A MACRO-MICRO MECHANISM DESIGN FOR LASER CUTTING PROCESS

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ABSTRACT

This paper is organized to provide the novel approaches during the design of a machine to shorten the laser cutting process. Macro-micro manipulation concept is employed for the design of this machine both in the mechanical design and in devising the trajectory planning algorithm. Micro-mechanism design along with its calibration process are also explained since they involve novel approaches in this application domain. Trajectory planning algorithms, which are developed in this work, are discussed based on their applicability to CNC system architecture. Finally, experimental results based on a benchmark workpiece are given and the system design is discussed with respect to these results.

Keywords: Macro-micro manipulation, laser cutting, trajectory planning, kinematic redundancy, mechanism calibration

1. INTRODUCTION

Laser cutting process is a heat-based separation process [Schulz et al., 2009] that has been used since 1960s [Lawson, 1966]. Currently, laser cutting machines are generally used for cutting contours off sheet metals and only a relative motion along X-Y Cartesian axes are sufficient. These machines are called two-dimensional (2D) laser cutting machines. The relative X-Y motion can be achieved in three ways: 1) Stationary laser type: a stationary laser cutting head and a work table handling the workpiece that has X-Y motion, 2) Hybrid type: a laser cutting head with single axis motion and a work table handling the workpiece that has a single axis motion, 3) Moving laser type: a stationary workpiece and a laser head that has two axes motion [Ready and Farson, 2001]. The first type is usually employed for smaller sized machines whereas the other two are preferred for larger sized machine designs [Grote and Antonsson, 2009]. In some machines, there is an extra axis along the Z axis which is normal to the XY plane that has limited stroke [Civan, 2008]. This Z axis motion is required to adjust the Z axis position of the laser head with respect to the irregularities of the sheet metal surface. In the moving laser type machines, workpiece is generally fed along the longer side of the work table (X axis). X axis motion is carried out by a frame which has either a single side slider (cantilever) or single slider on the top (hanging) or double slider (bridge) [Battheu, 2011]. In conventional systems, on the X axis frame, the Y axis motion is achieved by the motion of the laser head on the sliders attached along the Y axis direction.

The maximum speed of the laser cutting process is determined by the workpiece material and thickness, and the laser power [Schulz et al., 2009]. Especially, in cutting processes that have many cutting contours, the process completion durations are determined by the transfer duration in between the two cutting contours. Also, when the cutting contours have very small radius of curvatures, the operation duration is affected adversely since the dynamic behavior of the conventional machines are limited due to their relatively large inertial properties. In order to overcome this limitation, laser cutting machine manufacturers have developed kinematically redundant machines. However, these machines are a special subset of kinematical redundancy in which they are composed of two separate mechanisms (macro- and micro-mechanisms) with different properties. In the planar laser cutting case, the macro-mechanism is composed of the X-Y axes that have relatively larger workspace but relatively lower acceleration capabilities. In contrast, the micro-mechanism is designed to have relatively smaller workspace and relatively larger acceleration capabilities. Trumpf [Leibinger et al., 2004] and Amada [Masakata, 2006; Morikatsu, 2007; Taisuke, 2009] companies proposed to use a micro-mechanism with a single axis that is parallel to either X or Y axis of the macro-mechanism (XY+x). A commercial product was developed by Prima company in which a parallel mechanism with PPPP (P: prismatic joint) configuration was used as the micro-mechanism [Sartario, 2004; Gattiglio et al., 2008; Gattiglio and Chirico, 2008]. This machine that has XY+xy type of combined motion is claimed to have over 6g of laser head acceleration capability. Another Italian company called Salvagnini swapped the Y axis linear actuator with a PRRRP parallel mechanism to be used as the micro-mechanism [Battheu, 2011; Battheu 2012]. In this case, the macro-mechanism is composed of only the X-axis. They claim that this machine with the X+yθ motion is able to reach 5g of acceleration at the laser head's tip point. However, the mechanisms that are commonly used in industrial systems, the RRRR (4R) and RRRRR (5R) mechanisms, have not been used as micro-mechanisms in kinematically redundant laser cutting machines.

