Cooperative Contour Control of Two Robots under Speed and Joint Acceleration Constraints

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Abstract: The fundamental aim of this paper is to present a solution algorithm to achieve cooperative contour controlling, under joint acceleration constraint with maximum cooperative speed. Usually, the specifications like maximum velocity of cooperative trajectory are determined by the application itself. In resolving the cooperative trajectory into two complementary trajectories, an optimum task resolving strategy is employed so that the task assignment for each robot is fair under the joint acceleration constraint. The proposed algorithm of being an off-line technique, this could be effectively and conveniently extended to the existing servo control systems irrespective of the computational power of the controller implemented. Further, neither a change in hardware setup nor considerable reconfiguration of the existing system is required in adopting this technique. A simulation study has been carried out to verify that the proposed method can be realized in the generation of complementary trajectories so that they could meet the stipulated constraints in simultaneous maneuvering.

Keywords: Contour control, cooperative trajectory, joint acceleration constraint, maximum cooperative velocity, two robot arms

1. INTRODUCTION

With the advent of robotics technology, autonomous multiple robots are increasingly utilized in industrial environments and cooperative control of plural robots has attracted much attention in wide variety of applications. Entertainment robots, emergency support robots, robots employed for transportation, picking and placing, and manufacturing work cells are few of typical applications, where the cooperative control is demanded. The coordination and cooperation of multiple robots to optimize the operational efficiency is one of the key concerns underlying the concept of cooperative control. Expansion of the scope for missions inherently distributed in space, time and functionality, increased reliability and robustness through redundancy, decreasing task completion time through parallelism, and potential reduction in cost through simplex individual robot design are the motivation and driving factors to achieve cooperative control of robots [1].

‘Human being using two arms has a greater advantage over one hand used by two human beings’. This poses the importance of the concept of proper coordination for a cooperative task, and cooperation itself does not establish sufficient support to achieve higher operational efficiency. It is worth to note that the cooperative behavior is a sub class of collective behavior where coordination of individual entities is emphasized.

Cooperative control is defined as the controlling of multiple dynamic entities that share a common, though perhaps not singular, objective [2]. Cao *et. al.* in his survey on cooperative mobile robots [3] cooperative control is defined as given some task specified by a designer, a multiple robot system displays cooperative behavior if, due to some underlying mechanism (i.e. the mechanism of cooperation), there is an increase in total utility of the system. In both definitions, the integration of individual robot directions to accomplish a specified cooperative task or tasks is considered under cooperative control. In literature, cooperative control strategies are basically of two types. The first strategy is called loose cooperation, where the manipulation task is executed by controlling the two robots in an independent fashion, so that cooperation is realized only at task planning level. The second strategy called tight cooperation, realizes the cooperation not only at planning level, but also at the control level [4]. The former approach is simple, could be of off-line, operating without any sensory feedback and thrives well in structured environment, whereas the latter could operate even under unstructured environment, since sensory feedback could guide the task at operational level.

Researches related to cooperative control were addressed in several research directions and found in number of research domains including dual robot or multi-robot cooperation in single or multi-task environment, with artificial intelligence through learning behavior or fault tolerance robust control under sensory guidance in unpredictable environments. However, the complete review of this arena is beyond the scope of this article, we briefly outline the most relevant research attempts.

The topic of optimal motion planning or multi-arm robotic manipulators was addressed by Bonert *et. al.* in [5]. Bonert *et. al.* presented a multi robot optional assembly planning based on augmented traveling salesman problem, where both "sales person" (robot with a tool) and the "cities" (another robot with work piece) are subjective to move. This control approach was point-to-point control scheme and genetic algorithm based technique was employed to evaluate solutions. Two challenging issues, the derivation of motion equations according to the situation and compliance of desired control requirements, that the control engineer faces in designing a robot control system for dual arm configuration was pointed out by Carignan *et. al*. in [6]. Carignan applied a generalized 'reduction transformation' to the dynamics to remove the singularity of the system. Robust control of robots has been investigated for a planner dual arm manipulator system by Liu *et. al.* in [7]. An optimization algorithm is developed such that minimization of energy consumed by the participating arms subjected to equality and inequality constraints of grasp and friction constraints. Problem of achieving a cooperative behavior in a dual arm robot system was explained in [8]. In the strategy proposed by Caccavale *et. al.,* one robot is devoted to task execution, whereas the other robot copes with unavoidable misalignment between the two arms and task planning inaccuracies.

