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Trajectory Planning for a Redundant Planar Laser-Cutting Machine with Macro-Micro Manipulation

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Abstract: *Kinematic redundancy in robots provide the control designer with infinite number of possibilities for improving the process for a selected target optimization criterion. A special type of kinematic redundancy is devised by using kinematically different two mechanisms with different advantages. In this case, the control design including the trajectory planning should be devised taking into account the distinct advantages of both mechanisms. In this work, a macro mechanism with larger workspace is used along with a micro mechanism that has higher dynamics and lower inertia. A trajectory planning algorithm integrated with the control structure making use of the previously defined advantages of both mechanisms is explained in this paper. A case study is provided to validate the developed algorithm.*

Keywords: trajectory planning, redundant manipulator, redundancy resolution, macro-micro manipulator

I. Introduction

Kinematic redundancy is, in a general understanding, having more degrees-of-freedom (DoF) than required by the specified task. The usual case for serial industrial manipulators is to add to the manipulator more DoF by adding more of the similar type of links. There have been numerous studies mainly to change the configuration of the redundant manipulator while performing the primary task [1]. In this way, optimization criteria can be applied and redundancy can be resolved in different levels; position, velocity or acceleration.

A special type of kinematic redundancy is increasing the DoF of the robot manipulator by integrating two or more mechanisms with distinct kinematics. The common case of having a larger manipulator integrated with a smaller manipulator is termed as macro-micro manipulation. In this way, distinct advantages of both mechanisms can be used at the same time when an intelligent way of devising a control algorithm with a trajectory planner is also constructed.

One of the first examples of the macro-micro manipulator control algorithm construction was done by Sharon and Hardt [2]. Their main task was to increase the accuracy of the overall system. In the following years, reducing inertia effects using macro-micro manipulators [3], [4] are studied and several control schemes [5], [6] to take advantage of macro-micro manipulation for a desired goal were proposed.

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In this work, the macro-micro mechanism is intended to be used for planar laser-cutting process. The main challenges in planar laser-cutting process is having a relatively larger workspace in the range of meters depending on the application and shortening duration of the process. This study does not include any developments on the tool part. As a result of this, the only improvement that can be proposed is on the speed of the mechanism. However, the tool limits the maximum cutting speed. Another option to reduce the process duration is to increase the acceleration of the system. When a workpiece that has many contours with smaller radii of curvature is considered, the acceleration limits play an increased role in decreasing the duration of the process.

Most of the planar laser-cutting mechanisms in the industry have a workspace no smaller than 1 m x 1 m. The tool part, which is the laser head, is usually in the range of 5 kg. The conventional planar laser-cutting machines are designed to have an acceleration of 1 g. The precision of the conventional machines are designed to be kept just under 0.1 mm. With respect to the above design specifications, the conventional machines are built with X and Y axes translational DoFs that have relatively better rigidity. The rigidity to achieve the described acceleration and precision limits comes with a cost. This cost is usually the increased inertia of the system. Therefore there is a trade-off between the acceleration and precision of the system. As a result of this trade-off, conventional machines could not exceed the described acceleration limit.

In order to increase the acceleration limit of the laser-cutting machine, a macro-micro manipulation was proposed in this work. The macro mechanism, which is the primary mechanism, is the X-Y translational mechanism used in the conventional laser-cutting machines. The micro mechanism is a modified 5-bar mechanism with two-DoFs. The details of this design were given in [7]. The micro mechanism, which is the secondary mechanism, has an acceleration limit of 5 g and a workspace limit of 150 mm x 100 mm.

Previously, an initial work is conducted on devising a trajectory planner to divide the motion of the tool to both mechanisms to achieve the maximum acceleration throughout the manipulation which was based on the work presented in [8]. The trajectory planner worked offline after receiving the G-codes designed in a CAM program. Therefore, it worked like a post-processor in CNC systems to derive the motion trajectory of all axes with respect to time. The work was presented in [9] along with the case studies. However, there was a practical disadvantage of this algorithm. The jerks were considered to be infinite and since in the actual system this cannot be achieved, there will be precision problems.