In this paper, a recent work on developing a kinematically redundant planar laser cutting machine to shorten the task completion duration is presented. This work was carried out to develop a laser cutting machine that has the maximum acceleration of the laser cutting head over 4g while preserving the precision at ±0,03mm/m and repeatability at ±0,015mm. This paper is prepared to present the key works during the development phases, which embrace novel approaches. In the next section, the concept of macro-micro manipulation is explained and its application in manufacturing systems is discussed. The novel design of the micro-mechanism is presented in the 3rd section followed by a new approach in calibration process of this macro-micro mechanism. Trajectory planning algorithms that are developed in this work are explained and discussed in the 5th section for their applicability in industrial CNC systems. An example laser cutting scenario with the developed trajectory planning algorithm is presented and the results for the selected benchmark workpiece are given for the conventional machine and machine with the macro-micro mechanism. The efficiency of the developed system is discussed based on the benchmark test results and finally the paper is concluded with the developed system's specifications.

2. BACKGROUND ON MACRO-MICRO MANIPULATION

As humans, we have been using macro-micro manipulation during our daily activities. A very peculiar example is the process of writing on a paper. In this case shoulder and elbow are used only to position the wrist at certain location of the paper to start writing. The rest of the writing process which requires precise motion control is taken care of by the wrist and the fingers. In this example, the shoulder and the elbow constitute the macro-mechanism which is in charge of rough positioning and stability of the micro-mechanism's position and the micro-mechanism is used for higher bandwidth motion execution and controlling the forces exerted on the paper while precisely handling the pen or pencil. This example can be extended to writing on a blackboard with a chalk in which another macro mechanism, motion of the body other than the arm (i.e. legs, waist), is included in the definition of this macro-micro manipulation. We as humans use many degrees of freedom (DoF) to accomplish the above task that could have been accomplished with only six DoF. However, this type of redundancy is different from traditional industrial robot redundancy concept in which generally, only one of the same type of link and joint structure is added to a traditional six DoF industrial robot arm. In macro-micro manipulation, the two mechanisms are deliberatively chosen different in size, in function and in terms of physical capabilities. Hence, they have distinct however, complementary tasks and functions to accomplish the common job by working together.

In industrial robotics, although it is not explicitly termed as macro-micro manipulation, almost all industrial robots with a gripper can be considered as a macro-micro manipulator; six DoF robot arm being the macro manipulator that is responsible of positioning and orienting the gripper and the gripper being the micro-manipulator that is responsible of precisely handling the payload. In the literature, probably the first time the macro-manipulation term was explicitly used was in the work carried out to reduce the inertial effects of a macro-micro manipulator [Khatib, 1991]. Later, a surgery robot with macro-micro manipulation was proposed in which force control at higher bandwidth was in carried out by the micro-mechanism and course positioning was accomplished by the macro mechanism [Marzwell et al., 1994]. In later years, macro-micro mechanisms are employed in surgical robotics [Erturun, 2007] and manufacturing systems [Cho et al., 2005].

In this work, macro-mechanism is designed to have a relatively larger workspace to cover the full range of motion required for the worktable with dimensions 3m by 1.5 m. The maximum acceleration of the macro-mechanism is limited by 1g not to degrade the accuracy and repeatability measures due to excessive vibrational behavior. The micro-mechanism, which is positioned in XY axes by the macro-mechanism, is designed to reach relatively higher accelerations, over 3g, while preserving accuracy and repeatability levels assigned in the design criteria. The next section describes these two mechanisms and provides details on the application-specific novel design of the micro-mechanism.

