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# Energy Input per Unit Length – High Accuracy Kinematic Metrology in Laser Material Processing

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**Abstract**

Laser material processes require constant energy input per unit length. Besides focal z-position, spot size, laser power and other process parameters, the relative travel speed (feed rate) of the laser spot on the work piece has the highest influence on the resulting energy input per unit length. In this paper a new metrology method is introduced, which enables users in industry and research to measure the real travel speed of the laser spot and the resulting contour of the trajectory.

*Keywords:* Speed Measurement; Energy Input per Unit Length; Metrology of Trajectories; SLM; Remote Welding; Scanner Applications

## 1. Introduction

In this paper new metrology methods to optically measure the relative movement between work piece and processing head are presented. A software based solution enables end users to measure the kinematic parameters contact-free at high accuracy during machine setup. Additionally this paper also describes the setup of a hardware-based solution, which measures the actual speed of the tool center point while processing. This innovation measures at rates of several kHz with lower accuracy compared to the software solution but may be used for closed loop control.

### *1.1. Motivation*

By lasers of high brilliance, industrial end users are enabled to manufacture products of highest quality and at high feed rates which challenges handling systems and implies a demand for an improved control of process parameters. Advanced laser processes require a high degree of positioning precision and due to increasing intensities and decreasing spot sizes, the control over the energy input per unit length is increasingly important: This parameter is influenced not only by the intensity and the focal position of the laser, but also by the processing speed of the handling system. Only a constant process speed may ensure a steady process quality.

Most laser material processes require handling systems with one or more axes, which guide the focal spot over the work piece. The influence of inertia cannot be fully suppressed when moving with high accelerations which lead to oscillating processing heads. Small reflection angles at the processing head result in large displacements of the

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laser spot (tool center point) on the work piece. Hence, in order to detect deviations between the programmed motion and the actual motion of the lasers' trajectory, a computer vision system is developed, which measures the actual speed and direction of the laser spot.

The presented measurement method for laser material processing applications offers a high degree of quality gain by empowering the end user to optimize handling trajectories. Scientists may use this technology to ensure reproducibility of experiments on different handling systems. Scanner and remote processing applications like SLM or remote welding benefit from this technology as no other metrology method may directly measure the laser spot kinematics of deflection systems by today.

### *1.2. Optical Flow*

'Optical Flow' describes the motion of two-dimensional image points of two consecutive images. Regarding computer vision algorithms, the displacement of consecutive images has to be found. In order to find this displacement, the spatial derivatives of intensity (I) as well as its temporal derivatives have to be minimized as described in [1].

The Optical Flow can be seen as the projected motion vectors of visible objects. It represents the motion of three-dimensional objects. As long as this projection preserves all necessary information of the given motion it represents an appropriate method for kinematics measurement. This measurement of motion is used in many computer vision applications, such as object tracking, image segmentation, image and video compression and time-to-collision calculations.

### *1.3. Constraints of Optical Flow*

Unfortunately, the exact displacement of image points cannot be determined. In an image sequence an image point can be seen as a function mapping the time to an intensity value. Thus, determining the motion of a single image point between two consecutive images is impossible, since the only available information is the change of intensity. This is related to the 'aperture problem' described in [2].

Horn-Schunck [3] introduced a global constraint of smoothness to overcome this problem. They assumed that for some time-varying region of the image sequence the local image intensity is constant for at least a short duration of time. In the given laser processing environment the Lucas-Kanade algorithm [4] is used, which assumes that the image point motion is homogeneous in a small neighborhood, which meets the smoothness constraint proposed by Horn-Schunck.

In many applications the given image sequence is produced by a three-dimensional projection of a scene onto an image plane. For example the image is produced by a visual sensor like a camera. Such a projection induces a loss of information, since the depth of the scene is no longer available. Object movement away or towards the point of view is only indirectly observable given that the projected object expands or reduces in size over time due to the perspective foreshortening. So the reliable motion measurement can only be done for movements parallel to the image plane. In the given laser processing environment the point of view is always a top-down view onto a planar surface, which usually neither changes its distance nor its angle to the work piece. If applications demand different angles and z-positions, the optics and the algorithm can be adjusted.