In this paper, a new algorithm that integrates the trajectory planner with an online controller is presented to devise a solution for the previously defined problem. The main purpose of the algorithm is to derive a continuous motion of primary mechanism. This means that the primary mechanism will never come to a full stop during the process since its acceleration capabilities are limited. The offsets between desired trajectory and continuous trajectory of the primary mechanism will be sent online as motion demands to the secondary mechanism. The derivation of the continuous motion of the primary mechanism's trajectory is to be accomplished with respect to the workspace limitation of secondary mechanism and motion limitations of both mechanisms. As a result, the algorithm have the primary mechanism's motions to be planned without a full stop with its own acceleration and jerk limitations throughout the process, while the precise and fast acceleration motions are carried out with secondary mechanism.

The algorithm is described in the next section. A case study for the proposed algorithm is given in the following section. Finally, the paper is concluded with the observations and discussions on the new algorithm.

II. Trajectory Derivation

In this approach, a continuous motion (without coming to a full stop) is derived from end-effector (tool) trajectory in global space for the primary mechanism. Discontinuous motions with full stops and motion initiations are reserved for the secondary mechanism that has higher acceleration capability. This results in the reduction of task completion duration with respect to a conventional 2-DoF mechanism. A new method is proposed for offline continuous motion generation for the primary mechanism taking into account the motion capabilities (velocity, acceleration and jerk) of both mechanisms and the desired end-effector motion, which are discussed in the next subsections. The information flow for the new method is illustrated in Fig. 1.

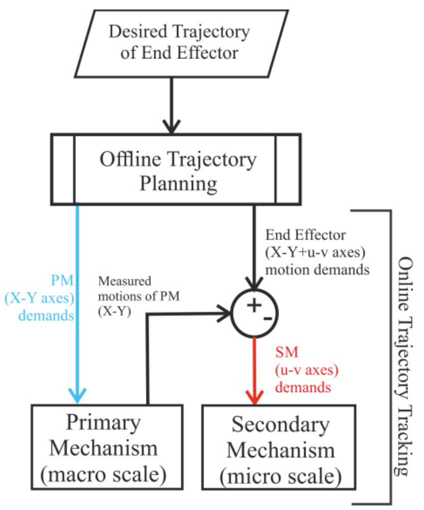

Fig. 1. Information flow of motion commands for redundant manipulator.

In the above scheme, trajectory of end-effector is configured to achieve highest combined accelerations of the mechanisms throughout the task. Later, this trajectory is used to extract primary mechanism's motion demands in X and Y axes. Secondary mechanism's motion demands, in u-v axes, are generated online by calculating offset between the global trajectory and the primary mechanism's measured position. The reason of this offset is that smoothened motion trajectory developed for the primary mechanism excludes the sharp edges in the trajectory. In the next subsections continuous motion generation for primary mechanism and point reduction steps are explained.

A. Continuous Motion Generation for Primary Mechanism

The proposed method takes into account the workspace limitation of secondary mechanism and optimizes the end-effector's global trajectory to obtain continuous set of motions for primary mechanism while excluding the sharp and discontinuous motions to be achieved by the secondary mechanism. The algorithm utilizes the Ramer-Douglas and Pecker algorithm RDP described in [10], [11]. RDP is used to reduce the number of points in a curve that is approximated by a set of points. The trajectory for primary mechanism is generated with the steps shown in the flowchart presented in Fig. 2.

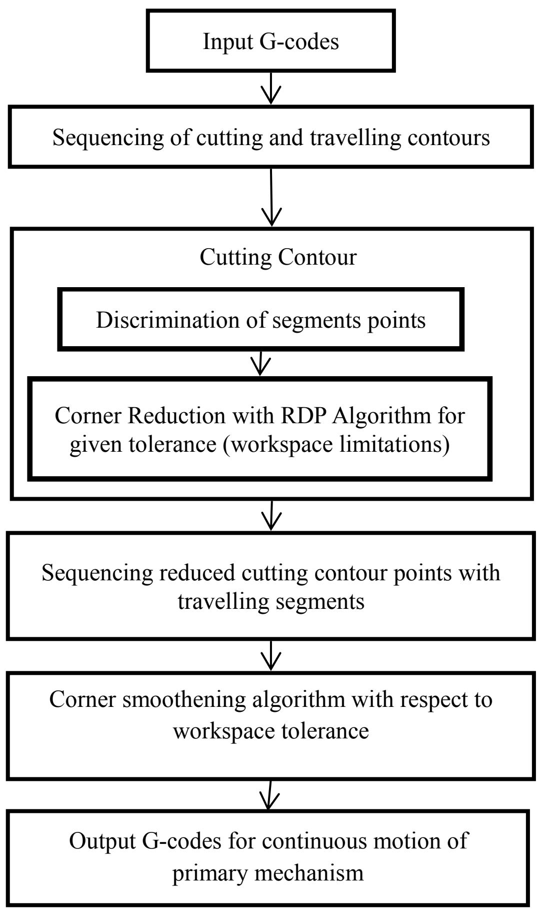

Fig. 2. Continuous motion commands generation for primary mechanism.