3. DESIGN OF THE MACRO-MICRO MECHANISMS FOR LASER CUTTING

A planar Cartesian manipulator (XY table) is used as the macro mechanism. The XY tables of manufacturing machines differ in construction of the housing for the X- (long) axis. Five main types are evaluated in this study: 1) gantry type: two parallel guides at about the same level as the workpiece table, 2) cantilever type: single guide on one side, 3) airplane type: single guide on top, 4) L-type gantry: a guide on one side and a guide on top and 5) suspended gantry: two parallel guides on top. The advantages/disadvantages of these different types of constructions were evaluated according to their rigidity, motion performance, ergonomics, balanced positioning of the micro-mechanism, footprint, weight, ability to support the cover of the machine, manufacturability, assembly and installing in site [Dede et al., 2013]. As a result, the cantilever form is selected.

A thorough investigation is carried out for the design alternatives for the micro-mechanism. First, it is decided that the micro-mechanism will have 2-DoF, i.e. the machine will have kinematic redundancy in both x- and y-axes. For high-acceleration applications parallel manipulators (closed-loop mechanisms) are preferred over serial manipulators, so a parallel kinematic structure is preferred. A single loop planar two-DoF mechanism should have five links and five (single DoF) joints. To narrow down the alternatives, some rules are set for the design of a highly dynamic mechanism:

1) The mechanism should have only revolute (R) and prismatic joints (P),
2) There can be at most two P joints, because otherwise the DoF of the mechanism increases,
3) If there are P joints, they should be actuated,
4) The actuators should be supported on the base (base is attached to the macro-mechanism),
5) The actuator types should be the same (R or P) for symmetric modeling and control,
6) The two limbs (kinematic chains connecting the base to the end-effector) should have the same configuration, i.e. the linkage should be symmetrical.

There are just two planar five-bar linkages which obey these rules: RRRRR (5R) and PRRRP linkages (_ means that the joint is actuated). PRRRP linkage is already used in laser cutting machines [Battheu, 2011] so, the 5R linkage is chosen for the micro-mechanism. The 5R linkage is well studied in literature and found application in various areas [Dede et al., 2013].

If the end-effector of a 5R linkage is small enough, it can be imbedded inside the middle R joint. However, laser cutting heads have diameters about 10 cm and in the case of imbedding the laser head inside the idle R joint, the orientation of the head should also be controlled. Therefore, the 5R mechanism had to be modified. Some design alternatives are evaluated, as explained in detail in [Dede et al., 2014], and the mechanism shown in Figure 1 is selected. This mechanism is a modified 6R linkage supported with parallelogram loops along the limbs in order to keep the platform orientation constant.

The mechanism is over-constrained with two-DoF, i.e. it still has two-DoF even if one of the links is removed. Just as hyperstatic structures are more durable than the statically determinate structures, overconstrained mechanisms are stiffer than the simply constrained mechanisms. High stiffness is advantageous in terms of repeatability of the manipulator.

A laser cutting head weighing 4 kg is selected for the application and a rectangular workspace with 100 mm x 150 mm is selected after careful analysis of motion limitation due to required maximum accelerations. A CAD design is virtually tested with a dynamic motion simulation using ANSYS® and it is found that an I-beam section (blanks on the sides) provides more stiffness compared to an H-beam section (blanks on top and bottom). The mechanism parts are manufactured and assembled after the model is verified via simulations. Also, an analytical model for the dynamics of the system is constructed. The analytical model is verified with dynamic simulations run on a Matlab Simulink® model. Asa result of these analyses, the necessary actuation torques are determined and motors are selected accordingly. Zero backlash harmonic drives are selected as reducers however, after the tests, it is concluded that these reducers are not suitable for highly dynamic applications. Also, dynamic balancing options are studied. The theoretical formulations for balancing are presented in [Dede et al., 2014]. However, the performance tests on the real system showed that counter-mass balancing did not reduce the vibrations as desired due to the manufacturing and assembly errors.

