and tasks in a limited space at high speeds, have high processing capacity, and should be economical. In the future, the small robot technology should be able to meet the diverse demands and be useful in everyday life. The easy and convenient technology must be developed to operate robots under regulated conditions [1-4].

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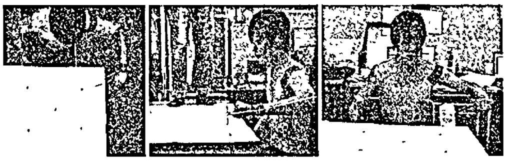

Fig.1. Human motion analysis

Generally, robots are designed by studying human movements, some of which are made involuntarily. The application of the movement algorithm to robots has been found to be inefficient. The computation involved in enabling robots to imitate human behavior should not be complex. Not many studies have been conducted on the application of fuzzy control to small autonomous robots.

In this paper, we propose an inverse kinematics algorithm to reduce the burden of control microprocessors in multijoint robots, which is necessary to integrate small autonomous robots into daily life. In addition, we apply it to study a link mechanism with multiple joints and experimentally verify the effectiveness of the proposed control method.

2. Multijoint Control and Our Cerebration

In the future, the desktop might become the general working area of small robots. In this study, we have focused on the behavior of the arm joint of the participant of an experiment.

2.1 Relationship Between Actions of Robots and Humans

When a person extends his/her hand toward an object on a desk to touch or lift the object, he/she is subconsciously controlling the joint angles of the shoulders and elbows. In this case, the person controls the movement while imaging the movement of the finger in a head. We say or think, "more left" or "a little back" etc. When the person explains an action by words, or is explained, these are similar to the thinking process of person. In addition, the joint angle is calculated using a function for different types of robots exhibiting the same behavior and having the same motion trajectory. However, humans do not make such movements. When a person tries to touch an object, his/her hand movements are different for different types of objects. Moreover, humans do not consider the joint angles while making such movements.

Therefore, in this study, we use modeling languages to human arm movements model, realized through a control system with reduced computational complexity, and generate appropriate movements. Our aim is to apply the results of this study to control the movements of multijoint robots. We focus on multijoint robots and study their movements over a desktop.

1) The relation between the coordinate position of an object and the joint angle controlled by rule-based control is expressed using a linguistic expression.
2) The control algorithm used to calculate each joint angle reduces the burden on the microprocessor by performing all calculations using an integer.

2.2 Human Motion Analyses

To achieve these aims, we analyzed the movements of a moving arm on a desk, i.e., a 2D plane surface, as shown in Fig.1. In this analysis, nine points (corner points, diagonal intersection point, and midpoints of the sides of a rectangle) were selected beforehand. Next, a male participant was asked to continuously move his arm over the plane containing the nine points. His movements were video recorded from three directions (top, front, and side). We found that the participant extended his hand toward the object after judging the distance between his fingertips and the object position. This confirms that humans do not take into consideration their joint angle. In addition, we determined the following from the three sampling images:

1) Each joint angle (shoulder, elbow, and wrist; from the top image)
2) Straight line angle that connects the hand to the shoulder (from the side image)
3) Distance between the desktop and the fingertips (from the front image)

The results of this study will be useful for developing advanced small autonomous robots.

3. Control Model and Robot System

3.1 Model for Controlling Arm Joints

This study focused on a 4-DOF robot arm that can move over 2D planes such as tables. The control system of this robot has 2 inputs and 4 outputs. When the (x, y) coordinate of an arbitrary position on a 2D plane is inputted to this robot system, each joint angle can be changed by using the inverse kinematics algorithm. This model was developed on the basis of the results of the human motion analysis. The coordinates of the fingertips of the participant's continuously moving hand and his joint angles were modeled by using fuzzy sets. In addition, the collected information was compressed by quantifying the large amount of data obtained from motion capture systems. We used the data on the "picking up" action executed by the participant, for developing a fuzzy control model. The quantification of behavior of the participant and this formulation of linguistic rules is enabled by the abovementioned algorithm. In addition, this algorithm can be used to describe the behavior of the participant easily by means of all four arithmetic operations involving integers. Thus,

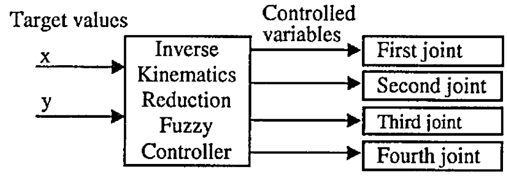

Fig.2. Block diagram of the Fuzzy Controller

we have realized a flexible control system and a small robot system. The advantage of the fuzzy model is that it can be applied to small microprocessors for developing small robots or for easily modeling the behavior of humans or animals. We attempted to apply the fuzzy controller to a 4-DOF manipulator of a small autonomous robot controller. Fig. 2 shows the block diagram of the control section of this system.