In the first step, trajectory information is extracted from G-codes as sequential travelling and cutting contours. Each cutting contour represents a closed or open contour of cutting (machining) trajectory, where the end effector (machining tool) is demanded to track. Travelling contours represents the motions that the end effector should travel between cutting contours without any motion limitation with respect to the cutting speed.

In the next step, a set of points, which define the segments in a G-code sequence, for the desired trajectory of end-effector is generated for trajectory planning algorithm. Points extracted from the cutting contours are subjected to corner reduction algorithm. RDP algorithm is run for reducing the number of points in discontinuous trajectory with the tolerance defined by the limited workspace of the secondary mechanism.

For the next step, reduced points of each cutting contour are combined with travelling points to derive overall trajectory points with the same sequence as in the G-code list. Points are combined with lines in between. As a result of this, there are velocity level discontinuities at each point. This discontinuity is smoothened by increasing the radii of curvature at these sharp edges so that a continuous motion is generated for primary mechanism. Finally, continuous motion demands for primary mechanism are generated in G-code language, as motion demands.

B. *Corner Reduction for Continuous Motion Generation*

Corner reduction and trajectory smoothening process used in the derived algorithm are based on RDP and a corner curve fitting algorithm. The basic principle of the corner reduction algorithm is illustrated in Fig. 3. as follows:

(a) A basic trajectory for the end-effector composed of points is sequenced starting from P0 to P5, and it is illustrated with the green line in the following steps.

(b) For a set of given points, the algorithm first combines the initiation and termination point to construct the line. The created line $\overline{P_0P_5}$ is drawn with dashed blue line in Fig 3. The distances of points, in between P_0 and P_5, to line $\overline{P_0P_5}$ are calculated and the distance which has the highest magnitude is marked as maximum distance, dmax. Later, the algorithm checks if dmax is higher than given tolerance, which is the workspace limitation of the secondary mechanism. For line, $\overline{P_0P_5}$, dmax is calculated to be higher than the tolerance and the algorithm determines that the corner reduction for P_0 and P_5 point are out of bounds.

(c) In this step, the algorithm excludes the point P_5 and searches the distances of points P_2 and P_3 to $\overline{P_0P_4}$. dmax in this case is calculated again to be out of tolerance and point P_4 is excluded.

(d) Calculation procedure for maximum dmax is carried out again in between P_2 and P_3 and dmax is calculated to be out of bounds. Thus, the algorithm excludes point P_3.

(e) Finally, dmax, the distance of point P_1 to $\overline{P_0P_2}$ line is calculated to be below the tolerance and algorithm sets the first reduction by excluding P_1.

(f) In this step, the points from P_2 to P_5, are investigated with respect to line $\overline{P_2P_5}$, since the algorithm already fit a line between previous points. Calculating the magnitude of dmax below the tolerance value, the algorithm excludes points P_3 and P_4. As a result of the implementation of RDP algorithm for a set of given points, corner reduction is completed and motion segment is reduced to 3 points as P_0, P_2 and P_5.

(g) After the points are reduced, the proposed method fits a curvature to each corner complying with the workspace limitations. In this case, a curve is fitted to $\widehat{P_0P_2P_5}$, where the center of curve is represented with P_c.

(h) As a result of corner reduction algorithm, segments that are necessary to be generate with G-codes, to be constructed with G0, G1, G2, and G3 line segments, are illustrated with the blue line from point P_0 to the new P_4.