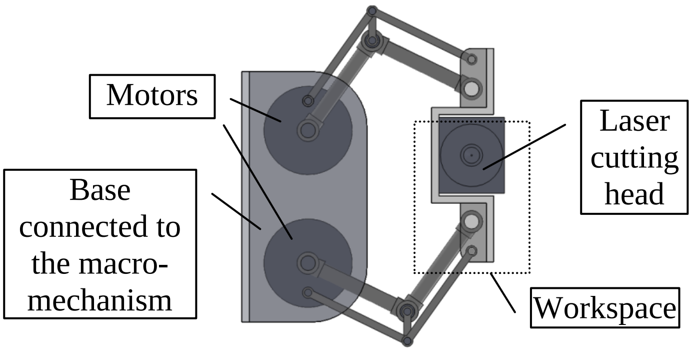

Figure 1. Micro-mechanism.

4. CALIBRATION PROCESS OF MACRO-MICRO MECHANISMS

Although the parts of the mechanism are manufactured as precisely as possible, it is seen that the link lengths uncontrollably vary after these parts are assembled. A major reason to this fact is the varying internal stresses due to the overconstrained mechanism and the joint clearances. Since the link lengths in the theoretical model, which was used in the control, and in the actual mechanism differ, the desired positioning accuracy was not achieved in the initial trials. The initial measurements of accuracy were as high as 1500 μm, which is way above the targeted value, 30 μm. A two-step solution is devised to decrease the positioning errors: 1) estimate the proper link length values that fit to the actual system by measuring the end-effector position directly (by using a laser interferometer) and corresponding motor input values on several points in the workspace; 2) estimate the positioning errors at many points in the workspace and feed these errors to the motor inputs.

Application of the first step is trivial for simply constrained mechanisms however, it is tricky for overconstrained mechanisms. The problem is that there is no analytical kinematics solution for overconstrained mechanisms. Therefore, a simplified and theoretically equivalent kinematic model is constructed for the model to be used for the control. The simplified kinematic model is called a “hidden robot” of the overconstrained mechanism. The application of the hidden robot concept for overconstrained mechanisms is described in [Kiper et al., 2015]. The hidden robot used in this study (Figure 2a) instead of the modified 6R mechanism (the actual robot presented in Figure 2b) is a 5-bar (5R) mechanism with concurrent fixed joints (at A_0). The two mechanisms are kinematically equivalent in terms of the relationship between the inputs (θ_1, θ_2) and the outputs (C(x, y)) when $|A_0A| = |B_0B|$, $|AC| = |BC| = |AD| = |BE|$, $|A_0B_0| = |DE|$, $|DC| = |EC|$ and the peripheral loops in the 6R mechanisms are parallelograms. However, these conditions are not satisfied in practice due to manufacturing and assembly errors. So, the hidden robot model in Figure 2a is merely an approximate kinematic model for the actual robot.

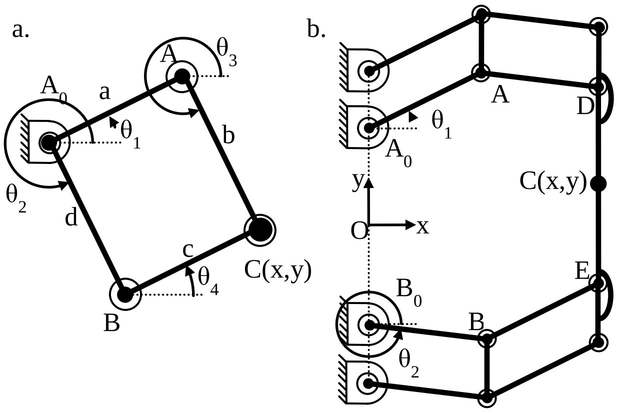

Figure 2. a) 5-bar mechanism as the hidded robot and b) the modified 6R mechanism of the actual system [Kiper et al., 2015].

A slight modification is made for the hidden robot model by taking $|A_0A| = a \neq d = |A_0B|$ and $|AC| = b \neq c = |BC|$ in order to obtain a better approximation of the real robot. Several motor input and end-effector data are collected from the actual system using a laser interferometer. Data are used to determine the proper link lengths for the hidden robot, which came out to be a = 149.868 mm, b = c = 150.000 mm and d = 149.890 mm (the mechanism was originally designed for a = b = c = d = 150 mm). The details of the calculations are presented in [Kiper et al., 2015]. Positioning measurements are taken again with the modified link lengths and the maximum error is found to be around 700 μm, which is of course better than 1500 μm, but still not good enough for the set design criteria.

