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Coordination of Multiple Robot Arms

L.K. Barker and D. Soloway
NASA Langley Research Center
Hampton, VA 23665-5225

ND210491

1. Abstract

~~This paper extends~~ kinematic resolved-rate control from one robot arm is extended to the coordinated control of multiple robot arms in the movement of an object. The structure supports the general movement of one axis system (moving reference frame) with respect to another axis system (control reference frame) by one or more robot arms. The grippers of the robot arms do not have to be parallel or at any predisposed positions on the object. For multiarm control, the operator chooses the same moving and control reference frames for each of the robot arms. Consequently, each arm then moves as though it were carrying out the commanded motions by itself.

2. Introduction

In the Intelligent Systems Research Laboratory (ISRL) at the Langley Research Center, an operator sits at a remote console with a six-axis hand controller and commands the motion of a robot arm. The operator has optional control modes, but of particular interest in this paper is kinematic resolved-rate control [1], which, for example, enables the operator to directly control the robot hand. The operator views the robot hand, decides that he wants it to move in a certain direction, and commands a velocity in that direction with the controller. The robot hand then moves in the desired direction with a velocity proportional to the controller deflection. Commanded hand velocities are transformed (resolved) into requisite movements (velocities) of the individual joints in the robot arm to effect the commanded hand motion. Currently, ISRL has two six-degree-of-freedom industrial robot arms.

There are some tasks which can not be done with just one robot arm, and other tasks which can be done with one robot arm, but not in a reasonable time. The advantage of using multiple robot arms is evidenced by humans in everyday activity. The major problem with multiarm control is that we do not know how to control robot arms in a general cooperative manner to accomplish a task. As noted in [2], the study of coordination problems between two robots doing a single job is in its infancy. Even then, work in dual-arm control ([2]-[4], for example) has dealt mostly with the master/slave architecture -- which is not of interest in the present paper. Recently, however, Hayati [5] proposed an interesting control architecture for position/force-torque control of multiarm cooperating robots. But, implementing this solution would require precise knowledge of the mass property of the arms as well as the object that is being grasped. In the present paper a simple kinematic (no mass properties) solution is devised and then implemented using two industrial robot arms. Toward this end, the well-known kinematic resolved-rate control is extended from the control of one robot arm to the coordinated control of multiple robot arms.

Resolved-rate control appears to be a natural way not only to move an object with one robot arm but also with multiple robot arms. After symbols/strings and axis systems are specified, equations are discussed for the general movement of one axis system (moving reference frame) with respect to another axis system (control reference frame) -- first, by one robot arm and then by multiple robot arms.

3. Symbols/Strings

alpha	a real number that locates a point along a line between two selected robot grippers or tools
base	base axis system
crf	control reference frame for operator inputs
hnd	hand axis system
i, j, k	integers

$$\text{matrix\_from\_\#\_to\_\#\#} = \left[\begin{array}{ccc|c} \multicolumn{3}{c|}{\text{r\_matrix\_from\_\#\_to\_\#\#}} & \text{vector\_from\_\#\#\_to\_\#} \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

mrf	moving reference frame

n	number of robot arms
obj	object axis system
r_matrix_from_#_to_##	rotational transformation matrix from axis system # to axis system ##; 3X3 matrix in upper left corner of the homogeneous transformation matrix from # to ## (i.e., matrix_from_#_to_##)
robot(i)	robot arm associated with integer i
robot(i).#	attribute # (such as axis system or velocity) of robot(i)
rvel_#	rotational velocity in axis system #
sta	station axis system, which is known with respect to the world axis system
tool	tool axis system
tvel_#	translational velocity in axis system #
vector_from_#_to ##	vector from # to ##
vector_cross_product_q_#	vector q in axis system # resulting from cross-product operation
vector_input_q_#	operator vector input q in axis system #
world	world axis system

Note: In equations, an asterisk (*) denotes multiplication, and x signifies a vector cross product.

4. Axis Systems

Axis systems allow quantities in the robot's environment to be geometrically related. Pertinent axis systems associated with a given robot(i) are:

(1) Base axis system (robot(i).base), which is located at the base of robot(i). If the base moves, which does not happen in this paper, the homogeneous transformation from world to robot(i).base is updated to reflect this movement.

(2) Control reference frame (robot(i).crf), which is an axis system on or off robot(i) that is selected by the operator for his velocity input to direct the moving reference frame. This frame may coincide with the moving reference frame or any other convenient axis system. Default of robot(i).crf is robot(i).tool.

(3) Hand axis system (robot(i).hnd), which is a moving axis system representing the hand of robot(i).

(4) Moving reference frame (robot(i).mrf), which is a definable axis system that is moved by the robot hand with respect to a control reference frame. Default of robot(i).mrf is robot(i).tool.

(5) Object axis system (robot(i).obj), which refers to an object associated with robot(i). Default of robot(i).obj is robot(i).tool.

(6) Station axis system (robot(i).sta), which is known with respect to the world axis system and does not move with joint-angle changes in robot(i). Default robot(i).sta is the world axis system.