In last two decades, research attention on cooperative control is mainly focused either on coordination of multiple robots for a unified task compromising the efficiency of cooperation or a dual arm cooperative control. An extensive amount of researches have carried out on dual arm cooperative control to achieve compliant motion, foremost in custom design products. A great concern as well as attention has been paid either to enhance the speed of operation in point to point control or to augment the performance characteristics of compliant motion. However, in the literature of cooperative contour controlling, cooperative trajectory planning was not sufficiently addressed yet. In this paper, authors attempt to discuss the issues related to achieve contour control within the framework of cooperative control of two robots, and also propose a deterministic algorithm based on kinematics control to achieve cooperative control of two robots under joint acceleration constraint and maximum cooperative speed.

The cooperative trajectory is resolved into two conjugate trajectories under joint acceleration constraint, so that the task is evenly distributed between two robot arms. Being an off-line algorithm, issue on computational time does not impose any limitation and hence this method could be directly adopted to the existing servo systems without any change of hardware or a considerable reconfiguration of the system. Besides, the above advantages, the usage of two robots causes to expand the scope of the working space cum reduce the task completion time achieving higher cooperative velocity without experiencing the joint acceleration limitation, despite the potential jamming and inter collision of two robots in case of improper trajectory planning.

The issues relevant to contour planning are discussed in Section 2.1 and the proposed algorithm presents in Section 2.4. In Section 3, simulation results are illustrated and conditions for simulation are also stated. Final section is devoted to concluding remarks.

2. METHOD

2.1 Problem statement

The relative motion between the end effectors of two robots generates the cooperative trajectory, when the two manipulators maneuver simultaneously. Therefore the cooperative trajectory should be resolved into two conjugate trajectories such that the relative trajectory between them exactly constitutes the cooperative trajectory.

Specifications, constraints and performance criteria of industrial tasks are generally expressed in the working space, frequently referred to as Cartesian space. The cooperative trajectory specifications such as maximum permissible velocity are generally governed by the application itself and to realize the minimum time operation under the maximum velocity constraint, velocity profile must be of trapezoidal shape. In the cooperative trajectory, velocity is bounded by an upper limit specified by the application.

$$|v^c| \le v^c_{\lim} \qquad \forall t \tag{1}$$

where v^c and $v^c_{\lim}$ are velocity of cooperative trajectory and its maximum limit respectively. However, it is not pragmatic to realize the maximum velocity of cooperative trajectory in zero time and the maximum cooperative velocity should be reached under practically viable cooperative acceleration. This cooperative acceleration constraint could be mathematically expressed by

$$|a^c| \le a^c_{\lim} \qquad \forall t \tag{2}$$

where a^c and $a^c_{\lim}$ be cooperative acceleration and its upper limit respectively.

Motion of robot arms originates at the servomotors connected to the joints and hence control action should be expressed in joint space. In most practical consequences, the maximum end effector velocity imposed by the application does not limit by the joint velocity limit of servomotors even with a mono-robot case and therefore, joint velocity limit governed by hardware limitations of motors is beyond consideration in this paper. However, torque constraint imposed by the hardware, referring to the power amplifier current rating, inflicts a joint acceleration limit. In cooperative control of two robot arms, acceleration of neither joint of robots could exceed the joint acceleration limit. The bounded acceleration limits for each robot could be stated as

$$\begin{aligned} |\ddot{\alpha}_A| &\le (\ddot{\alpha}_A)_{\lim} \\ |\ddot{\beta}_A| &\le (\ddot{\beta}_A)_{\lim} \\ |\ddot{\alpha}_B| &\le (\ddot{\alpha}_B)_{\lim} \\ |\ddot{\beta}_B| &\le (\ddot{\beta}_B)_{\lim} \end{aligned} \tag{3}$$

where $\ddot{\alpha}_A$, $\ddot{\beta}_A$, $\ddot{\alpha}_B$, $\ddot{\beta}_B$, $(\ddot{\alpha}_A)_{\lim}$, $(\ddot{\beta}_A)_{\lim}$, $(\ddot{\alpha}_B)_{\lim}$ and $(\ddot{\beta}_B)_{\lim}$ denote the accelerations of joint 1 of robot A, joint 2 of robot A, joint 1 of robot B, joint 2 of robot B, and acceleration limits of corresponding joints respectively.