The second step, error estimation, is utilized to further decrease the amount of positioning errors. A mesh of 5 mm x 5 mm is constructed on the 100 mm x 150 mm workspace and errors are measured at every point on this grid. By means of inverse kinematics and the

Jacobian matrix for the hidden robot, error compensation values for the motor inputs are calculated. The errors for the points inside the grids are estimated via bilinear interpolation. The details of the calculations are presented in [Kiper et al., 2015]. After implementing the error compensation values, positioning tests are repeated for the macro- and micro-mechanisms working together, and the positioning errors are found to be bounded to ±37 μm/m and repeatability is determined as ±26 μm/m, which is considered to be close enough to the design objectives. The values are determined according to VDI Standard no VDI/DGQ 3441 - Statistical Testing of the Operational and Positional Accuracy of Machine Tools; Basis.

5. TRAJECTORY PLANNING ALGORITHM

As explained in the previous sections, the macro-micro mechanism is devised to minimize the total task execution time. For this purpose, two different approaches are devised for trajectory planning algorithm of the macro-micro mechanism. One of them is the offline trajectory planning method, presented in [Uzunoğlu et al., 2014], which embraces the idea of generating macro- and micro- mechanisms' velocity profiles separately for a desired end-effector trajectory. In this previous study, the algorithm for macro-micro case is promoted because of its reduced complexity and lower computational cost compared to pseudo-inverse methods for macro-micro manipulation.

In Figure 3, the flowchart of the offline trajectory generation algorithm is illustrated. The algorithm is initiated by entering G-codes which are derived from CAM program for a desired cutting trajectory. These G-codes are later sequenced as data segments to be sent to the motion planning portion of the algorithm. The motions generated are separated into two categories. Machining segments are motions where the tool is cutting the workpiece by following a desired cutting contour. Travelling segments are the necessary motions needed to be travelled between two cutting contours. For each segment, velocity profiles are generated for macro- and micro- mechanisms by taking into account the mechanisms' acceleration and velocity limits as presented in [Uzunoğlu et al., 2014]. However, the algorithm only ensures the motion to be bounded with acceleration and velocity limitations of both mechanisms, which means that the jerk limits are not taken into account. It has been foreseen that the actual system will not be able to track the motion demands precisely and the unlimited k-jerk demands may generate increased stresses on the mechanisms.

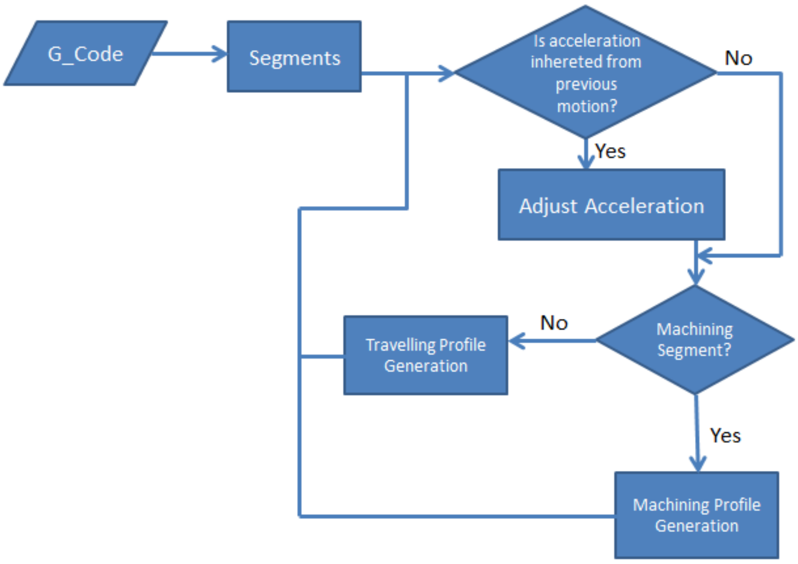

Figure 3. Flowchart of trajectory planning algorithm [Uzunoğlu et al., 2014].