The projection of a three-dimensional scene onto a two-dimensional image plane usually induces a rasterization, since the image is stored as a pixel array of discrete pixel size. This also causes a loss of information, since the continuous surfaces of the projected objects are now represented by a discrete set of image points.
The degree of image resolution limits the detection of small movements. An object's edges are represented by a set of image points which may be used to find this object in successive images. For small enough movements the edges of the object would not reach new image points due to the discretization. Instead the set of image points representing the object would slightly change its intensities, which would prevent the pattern from being recognized in a strict pattern matching.

To overcome this problem, the time between images as well as the optical magnification has been adjusted, so that the object movement advances far enough in the preselected speed range. This consequently means that there is a limit in accuracy of the observed movement, which directly depends on the setup of the image sequence (see errors described in 2.5).

When projecting a three-dimensional scene onto an image plane, an occlusion of objects may occur. In regard to consecutive images of an image sequence this means that a set of image points representing an object are visible in the first image, but the next images are fully or partly occluded and the pattern is nonexistent anymore. When using this measurement method in laser applications, this restriction implies that the work piece surface may not be covered by any other object.

### *1.4. Lucas-Kanade Algorithm*

The optical flow may be computed by many different algorithms. The paper 'A Database and Evaluation Methodology' [6] provides a good overview of existing models and their advantages. The Lucas-Kanade [4] algorithm meets the demands for short calculation time whilst providing an acceptable accuracy.

Algorithms presented in this paper represent an advanced solution to detect homogeneous motion in images beyond the state of the art of optical flow algorithms (see 2.4).

## 2. Experimental

### *2.1. Optical Setup*

The optical setup consists of laser collimation and laser focusing optics and is equipped with a dichroic mirror which is integrated inbetween both optical elements. The work piece reflects radiation of external illumination which is observed coaxially through the dichroic mirror and laser focusing lens with a high speed camera system as described in [7].


(a) (b)

Figure 1. (a) Example setup for laser welding with coaxial camera and illumination setup; (b) Block detection of two consecutive frames and resulting displacement vector

## *2.2. Scanner and Remote Laser Applications*

As the coaxial setup can also be implemented in scanner applications, laser spot trajectories created by moving mirrors may also be measured. Compared to laser applications like welding or brazing, the measurement accuracy in applications with scanner systems (i.e. marking, remote welding, SLM, …) depends not only on the algorithm and optical properties but also on the occurring reflection angles and also on the properties of the F-theta lens.

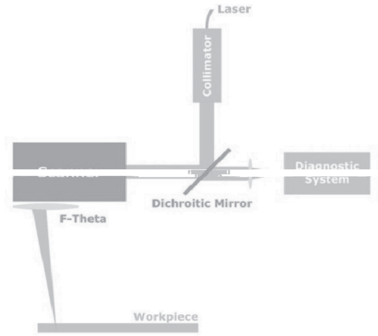



Figure 2. Optical setup of a scanner/remote application

Especially in remote laser welding with multi axes handling systems, high deviations from the preselected feed rate can be expected due to accelerating cantilever arms. The optical setup for these applications is realized as described in Figure .

## *2.3. Illumination*

In order to meet the constraints of optical flow regarding the illumination, a homogeneous light source had to be developed. Coevally it has to fit the demands of high-speed image processing which leads to the demand for high intensities due to short exposure times. Optical constraints of the algorithm make laser sources not applicable because of the coherence of these sources as they produce speckles in camera images.