(7) Tool axis system (robot(i).tool), which is located on a tool attached or held in the hand of robot(i). Default robot(i).tool is robot(i).hnd.

(8) World axis system (world), in which the positions of each base and station axis system are known. When movement only involves a single robot arm, default world is the base axis system of that robot arm.

Moreover, each joint in the robot arm has an associated joint axis system. The first three joints are sometimes referred to as the base or waist, shoulder, and elbow joints. The latter three joints constitute the robot wrist. Other axis systems not used in this paper are those associated with cameras, sensors, and goals.

5. Single Robot Arm Control

In general (fig. 1), an operator commands a velocity (expressed in a control reference frame (robot(i).crf)) to direct the movement of a moving reference frame (robot(i).mrf). The moving reference frame is actually moved by the robot hand (robot(i).hand). The required velocity of the robot hand is subsequently calculated as a consequence of the commanded velocity for this movement.

The homogeneous transformation matrix from the control reference frame to the moving reference frame is computed as

$$\begin{aligned}&\text{matrix\_from\_robot(i).crf\_to\_robot(i).mrf}\\ &\quad = \text{matrix\_from\_world\_to\_robot(i).mrf}\\ &\quad\quad * \text{matrix\_from\_robot(i).crf\_to\_world}\end{aligned}\tag{1}$$

where the matrices on the right side of equation (1) are available when the moving and control reference frames are selected.

The operator issues velocity commands in the control reference frame to direct the moving reference frame. In the moving reference frame of robot(i), the translational velocity (tvel) and the rotational velocity (rvel) that correspond to these commands are

$$\begin{aligned}\text{vector\_robot(i).rvel\_mrf} &= \text{r\_matrix\_from\_robot(i).crf\_to\_robot(i).mrf}\\ &\quad * \text{vector\_input\_robot(i).rvel\_crf}\end{aligned}\tag{2}$$

$$\begin{aligned}\text{vector\_robot(i).tvel\_mrf} &= \text{r\_matrix\_from\_robot(i).crf\_to\_robot(i).mrf}\\ &\quad * \text{vector\_input\_robot(i).tvel\_crf}\\ &\quad + \text{vector\_cross\_product\_robot(i).tvel\_mrf}\end{aligned}\tag{3}$$

where

$$\begin{aligned}&\text{vector\_cross\_product\_robot(i).tvel\_mrf}\\ &\quad = - \text{vector\_input\_robot(i).rvel\_crf}\\ &\quad\quad \times \text{vector\_from\_robot(i).mrf\_to\_robot(i).crf}\end{aligned}\tag{4}$$

In response to an operator rotational velocity input in the control reference frame, equation (4) makes the origin of the moving reference frame translate in a circular motion about the commanded rotational velocity vector. If it is desired that the moving reference frame only change its orientation and not translate in response to a rotational velocity command, then equaion (4) is not used.

The homogeneous transformation matrix from the moving reference frame to the robot hand is computed as

$$\begin{aligned}&\text{matrix\_from\_robot(i).mrf\_to\_robot(i).hnd}\\ &\quad = \text{matrix\_from\_world\_to\_robot(i).hnd}\\ &\quad\quad * \text{matrix\_from\_robot(i).mrf\_to\_world}\end{aligned}\tag{5}$$

where the elements of the first homogeneous transformation matrix on the left side of equation (5) is a known function of the robot joint variables.

To cause the moving reference frame to move with the commanded velocities, the hand axis system must move with the velocities:

$$\begin{aligned}\text{vector\_robot(i).rvel\_hnd} &= \text{r\_matrix\_from\_robot(i).mrf\_to\_robot(i).hnd}\\ &\quad * \text{vector\_input\_robot(i).rvel\_mrf}\end{aligned}\tag{6}$$

$$\begin{aligned}\text{vector\_robot(i).tvel\_hnd} &= \text{r\_matrix\_from\_robot(i).mrf\_to\_robot(i).hnd}\\ &\quad * \text{vector\_input\_robot(i).tvel\_mrf}\\ &\quad + \text{vector\_cross\_product\_robot(i).tvel\_hnd}\end{aligned}\tag{7}$$

where

$$\begin{aligned}&\text{vector\_cross\_product\_robot(i).tvel\_hnd}\\ &\quad = - \text{vector\_input\_robot(i).rvel\_mrf}\\ &\quad\quad \times \text{vector\_from\_robot(i).hnd\_to\_robot(i).mrf}\end{aligned}\tag{8}$$

Equation (8) is necessary because the robot hand must also translate to produce a pure rotation in the moving reference frame.

The rotational and translational velocities in equations (6) and (7) are expeditiously treated as operator inputs (rvel_hnd and tvel_hnd) in the hand axis system and used in previously programmed resolved-rate equations that take velocity commands in the robot hand axis system and transform them into joint rates in the robot arm to accomplish the commanded movement (fig. 2). Resolved-rate control is implemented once the homogeneous transformation matrices from the world to the control reference frame and from the world to the moving reference frame are known.