3.2 Fuzzy Control Model

A fuzzy reasoning algorithm for simplifying the inverse kinematics of the 4-DOF arm part of a small robot is described below. For a joint of the i-th control rule, the (x, y, θ) space of the fuzzy relation Ri is given by equation 1.

$$(x, y, \theta) \text{ is } R_i \qquad (1)$$

Then, the 4-DOF the joints of the robot arm with a joint j is given by

$$(x, y, \theta j) \text{ is } R_{ij} \qquad (2)$$

The next rule bases of the four kinds are calculated by the sentence connective "also". Consequently,

$$R_{SP} = \bigcup_{i=1}^{9} R_{iSP} \text{ or } R_{SR} = \bigcup_{i=1}^{9} R_{iSR} \text{ or } R_{EB} = \bigcup_{i=1}^{9} R_{iEB} \text{ or } R_{WT} = \bigcup_{i=1}^{9} R_{iWT} \qquad (3)$$

Here, SP denotes shoulder pitch; SR, shoulder roll; EB, elbow; and WT, wrist.

Inputting the coordinate (x^0, y^0) gives the joint angle $B_j^0(\theta_j)$. The input membership function $A_1(x)$ of the x coordinate, the input membership function $A_2(y)$ of the y coordinate, and the output membership function $B_j(\theta_j)$ are defined as

$$\omega_i = A_{i1}(x^0) \wedge A_{i2}(y^0).$$

Then, ω_i becomes the grade of the i-th rule. Furthermore, the maximum grade set for this system is 255, and it truncates the decimal part to yield an integer.

In general, the fuzzy relation equation between the input and the output is

$$B_j^o(\theta_j) = \bigvee_{i=1}^{9} \left[\omega_i \wedge B_{ij}(\theta_j)\right] \quad (4)$$

The defuzzification operation is focused on reducing the amount of calculation. Therefore, we have applied equation (5) as a weighted average using centers of a singleton-type output membership function.

$$\theta_j = \frac{\sum_{i=1}^{n} \omega_i R_{ij}}{\sum_{i=1}^{n} \omega_i} \quad (5)$$

3.3 Linguistic Description and Quantification

We quantified the (x, y) coordinate of the fingertip position on the desktop by using fuzzy sets on the basis of the sampling images. The input membership function that is used to allocate a linguistic label to the fuzzy sets is shown in Fig.3. The construction of the output membership function (Fig.4) is described as follows. The participant is asked to continuously trace a rectangle of dimensions 400 [mm] × 300 [mm]. We consider nine points of the rectangle — the corner points, midpoint

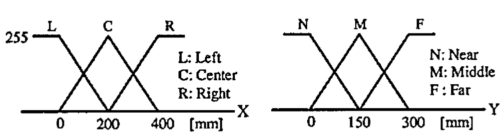

Fig.3. Input membership function

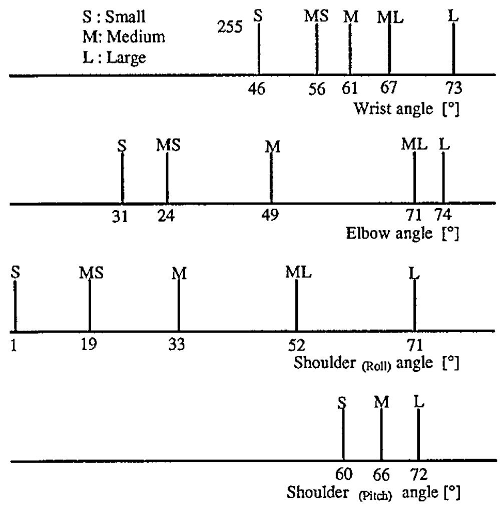

Fig.4. Output singleton membership function

Table 1. Rule table for 4DOF robot arm

		Wrist X			Elbow X			Shoulder(Roll) X			Shoulder(Pitch) X		
		L	C	R	L	C	R	L	C	R	L	C	R
Y	N	L	ML	S	L	L	ML	L	ML	MS	S	S	S
	M	L	M	S	M	M	M	ML	M	S	M	M	M
	F	ML	M	MS	MS	MS	S	M	MS	S	L	L	L

of each side, and the intersection point of the diagonals?for characterizing the participant' s behavior. Let the joint angles of the shoulder (pitch, roll), elbow, and wrist of the participant be the center of the fuzzy sets. In a similar manner, we used linguistic labels to express the angles and quantified each by using a singleton.

3.4 Inverse Kinematics Fuzzy Rule

Table 1 shows the fuzzy rule obtained from the study of the behavior of the participant. This rule constitutes the inverse kinematics model used to calculate the joint angle of the 4-DOF system by using fuzzy reasoning for the target coordinates. The inference algorithm uses the min-max composition method, and the output result of fuzzy inference using a singleton.

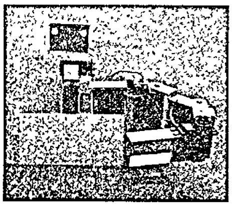

Fig.5. 4DOF arm robot

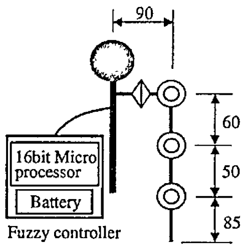

Fig.6. Hardware configuration

Table 2. Joint-angle calculation time [μs]

4DOF	8DOF	12DOF	24DOF
175	350	510	1040

3.5 Hardware Model of 4DOF Robot

Fig.5 shows the photograph of the small robot used in the experiment. The upper body of this robot is an autonomous 4-DOF humanoid robot with a 16-bit microprocessor. Fig.6 shows the hardware configuration of this robot.

