# Optimizing Motion Synchronization in Digital Photonics Production: Strategies for Enhancing Efficiency and Quality in Laser Material Processing

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Cascading multiple beam steering devices for laser material processing has become essential in many industrial applications. This paper presents a new approach for planning the trajectory of each device considering simultaneous motion during the processing. Main feature is to compute trajectories respecting the physical constraints of each device and then reducing tracking error during manufacturing.

## 1 Introduction

Currently, laser material processing (LMP) is employed in a wide range of industrial applications. Such success is due to its high precision, with tolerances often in the micron or nano range. On the other hand, recent applications also require a large processing area without compromising precision, e.g., depaneling of printed circuit boards, welding of battery cells for electric vehicles, and cutting of bipolar plates for fuel cells. One type of system gaining significant importance in this scenario is the combination of a linear stage and a scanner head, as illustrated in Fig. 1.

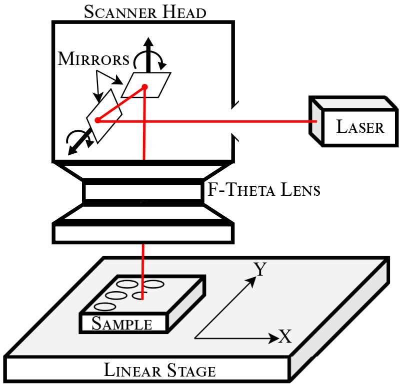

***Fig. 1*** *Schematic system composed of linear stage and scanner head*

The linear stage provides a long travel range while the scanner head offers high dynamics. Hence, the combination of both devices results in a system where the scanner's dynamics are available over an increased processing range [1]. Among the different methods to control this combination, one interesting approach is synchronized and simultaneous motion. In this case, all devices work simultaneously during the laser job, such that the combination generates the target geometry defined by the user. Advantages of this approach are: (i) no stitching error and (ii) shorter processing time compared to asynchronous motion [2].

One key factor to guarantee the performance and accuracy of the system from Fig. 1 is the computation of trajectories for each device. This paper proposes an approach to generate reference trajectories for the stage and scanner considering synchronized motion and their physical limits (max. position, max. velocity, max. acceleration, and max. jerk). The main goal is to compute feasible trajectories to achieve high laser processing speeds and thereby reduce processing time.

## 2 Related Literature

Previous researches have already described methods to handle the trajectory planning for the system shown in Fig. 1.

The most common approach employed to split the motion between the stage and scanner is the low-pass filter, as described in Ref. [3]. In this case, the control values for both devices are computed offline. By applying a low-pass filter to the reference trajectory, the low-frequency values are assigned to the stage, and the high-frequency values are assigned to the scanner. Furthermore, the cutoff frequency of the filter is used to adjust the motion split and indirectly consider the physical limits of both actuators.

The main advantage of the method described by [3] is its easy implementation. However, the main limitation is that the physical limits are not optimally used. Consequently, the system cannot achieve higher laser processing speeds without violating the kinematic constraints of the actuators.

## 3 Trajectory Planning using Model Predictive Control

Model Predictive Control (MPC) is an advanced control strategy that uses the model of the system to optimize control actions. It involves solving an optimization problem to minimize a cost function, subject to the physical limits of the system. MPC is widely used in industrial processes and has already been applied to trajectory planning [4].

Since a planning strategy considering stage and scanner at same time is much complex and does not provide

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perfect tracking error, a stepwise approach was used to compute the trajectories for the system shown in Fig. 1. In this case, the trajectories for the stage are first computed by MPC, and then the trajectories for the scanner are calculated based on the remaining deviation between the target and stage trajectories. The optimization problem involves minimizing the difference between the target trajectory and the computed trajectory for the stage, i.e., the trajectories for the stage are computed based on its physical limits and the target trajectories. A key improvement compared to the approaches described in section 2 is that it is also possible to consider the maximum position of the scanner when computing the optimal trajectory for the stage. Thus, besides the physical limits of the stage itself, an additional constraint is added to the optimization problem, stating that the maximal deviation between the reference trajectory and the computed trajectories for the stage must be the maximal position of the scanner. Fig. 2 illustrates the idea schematically.

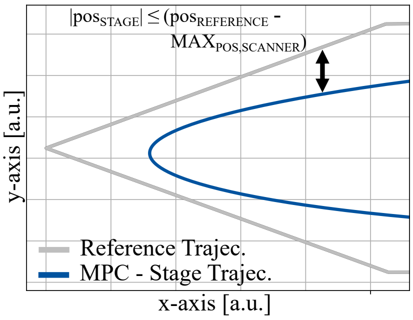

***Fig. 2*** *Schematic demonstration for trajectory planning using MPC*

Due to this improvement, it is possible to state that the stage does not have to track the reference exactly; however, the deviation between the reference and the stage must not exceed the maximal displacement of the scanner. The main advantages of this approach are: (i) the physical limits of the scanner are better utilized, and (ii) it is possible to compute feasible trajectories for both the stage and scanner, allowing for greater laser processing speeds.

## 4 Results

To validate the new approach using MPC, the system available at the Chair for Laser Technology at RWTH Aachen University was used. The physical limits of the stage and scanner are displayed in Table 1 with units in $mm/s^x$.

| Device | Pos. | Vel. | Acc. | Jerk |
|---|---|---|---|---|
| Stage | 1.5E2 | 8E2 | 8E3 | 8E4 |
| Scanner | 2E1 | 1.8E4 | 2.5E7 | 8E11 |

***Tab. 1*** *Constraints for scanner and stage*

The reference trajectory for the tests is a simplified model for welding bipolar plates from the Fraunhofer Institute for Laser Technology, illustrated in Fig. 3.

Using the low-pass filter approach described by [3], the maximum laser processing speed is 425 $mm/s$. Using the MPC approach described in section 3, feasible trajectories for the stage and scanner were computed for laser speeds up to 675 $mm/s$, resulting in an improvement of 60%.

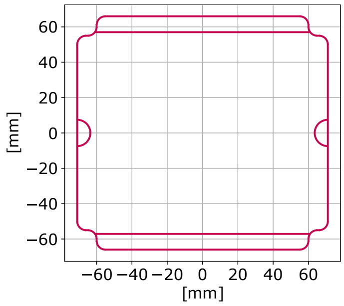

***Fig. 3*** *Simplified model for welding of bipolar plate*

## 5 Conclusion

This paper proposes an offline trajectory planning method for the combination of a scanner head and a linear stage, considering the simultaneous motion of both devices during the laser job. Using a stepwise approach based on MPC, the trajectories for the stage are first computed based on its physical limits and the maximum displacement of the scanner. Then, the remaining deviation between the reference and the stage trajectory is addressed by the scanner. Compared to the low-pass filter strategy described in [3], the novel approach can compute feasible trajectories for both the stage and the scanner, achieving greater laser processing speeds.

## 6 Funding

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