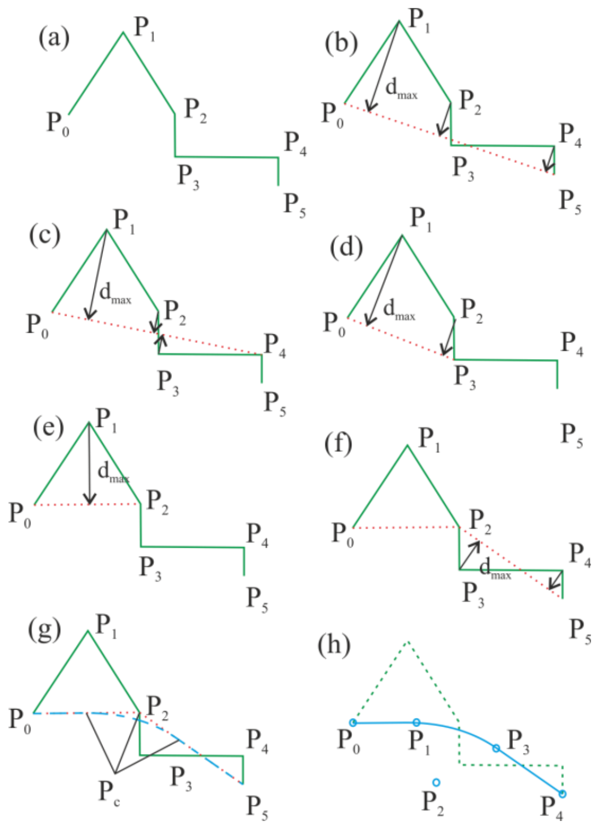

Fig.3. Corner reduction steps for a set of points.

The corner reduction process is carried out offline as proposed in continuous motion generation. It should be noted that circles and splines are represented with G2 and G3 commands in G-code language. The G2 and G3 commands generally include information about initiation, termination and center coordinates of the curve. In the corner reduction process given above, G2 and G3 segments are represented with these 3 points.

III. Case Study

As an implementation and verification of this method, the proposed algorithm is applied for a relatively complex trajectory and simulations are carried out with Matlab©. In this case study, the acceleration of the primary mechanism's axes are designated to be limited with 9.81 m/s^2, the acceleration of the secondary mechanism is set to 49.05 m/s^2, and the end-effector velocity is limited with 40 m/min of maximum speed.

The desired trajectory of the end-effector and the reduced trajectory of the primary mechanism (X-Y axes) are presented in Fig 4. Desired end–effector trajectory is illustrated with blue solid line while trajectory generated for the primary mechanism is illustrated with dashed red line.

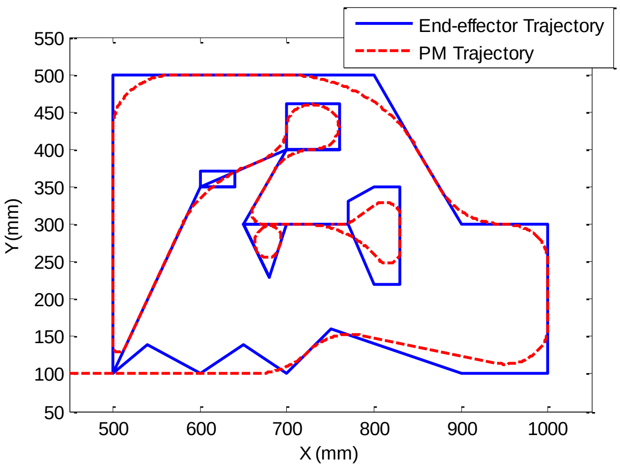

Fig. 4. Continuous motion commands generation for primary mechanism.

In Fig. 5, the motion demands for both in X and Y axes are illustrated. End-effector motion commands are generated with joint motion with respect to the combined motion limitations of both mechanisms. Primary mechanism's motion commands are generated with lower acceleration and jerk capabilities that was set previously. Primary mechanism's trajectories has smoothened trajectory where the continuous motions are planned without a full stop.