4. Application Experiments

4.1 Inverse Kinematics Fuzzy Control Model

Next, we investigate the validity of the model experimentally. We implemented the inverse kinematics fuzzy control model to a microprocessor and carried out an experiment using the model with the 4-DOF robot arm. Using the human motion analysis, we investigated the behavior of the robot during the tracing of a rectangle, a circle, and an inclined line, such that movement was limited within a rectangle of dimensions 400 [mm] × 300 [mm]. We investigated the behavior of the robot when it was operated continuously. Photographs of the robot arm tracing the rectangle at intervals of 5 [mm] are shown in Fig.7. Results of 100 [ms] sampling of each joint-angle trajectory of the robot arm are shown in Fig.8. Fig.9 shows photographs of the robot arm tracing a circle at intervals of 1[°] (π/180 [rad]). Fig.10 shows the joint-angle trajectories of the robot arm tracing the circle. Fig.11 shows photographs of the robot arm tracing the inclined line, and Fig.12 shows the change in the joint angle in this experiment.

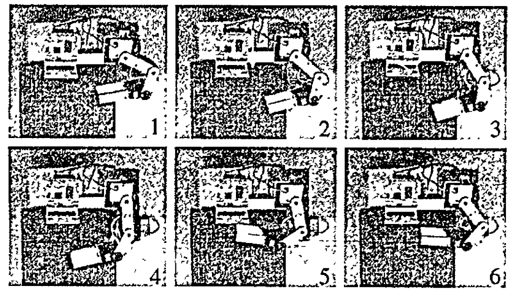

Fig.7. Robot arm tracing a rectangle

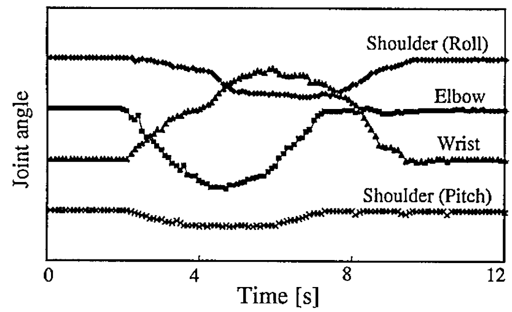

Fig.8. Joint-angle trajectory of robot arm tracing rectangle

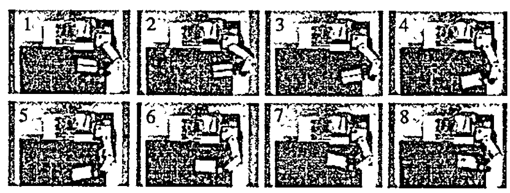

Fig.9. Robot arm tracing a circle

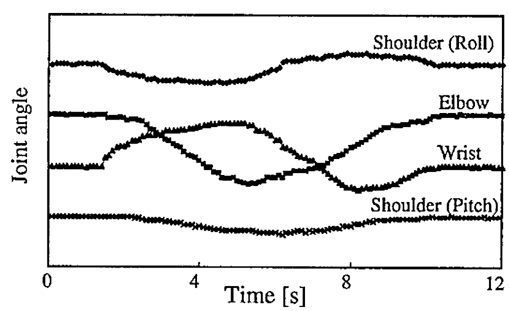

Fig.10. Joint-angle trajectory of robot arm tracing a circle

Fig.11. Robot arm tracing an inclined line

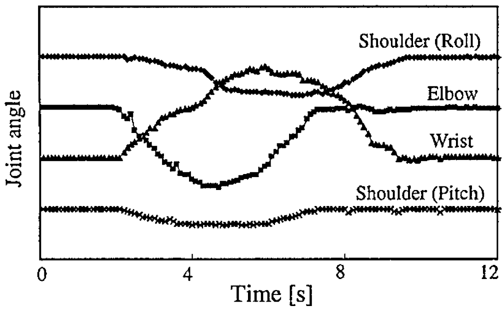

Fig.12. Joint-angle trajectory of robot arm tracing an inclined line

In all the experiments, the robot system appropriately interpolated the trajectories. Thus, the small autonomous robot produced swift and continuous movements.

4.2 Fuzzy Controller Processing Capacity

Table 2 shows results of the time taken for the calculation of the joint angles. The clock frequency of the system microprocessor is 25 MHz. The processing time for all the joint angles of 24 DOF, which is the approximate number of DOF of small humanoids, was approximately 1 [ms]. This processing time is equal to the control time of commercial standard RC servomotors. Moreover, the results show that the microprocessor could control all joints without overloading.

5. Conclusion

In this paper, we proposed a multijoint robot control method for inverse kinematics, which is based on a fuzzy control model. Experimental results show that this control method can be effectively used for small robots. Moreover, this system could efficiently control all of the multiple joints by means of integer operations. We could simplify the calculation of joint angles. In addition, this system optimizes the performance of low-cost or low power microprocessors.

Acknowlegment

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