An operator is free to choose the control reference frame and the moving reference frame. For example, he may specify these frames by using menu selection, keyboard inputs, or a combination of light pen (location) and turnball (orientation) on a graphics system. (The latter way has not yet been implemented in ISRL).

6. Multiple Robot Arm Control

The intention in this paper is to communicate a method for coordinating multiple robot arms as they collectively move an object. The solution here (fig. 3) is simply to choose a common control reference frame and a common moving reference frame for each of the robot arms; that is,

robot(i).crf = crf (9)

robot(i).mrf = mrf (10)

An object axis system, if considered common to the robot arms, is noted as

robot(i).obj = obj (11)

Then, resolved-rate control is applied to each robot arm with respect to the common control reference frame. Each arm moves by resolved-rate control as though it were carrying out the commanded motions by itself. Two particular cases of reference frames are identified here by the following homogeneous transformation matrix equalities:

Case 1: matrix_from_crf_to_world = matrix_from_obj_to_world
matrix_from_mrf_to_world = matrix_from_obj_to_world

Case 2: matrix_from_crf_to_world = matrix_from_sta_to_world
matrix_from_mrf_to_world = matrix_from_obj_to_world

The first case corresponds to the movement of an object with respect to velocities issued in its own axis system; whereas, the second case corresponds to an object that is moved with velocities that are specified in a station axis system. A particular set of object axis systems are formulated.

7. Object Axis System on Line Between Grasp Points of Two Selected Robot Arms

An object grasped by robot arms can be maneuvered with respect to an object axis system located at a point (automatically computed) on a line between the grasp points (tool axis systems) of two selected robot arms. For example, the operator may locate the origin of the object axis system at:

(1) a point midway between two selected robot tools

(2) either robot tool

(3) a specified distance along the line between the two robot tools

For each robot(i), the homogeneous transformation matrix from its tool to the world axis system is computed as

matrix_from_robot(i).tool_to_world = matrix_from_robot(i).base_to_world
* matrix_from_robot(i).hnd_to_robot(i).base
* matrix_from_robot(i).tool_to_robot(i).hnd (12)

where the transformation matrix from the hand to the base of a robot arm is the result of moving through the joint axis systems, and the transformation matrix from the tool to the hand is given.

Let the two selected robot arms be labeled as robot(j) and robot(k). Moreover, define the orientation of the object axis system to be like that of robot(k). The position vector (needed in matrix_from_obj_to_world) to locate a point on the line between the tools of robot(j) and robot(k) is computed as (fig. 4)

vector_from_world_to_obj = alpha * (vector_from_world_to_robot(k).tool
- vector_from_world_to_robot(j).tool) (13)

If the operator selects the origin midway between the tools, alpha = 1/2; if the origin is at robot(k).tool, alpha = 0; and if the origin is at robot(j).tool, alpha = 1. Other values for alpha put the origin at different locations along the line between the two selected robot tools.

Here, orientation of the object axis system is defined to be like that of the tool of robot(k). Hence, the required rotational matrix is

$$\text{r\_matrix\_from\_obj\_to\_world} = \text{r\_matrix\_from\_robot(k).tool\_to\_world} \qquad (14)$$

which is the rotational matrix part of equation (12), with i = k.

8. Object Axis System Located at Mean Grasp Point

The position vector needed to locate the control reference frame at the mean of the robot grasp points is computed as

$$\begin{aligned} \text{vector\_from\_world\_to\_obj} = (1/n) & \\ & * (\text{vector\_from\_world\_to\_robot(1).tool} \\ & + \text{vector\_from\_world\_to\_robot(2).tool} \\ & \quad \vdots \\ & + \text{vector\_from\_world\_to\_robot(n).tool}) \qquad (15) \end{aligned}$$

Orientation of the object axis system is then defined in some convenient manner. For example, if the orientation of the object axis system is like the tool axis system of robot(k) then

$$\text{r\_matrix\_from\_obj\_to\_world} = \text{r\_matrix\_from\_robot(k).tool\_to\_world} \qquad (16)$$

Or, if the orientation is like that of the world axis system then

$$\text{r\_matrix\_from\_obj\_to\_world} = \text{r\_matrix\_from\_world\_to\_world} \qquad (17)$$

where the matrix on the right side of equation (17) is just the identity rotational matrix.

9. Concluding Remarks

A method of controlling a robot arm is for an operator to command the hand to move with a velocity in a desired direction. The commanded velocity (rotational and translational) is then resolved into joint rates in the robot arm to actually move the hand as commanded. In the present paper, this simple method, known as resolved-rate control, is extended from the control of one robot arm to the coordinated control of multiple robot arms. The structure supports the general movement of one axis system (moving reference frame) with respect to another axis system (control reference frame) by one or more robot arms.

The approach in this paper has been applied to two industrial robot arms that grasp a 12-foot long aluminum tube, representing a structural element for space construction. The bases of the robot arms were separated by about 6 feet. The operator with a six-axis hand controller successfully translated and rotated the tube with respect to an axis system on the tube. Gross movements of the tube were accomplished with no force/torque feedback.

10. References

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