Hence in [Uzunoğlu et al., 2015], a semi online method is proposed to compensate the problems addressed in former method. This method includes: preprocessing of the trajectory, generating desired motions for end-effector's and macro mechanism's axes, and delivering the motion demands to the embedded controller of both mechanisms' axes. The difference of this method is that an upper control loop is included where micro-mechanism's motion demands are generated online.

The information flow of control algorithm is illustrated in Figure 4, which was formerly presented in [Uzunoğlu et al., 2015]. The time sequenced motion demands for the desired trajectory of the end-effector and macro mechanism are generated in Offline Trajectory Planning process. It should be noted that the motion of end-effector is generated by taking into account the combined motion (speed, acceleration, jerk) limitations of both mechanisms. Later, in the offline process, a continuous motion (without coming to a full stop) is derived from end-effector trajectory for the macro mechanism, in which discontinuous motions with full stops and highly accelerated motions are reserved for the micro-mechanism. The trajectory derivation is explained in detail in [Uzunoğlu et al., 2015] which comprises of smoothening the end-effector's trajectory.

In the online process, macro mechanism's axes commands are delivered to the system where the commands are actuated via joint level controllers embedded in servo motor controllers. On the other hand the secondary mechanism's motion demands are created by subtracting measured actual position (via linear encoder measurements) of the macro mechanisms from the desired end-effector trajectory. Since the micro-mechanism inherits a parallel structure, the motion demands are fed to the joint actuators using an inverse kinematics mapping function, which is also designed in the scope of this study. The inverse kinematics mapping function is embedded to be used in the online control loop inside the CNC controller.

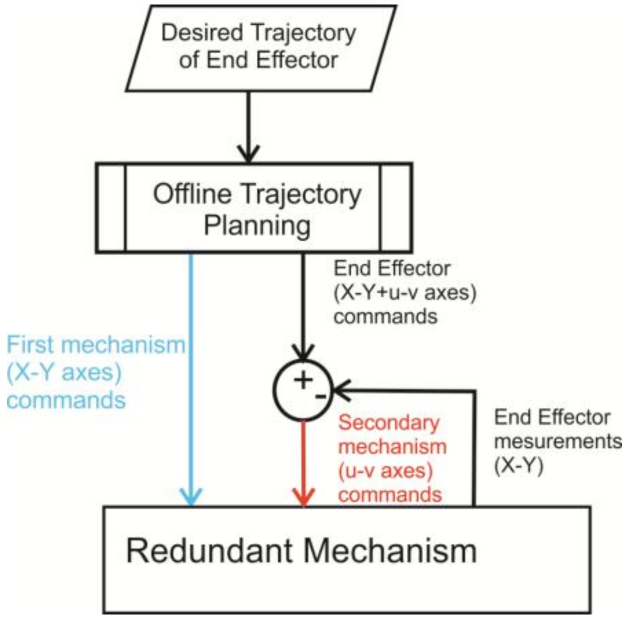

Figure 4. Control scheme of the proposed algorithm [Uzunoğlu et al., 2015].

6. BENCHMARK TESTS

The proposed semi online algorithm is tested initially in simulations developed in Matlab Simulink environment. After the validation of the proposed algorithm, in order to implement the algorithm in the hardware, C-compatible functions including trajectory planning algorithm and kinematics mapping functions are generated in Matlab environment. The compiled Matlab functions are then embedded in a real-time UNIX based CNC controller.