2.2 Preliminaries

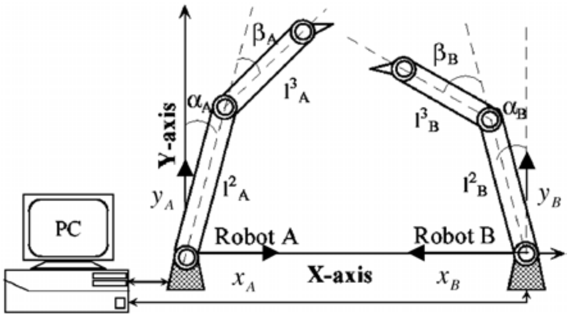

Fig. 1 Experimental setup

Fig.1 gives a comprehensive illustration of the orientation of two robots and selection of coordinate axes. α_A, β_A, α_B, and β_B denote the joint coordinates of joint 1 and joint 2 of robot A and robot B respectively. Similarly l_A^2, l_A^3, l_B^2, and l_B^3 represent the lengths of link 2 and 3 of robot A and B respectively. Joint 1 of robot A is selected as the origin of the common coordinate system referred to as 'global coordinate system' hereafter in this paper. Two Cartesian coordinate systems $[x_A, y_A]$ and $[x_B, y_B]$ are defined referring to robot A and robot B as indicated in Fig.1. The end effector positions of robot A and B could be represented with $[x_A, y_A]$, $[x_B, y_B]$ with respect to the coordinate systems attached to each robots respectively, whereas the origins of these coordinate systems are $(0,0)$ and $(X_{B0},0)$ referred to global coordinate system. The Cartesian coordinate transformation can be stipulated by equation (4).

$$\begin{aligned} X_A &= x_A \\ Y_A &= y_A \\ X_B &= X_{B0} - x_B \\ Y_B &= y_B \end{aligned} \tag{4}$$

where (X_A, Y_A) and (X_B, Y_B) give the spatial representation of the end effectors of robot A and B with respect to global coordinate system. The cooperative trajectory (X^{in}, Y^{in}) can be expressed by

$$\begin{aligned} X^{in} &= x_A + x_B - X_{B0} \\ Y^{in} &= y_A - y_B \end{aligned} \tag{5}$$

The relationship between cooperative velocity and acceleration could be represented with the following equations given by (6) and (7).

$$v^c = \sqrt{(\dot{X}^{in})^2 + (\dot{Y}^{in})^2} \tag{6}$$

$$a^c = \sqrt{(\ddot{X}^{in})^2 + (\ddot{Y}^{in})^2} \tag{7}$$

2.3 Strategy

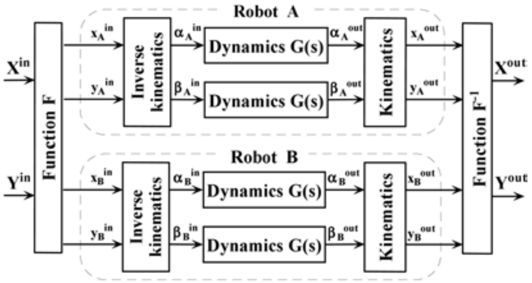

Fig. 2 Block diagram of cooperative control

The realization of cooperative control is shown in Fig.2. The cooperative trajectory specified in the Cartesian coordinates decomposes into two individual Cartesian time sequences for each robot. Using the task decomposition function F, inverse kinematics transforms Cartesian coordinates into joint coordinates so that it could be used for controlling purposes.

Simulation study was carried out for the joint positions of robot arms, subsequently applied kinematics to convert them into working coordinates and hence the simulated cooperative trajectory is obtained. Popular second order linear kinematics model is used for simulation and it is represented in equation (8).

$$G(s) = \frac{K_p K_v}{s^2 + K_v s + K_p K_v} \tag{8}$$

where K_p and K_v are the position and velocity loop gains of the servo system.

2.4 Algorithm of trajectory generation

The key concept of optimal cooperative trajectory generation is the decomposition of cooperative task into two complementary sub tasks. Having specified the cooperative trajectory (time history of contouring locus) there is no room to optimize the operational time but to optimize the performance characteristics of individual robots. Even decomposition of the task evenly between two robots satisfying the joint acceleration constraint is the ground for optimization. For that, an objective function H is defined.

$$\text{Minimize} \quad H = \{|\max\{|\dot{\alpha}_A|,|\dot{\beta}_A|\} - \max\{|\dot{\alpha}_B|,|\dot{\beta}_B|\}|\} \tag{9}$$

subjected to constraints given by equation (3).