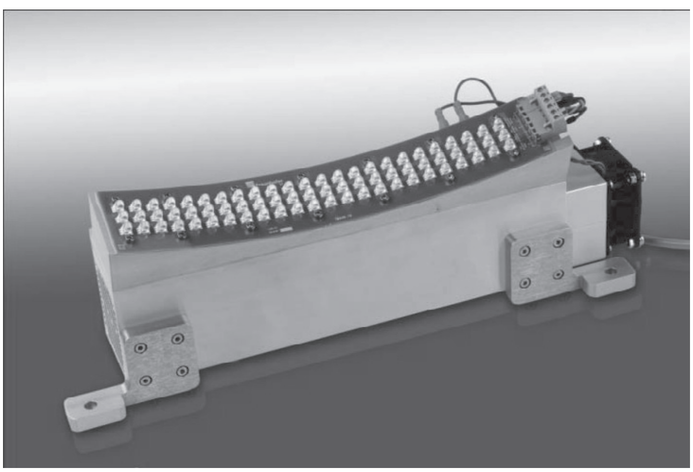


Figure 3. Illumination module with active air cooling

As shown in Figure  the developed illumination source consists of 2 x 72 high power LEDs. The range of the working distance is chosen to use it in both scanner and conventional applications. The illuminated area is 100 x 100 mm² and the intensity is I = 1,72 mW / mm². The center wavelength is λ = 810 nm. By choosing an illumination wavelength close to the wavelength of the processing laser (here 1064 nm, 1030 nm and 1070 nm), the measurement error induced by the optical distortion caused by chromatic aberrations of F-Theta lenses in scanner systems is reduced.

### *2.4. Software Algorithm*

As mentioned in 1.2, the applied software algorithm is based on the Lucas-Kanade algorithm [4]. In order to meet the demands of laser applications and to provide reliable measurement results the algorithm has been modified by two major extensions. First, the algorithm makes use of the information of multiple calculated vectors (integer values), but not for each pixel position of every image. Afterwards, the mean value of all resulting vectors is calculated which creates floating point values.

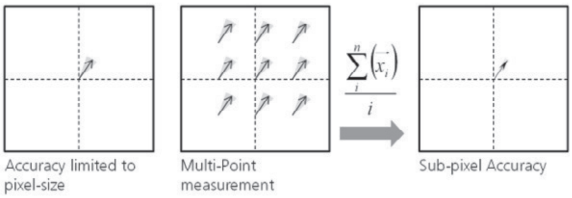
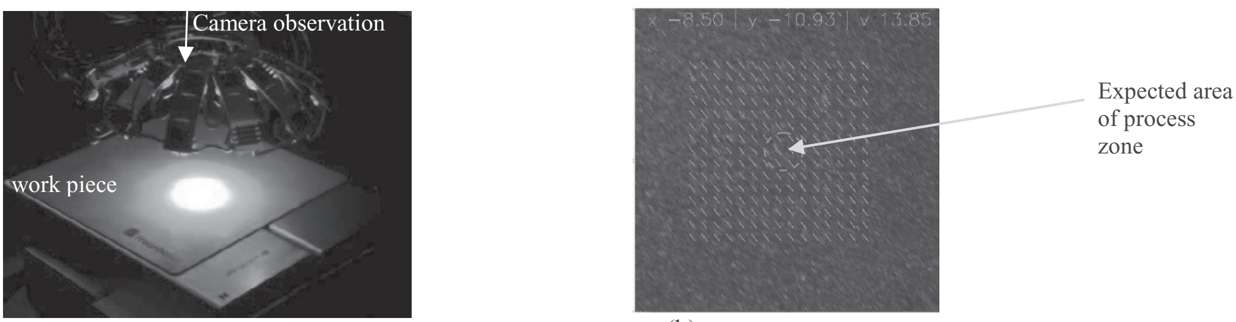



Figure 4. Quasi sub-pixel calculation

Figure  shows the calculation strategy of the modified algorithm. This method corresponds to a sub-pixel calculation while skipping the time consuming calculation of a sub-pixel based cross correlation method.




(a) (b)

Figure 5. (a) Example setup: Camera system guided by a 6-axes robot observes a galvanized steel sheet. The work piece is illuminated by 24 high power LEDs; frame rate is 5000 fps; (b): Camera image of the work piece surface and overlay of calculated motion vectors in pixels

Figure  (b) shows a snapshot of the created software application. The graphical interface shows the actual image (work piece surface) and the results are overlayed with a grid of 15 x 15 vectors. In the top row, the calculated displacement from frame to frame is displayed. It represents the mean value of all vectors which withstand a plausibility check. The acquired images have a resolution of 256 x 256 px.