The overall system is described along with the hardware used and the information flow in Figure 5. The desired workpiece cutting trajectories are entered to the CNC interface via G-codes, which are derived from the CAM program. Then, the G-codes are converted into two time series data. One time series data are the motion demands ready to be delivered to the servo drivers of the macro mechanism. The other time series data are the desired motions of the end-effector. The motion demand for the micro-mechanism is calculated online, as described in the previous section, and the resultant motion demands are directed to the servo drivers of the micro-mechanism after the motion is mapped from the workspace of the micro-mechanism to the joint space of the micro-mechanism. The motion demands are generated and fed forward to the servo drivers of the actuators with a sampling rate of 2 kHz via EtherCAT bus. The servo drivers comprise a cascade PID controller, which has position, velocity and current loops. To show the performance of the joint level controllers, an example trajectory is generated for the micro-mechanism in which the maximum accelerations are bounded along each axis by 3 g. In Figure 6, in the first plot, the desired trajectory and achieved trajectory are given for this example study. In the second and the third plots from the top, positioning errors in each axis are given. The position errors are observed to be bounded in ±0.1 mm during the 3 g acceleration.

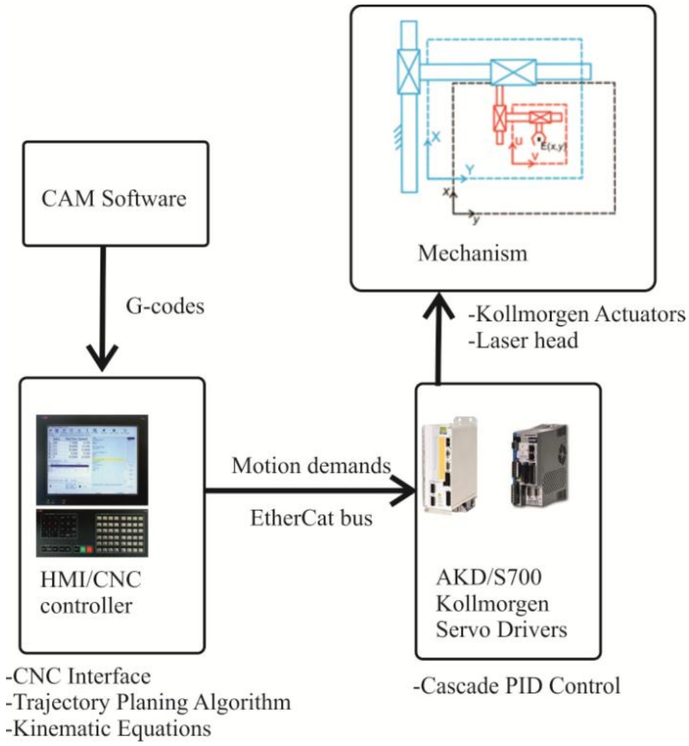

Figure 5. Hardware description of the control.

A test result for a benchmark workpiece is provided to show that the proposed algorithm with the designed machine minimizes the task execution duration. For this purpose, a benchmark piece is designed as shown in Figure 7. The test is carried out with both the conventional machine (only with the macro mechanism's X- and Y- axes) and the machine with the macro-micro-mechanism (all of the four axes are operated) using the developed algorithm. For the conventional cutting experiment 1g acceleration limit is set for each of the macro mechanism's axes. During the test with the proposed algorithm, trajectory for the end-effector are generated with 3.5g acceleration limits however, the macro mechanism's axes are limited with a maximum acceleration of 1 g.