Initially the desired trajectory is segmented based on the distance traversed in equal time intervals, and each segment is approximated with linear line segments. The segmentation time interval is reduced as low as 50 times of the sampling time enabling to achieve a precise following contour. Trajectory generation is carried out piecewise manner under the maximum joint acceleration constraint. The potential solutions in each segment are short-listed and append to solution space structured in the form of tree. Generation of children is allowed only for the optimum node based on the value of objective function. The occurrence of no solution at the optimal node in particular segment of cooperative trajectory causes to fold back one level up in the tree-structured solution space deleting that node, in search of second optimal node for ensuing branching. This iterative procedure is repeated until it covers all the segments of the cooperative trajectory. This algorithm is concisely represented in trajectory generation criteria in Fig.3. The solutions that cover the entire cooperative trajectory in segment wise constitute the conjugate trajectories for robot A and B. The trajectories generated in such, are interpolated for intermediate positions having sampling time spacing.

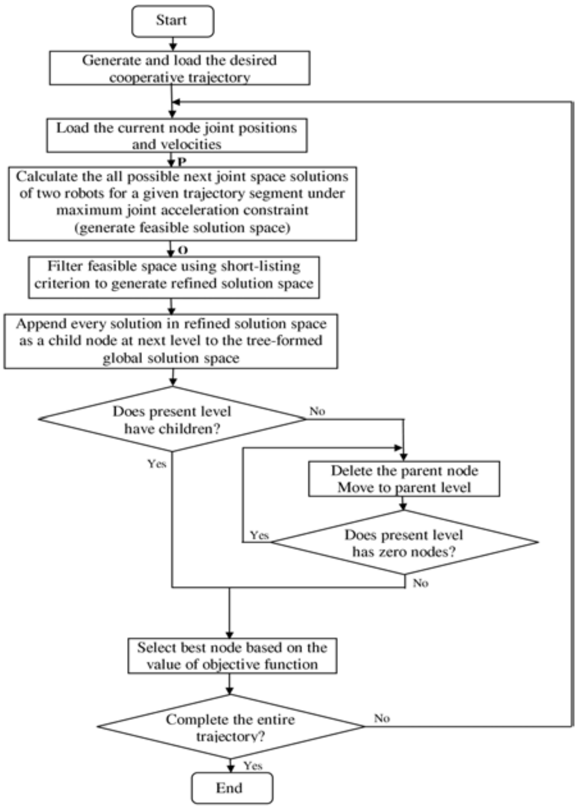

Fig. 3 Trajectory generation criterion

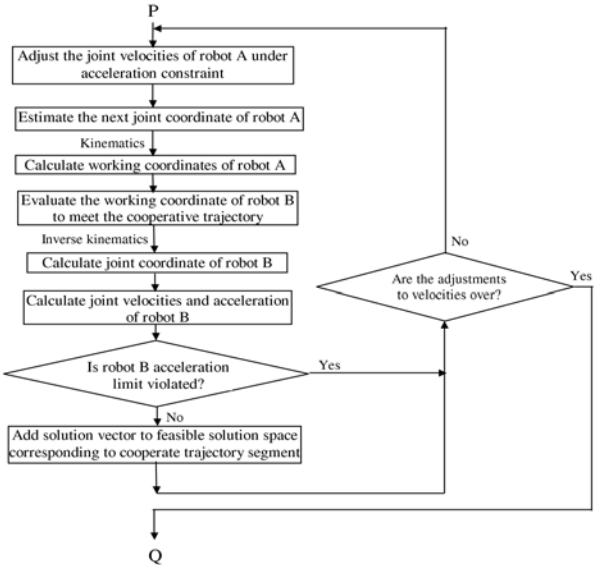

Fig. 4 Algorithm to generate feasible space

Generation of feasible solution space for a particular segment of the cooperative trajectory is given in Fig.4. Joint velocities of robot A are selected as parameters to generate solutions.

$$\begin{aligned} \dot{\alpha}_A(t_i) &= \dot{\alpha}_A(t_{i-1}) + k_1 T(\ddot{\alpha}_A)_{\lim} \\ \dot{\beta}_A(t_i) &= \dot{\beta}_A(t_{i-1}) + k_2 T(\ddot{\beta}_A)_{\lim} \end{aligned} \tag{10}$$

where k_1 and k_2 are parameters within the interval [-1,1]. T is the time interval used to segment the cooperative trajectory. The next joint position of robot A is evaluated using the Euler formula.

$$\begin{aligned} \alpha_A(t_{i+1}) &= \alpha_A(t_i) + T\dot{\alpha}_A(t_i) \\ \beta_A(t_{i+1}) &= \beta_A(t_i) + T\dot{\beta}_A(t_i) \end{aligned} \tag{11}$$