Although each vector of the grid shown in Figure  is calculated as a displacement of whole pixels, the resulting velocity [px/frame] shown in the top right indicates floating point values due to the applied mean value calculation.

As the Multi-Point Contour Control algorithm calculates multiple displacements from frame-to-frame in many regions of an image, faulty measurements of single vectors may be detected. The plausibility of measurement of each calculated vector is calculated by comparing the directions (angles) and lengths of all vectors. Vectors which do not point into the main direction will not contribute at the mean value calculation.

The amount of main vectors is a profound indication of the degree of accuracy of the actual measurement.

### 2.5. Hardware Algorithm

In order to use the motion information for a closed loop control a hardware based algorithm is developed. Preliminary test results prove its capability to measure in real-time. For online and automatic process control high frame rates are needed to capture high-dynamic laser welding and brazing processes. On the other hand a programmable and flexible system is essential for the evaluation process. A 'Field Programmable Gate Array' (FPGA) is able to meet both speed and flexibility requirements.

A frame grabber which combines a full CameraLink and FPGA is used as processing card. It comes with a PCI-Express x4 interface and is equipped with 512 MB RAM to buffer images and data. Additionally it offers digital IO for closed-loop control.

A high speed camera is connected via Full CL to the frame grabber what offers frame rates of several kHz. Concerning the performance, software algorithms are suitable for recursive loops but not for processing vast amounts of data. The proposed software optical flow algorithm using the pyramid Lucas-Kanade algorithm is not suitable for hardware realization because of its mathematical complexity and irregularity. Instead a Full Search Block Matching algorithm (FSBM) is implemented. It offers robustness, a regular data flow and a fixed amount of operation steps [8]. The basic idea of the FSBM is to find the best match of all possible displaced candidate blocks within the searching range in the previous frame.

Using a 'Sum of Absolute Differences' (SAD) as matching criterion, the operations required to process a single block at position $(x, y)$ can be considered as four nested loops *(1)* [9].

$$For\ d_x = \left[-\frac{W}{2} .. \frac{W}{2}\right]$$

$$For\ d_y = \left[-\frac{H}{2} .. \frac{H}{2}\right]$$

$$SAD(d_x, d_y) = \sum_{j=0}^{B_y} \sum_{i=0}^{B_x} |L_t((x+i, y+j) - L_{t-1}(x+d_x+i, y+d_y+j)| \quad (1)$$

$End$

$End$

$W, H{:}\ window\ size;\ B_x, B_y{:}\ block\ size;\ x, y{:}\ current\ position;\ L_t(x, y){:}\ luminance\ function$

The resulting displacement vector $(d_x, d_y)$ of the current block is the one that minimizes the SAD function [10]. These four loops are processed for every block in a frame. Thus they represent the main part of the computational cost of the FSBM. While blocks are processed in their order of appearance as provided by the camera, SAD calculation within each block for a certain displacement is independent from other displacements. Using this information, the FSBM algorithm can be heavily parallelized and is therefore well suited to be realized in hardware.

A vector filter is used to determine a global displacement vector, which is compared to a reference displacement (which might be 0). The difference is then supplied to the scanner control and driver to compensate for unwanted motion. Instead, the deviation information may also be used to control the laser power.

For simplicity, FSBM is computed on a fixed number of blocks which are equally distributed over one frame. Search windows do not overlap. In a first approach the block size is set to 3x3 with a window size of 32x32. Using 1000 blocks a frame rate of 946 fps is achived. By reducing the window size and the number of blocks per frame, the frame rate can easily be increased (2). The FPGA's operational frequency is set to 62.5 MHz and FSBM works with a parallelism of 16.

$$f_{max} = \frac{f_{fpga} * p}{(W+1) * H * N} \quad (2)$$

$f_{max}$: max archievable frame rate; $f_{fpga}$: FPGA frequency; p: parallelism
W, H: window size; N: number of blocks

The window size can be decreased if a fixed, maximum block displacement can be guaranteed. A window size of 16x16 for instance results in a maximal detectable displacement of 8 pixels in horizontal and vertical direction. Since only the overall movement should be detectable, a much smaller number of blocks might be sufficient.