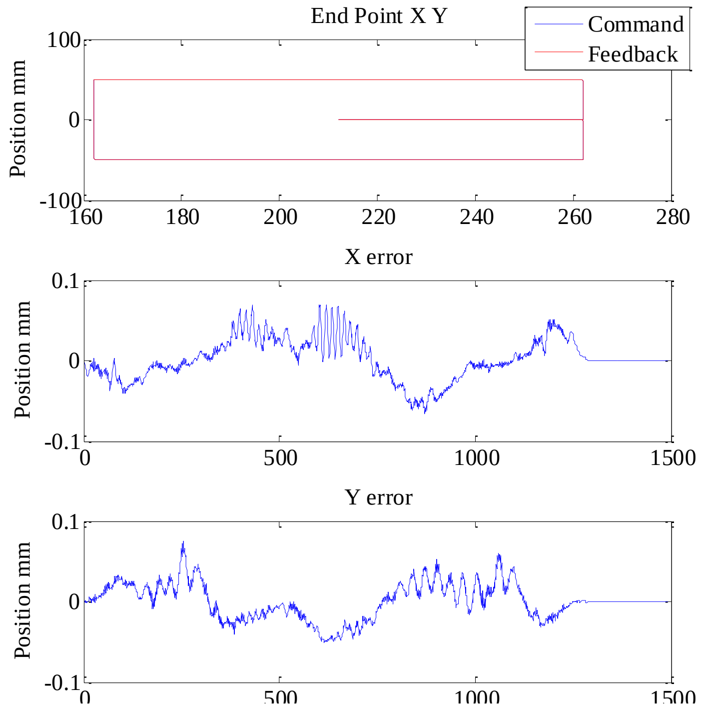

Figure 6. Performance of joint level controllers.

In Figure 8, the end-effector trajectory generated for the benchmark part is drawn in red color and simplified trajectory for the macro mechanism, which is extracted in motion planning, is indicated with blue lines. During the process, motion demands for the micro-mechanism are generated online as explained in the previous section.

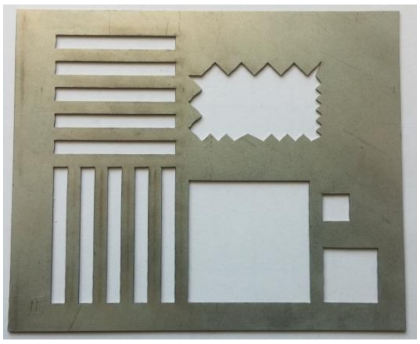

Figure 7. Benchmark part.

During the tests using the presented benchmark part, the task completion duration for the conventional machine is calculated to be 87.28 seconds while the machine with the macro-micro-mechanism completed the cutting process in 14.7 seconds.

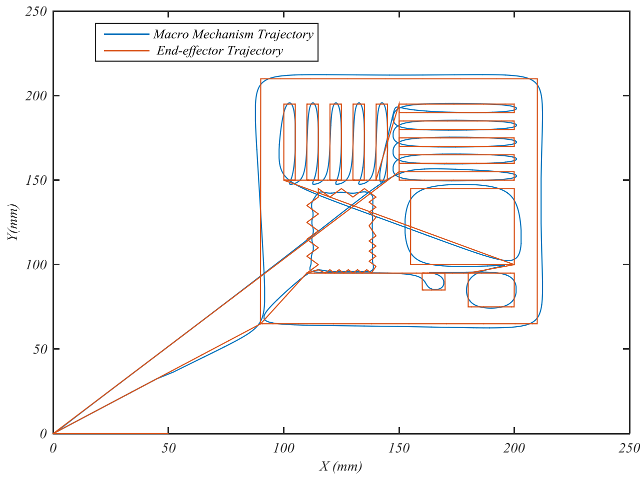

Figure 8. End-effector's and macro-mechanism's trajectories.

7. CONCLUSIONS

This paper summarizes the novel approaches implemented during the development of a planar laser cutting machine that can drastically reduce the task completion durations. The general concept adopted in this work is the macro-micro manipulation. Although this concept is not new in this application domain, the micro manipulator design, calibration process and trajectory planning algorithms incorporated innovational designs. These designs are embodied in a prototype machine. During the initial tests, this machine was measured to have a maximum combined acceleration of 3.5g, accuracy of ±37μm/m and repeatability of ±26μm. Finally, in an experimental test with a benchmark part that had many small contours, it was calculated that the total task execution duration was reduced by 6 to 1 compared to the task completion duration of a conventional laser cutting machine. Obviously, the task completion duration gain will be different from one workpiece to another one. However, for the workpieces that include many contours and relatively smaller radius curvatures, this machine is shown to reduce the task execution time by a considerable amount.

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