The kinematics equations transform joint space robot configuration into that of working space.

$$\begin{aligned} X_A(t_{i+1}) &= l_A^2 \sin[\alpha_A(t_{i+1})] + l_A^3 \sin[\alpha_A(t_{i+1}) + \beta_A(t_{i+1})] \\ Y_A(t_{i+1}) &= l_A^2 \cos[\alpha_A(t_{i+1})] + l_A^3 \cos[\alpha_A(t_{i+1}) + \beta_A(t_{i+1})] \end{aligned} \tag{12}$$

The movement of two robots must realize each segment of cooperative trajectory, and hence new Cartesian position of the robot B is evaluated.

$$\begin{aligned} X^{in}(t_{i+1}) - X^{in}(t_i) &= [X_A(t_{i+1}) - X_A(t_i)] + [X_B(t_{i+1}) - X_B(t_i)] \\ Y^{in}(t_{i+1}) - Y^{in}(t_i) &= [Y_A(t_{i+1}) - Y_A(t_i)] - [Y_B(t_{i+1}) - Y_B(t_i)] \end{aligned} \tag{13}$$

where $X^{in}(t_{i+1}) - X^{in}(t_i)$ and $Y^{in}(t_{i+1}) - Y^{in}(t_i)$ represent the abscissa and ordinate of the ith segment of cooperative trajectory. New yielding positions of robot B is converted into joint space using inverse kinematics relationships given by

$$\begin{aligned} \alpha_B(t_{i+1}) &= \sin^{-1}\left\{ \frac{X_B(t_{i+1})}{\sqrt{X_B^2(t_{i+1}) + Y_B^2(t_{i+1})}} \right\} - \sin^{-1}\left\{ \frac{l_B^3 \sin\beta_B}{\sqrt{X_B^2(t_{i+1}) + Y_B^2(t_{i+1})}} \right\} \\ \beta_B(t_{i+1}) &= \cos^{-1}\left\{ \frac{X_B^2(t_{i+1}) + Y_B^2(t_{i+1}) - (l_B^2)^2 - (l_B^3)^2}{2 l_B^2 l_B^3} \right\} \end{aligned} \tag{14}$$

The joint accelerations of robot B are calculated by the following equation.

$$\begin{aligned} \ddot{\alpha}_B(t_i) &= \frac{\alpha_B(t_{i+1}) - 2\alpha_B(t_i) + \alpha_B(t_{i-1})}{T^2} \\ \ddot{\beta}_B(t_i) &= \frac{\beta_B(t_{i+1}) - 2\beta_B(t_i) + \beta_B(t_{i-1})}{T^2} \end{aligned} \tag{15}$$

If the magnitudes of evaluated joint accelerations of robot B obey the acceleration constraint, the solution is assumed to be a feasible solution. The above feasible solution generation is reiterated for other equi-spaced set of values taken by k_1 and k_2.

3. RESULTS

3.1 Conditions for simulation

The objective trajectory is an S-shape contour with the curvature of 1[cm]; the maximum cooperative velocity is of 2[rad/s] and the maximum cooperative acceleration is 2.0[rad/s^2].

The Performer MK2 and MK3 industrial robot arms will be intended to utilize to carry out the experiment of proposed method, the link lengths of the two robots are assumed to be the actual parameters of these two robots. The link lengths could be stated as $l_A^2 = 0.27[m]$, $l_A^3 = 0.23[m]$, $l_B^2 = 0.25[m]$, $l_B^2 = 0.215[m]$. Referring to the equation (8), the servo parameters $K_p = 25[1/s]$ and $K_v = 150[1/s]$ are used for simulation common to both robots. The joint acceleration is limited to $0.63[rad/s^2]$ for either robot.