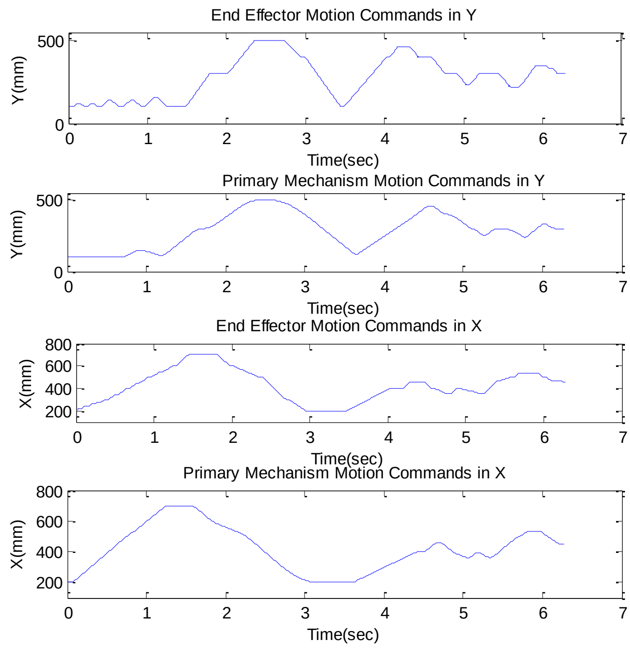

Fig. 5. Motion commands for end-effector and Primary mechanism

Position demands delivered to secondary mechanism were held within the workspace limitations as predesigned to be ±75 mm along v axes and ±50 mm for u axis. These values are used in the corner reduction process as tolerances for RDP algorithm. The motion demands for secondary mechanism is obtained by subtracting the end-effector motion demands from primary mechanism's measured position along X and Y axes. This calculation happens online as the position of the primary mechanism is measured by integrated position sensors. The resultant motion is fed into the secondary mechanism's online controller as u and v axes demands. The u and v axes motion demands are shown in Fig. 6. and Fig. 7, respectively. It can be observed that he motion happens in higher frequency, meaning that the accelerations are higher with respect to the primary mechanism's trajectory, and the motions along u and v axes directions are bounded within the workspace limitations of the secondary mechanism.

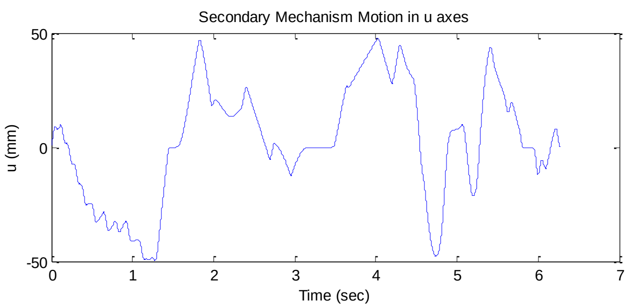

Fig. 6. Motion commands for secondary mechanism along u axis

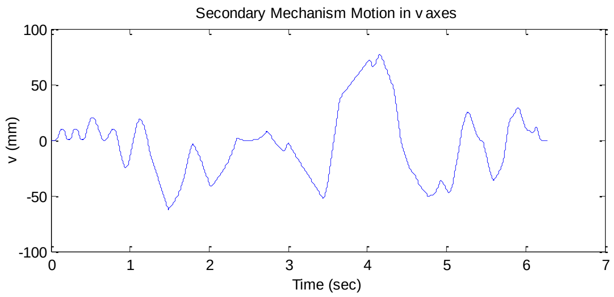

Fig. 7. Motion commands for secondary mechanism along v axis

Process duration for the case study is calculated to be 7.84 seconds when a conventional machine with only X and Y axes and a 9.81 m/s^2 acceleration limit was used. On the other hand completion time with proposed method is calculated to be 6.24 seconds. This means that there is a reduction of 20.41% in this task completion duration.

IV. Conclusions

In this work, a method for trajectory planning integrated in a control scheme is proposed for a kinematically redundant macro-micro mechanism to be used in industrial application. The control scheme is developed to distribute end-effector's motion into macro mechanism's motion micro mechanism's motion. The macro mechanism's motion is generated offline complying with the motion limitation of both mechanisms. However, the micro mechanism does not have a predefined trajectory and controlled online by generating offset commands through comparing the end-effector position with the actual primary axes' position at a given time.

In order to accomplish the above sequence, a trajectory generation algorithm is adopted for continuous motion generation for macro (primary) mechanism. In the proposed method, the end-effector trajectory, trajectory data defined with G-Codes as line segments, is reduced to a smoother continuous trajectory by using RDP and curve fitting algorithm.

An example case study is designed and limitations of previously designed redundant planar mechanism are used. The results indicate that the limitations of mechanism are preserved and 20.41% reduction in process duration is achieved with respect to a conventional machine. It should be noted that the method shows better performance in task completion time, especially with complex and small contour trajectories.

Compared to previously studied method, in which both trajectories for the primary and secondary mechanisms are calculated offline, the problem of having limited jerks is solved in the proposed control scheme by implementing an online control of the secondary mechanism. As a future work, this algorithm will be implemented and experimentally tested for the specific industrial application.

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