3.2 Simulation results and discussion

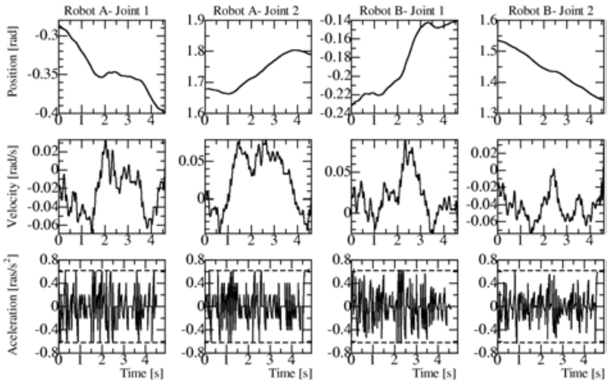

Fig. 5 Dual-robot input joint positions, velocities and accelerations

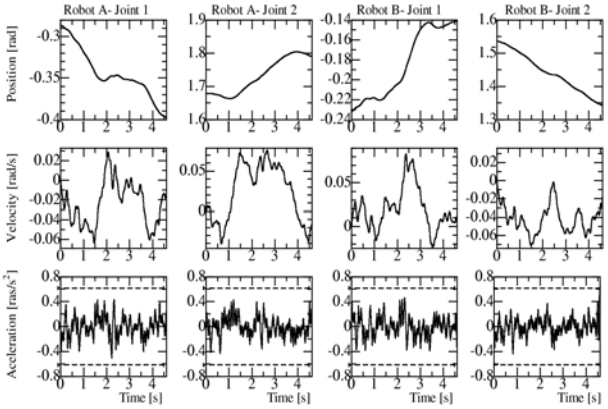

Fig. 6 Simulation results for dual robot cooperative control

Fig.5 illustrates the conjugate input trajectories of robots A and B. The joint positions of these trajectories are spaced at sampling time in time domain. Fig.6 shows the simulation output of the joint positions, velocities and accelerations using the second order model given by equation (8).

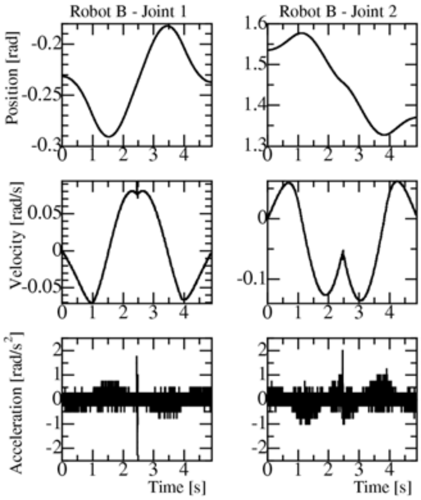

Fig. 7 Mono robot input joint positions velocities and acceleration

Contour controlling of the same trajectory is achieved with a single robot for the comparison purpose and results are given in Fig. 7. This mono robot case is obtained with the same algorithm by setting the velocities of one robot to be zero.

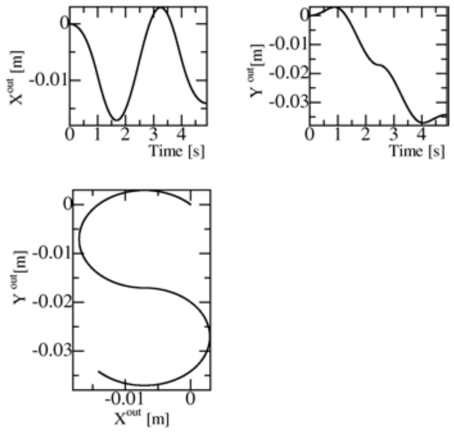

Fig. 8 Cooperative trajectory of two robots and mono robot trajectory

A concise comparison of the cooperative trajectory obtained by simulation when simultaneous maneuvering of two robots and mono robot simulated trajectory are depicted in Fig. 8. The both trajectories are almost coinciding with each other and no significant deviation could be noted.

In comparison of mono-robot contouring, joint acceleration limit could be brought down with cooperative contour controlling. However far better results could be obtained with straight cooperative trajectories. Nevertheless, no remarkable improvement or deterioration could be noted in the trajectories followed in either case.

5. CONCLUSION

In this paper, we present a novel strategy for contour controlling of a given cooperative trajectory with two robots. The proposed method minimizes the joint velocity deviation of maximum joint velocities of two robots. With the cooperate contouring approach, it is possible to reduce the maximum joint acceleration, in turn the maximum joint torque, than the mono-robot application, further to span the working space. This reduction in maximum acceleration requirement is verified with a simulation study. This cooperative contouring could be directly and conveniently adapted to the existing servo controllers neither with hardware change nor a considerable reconfiguration of the system for adaptation.

As the proposed method falls under loose control strategy, the implementation scenario is quite simple though the application scope is confined to structured environment. Number of different levels of sophistications could be made in conjunction with sensory feedback system to realize tight control strategy and hence possesses a potential to widen the horizons of applicability. Operation of two robot arms using a single controller with complete integration of individual robot motion for a unified task facilitates to achieve synergetic effect and hence it is analogous to use the both hands of a human being. Therefore this method would definitely have strong implications in dual arm robots.

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