This setup works well (i.e. tracked movement) on a test sequence which was supplied to the frame grabber instead of real images. By increasing the block size, the reliability of displacement vectors increases as well, as previous experiments on software implementations with different block sizes and real image data proved.

Even if the displacement is perfectly estimated, a minimum positioning error will occur. It is induced by the speed of the displacement and the overall reaction time of the system. Additionally, motion estimation with FSBM and vector filter will not result in real displacement (due to integer rounding, noise, limited resolution, optical characteristics, etc.) and the scanners will not settle to the exact position. The overall residual error is then given by [9]. This error limits the achievable accuracy of the positioning system.

$$e = v * \left(\frac{1}{f} + t_{fpga} + t_{control} + t_{scanner}\right) + e_{fsbm} + e_{scanner} \quad (3)$$

v: displacement velocity per frame; f: frame rate; $t_{fpga}$: computation time to find best vector
$t_{control}$: controller and driver latency; $t_{scanner}$: scanner latency

### *2.6. Reference System*

For verification reasons a Heidenhain KGM measurement system was integrated to a standard 2-axes handling system. This reference system is based on interferometric measurement and provides absolute position measurement accuracy in the range of several microns.

The system consists of a reference plate and a measurement head which is mounted to the handling system in the same height as the camera system which records images for the calculation of motion.

## 3. Results and Discussion

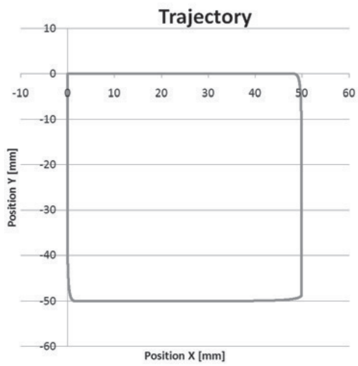
Experimental setups include welding systems with robot handlings, gantry handlings, scanner (SLM) and remote welding. In each setup the work piece surface is visualized by a high speed camera system as shown in Figure 1. By comparing two consecutive images, the displacement of both images is calculated on pixel level. The resulting displacement vector in the x-y-plane on the surface is multiplied by the magnification of the optical system.

The resulting vector indicates the displacement of two consecutive images in millimeters. Precise information on how much time has elapsed between both consecutive images allows the ability to calculate the actual speed in SI units. Processing all images provides a full kinematic measurement of the entire trajectory. Modified optical flow algorithms are shown to provide kinematic data of the trajectory of the tool motion. Fixed head laser processing setups and scanner setups have been tested.

End users are enabled to optimize the trajectories of their handling systems. The programmed trajectory (i.e. PTP) and the resulting trajectory measured can be compared.

### *3.1. Measurement Results*

The accuracy of the applied software algorithm is tested. The applied system measures process speeds from 0 to 10 m / min with an accuracy of less than ± 0.03 m / min of the actual value. In scanner applications speeds of up to 15 m / s have successfully been measured. The system's accuracy as well as the achievable measurement rate depend on the magnification, the optical resolution and the quality of the applied optical system. For a coaxial measurement at the tool center point, the system must be adapted and integrated to each processing head individually.



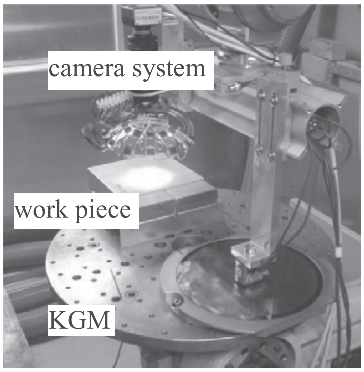




Figure 6. Left: Measured trajectory of a NC programmed square motion (50 x 50 mm). Right: Handling system (2-axes-motion) and experimental setup with Heidenhain KGM and camera system

The tested handling system is not capable to move the processing head with constant speed in the trajectories' corners as shown in Figure . The positioning deviation from the programmed contour can be measured by the coaxially integrated camera system and the signal processing algorithm.

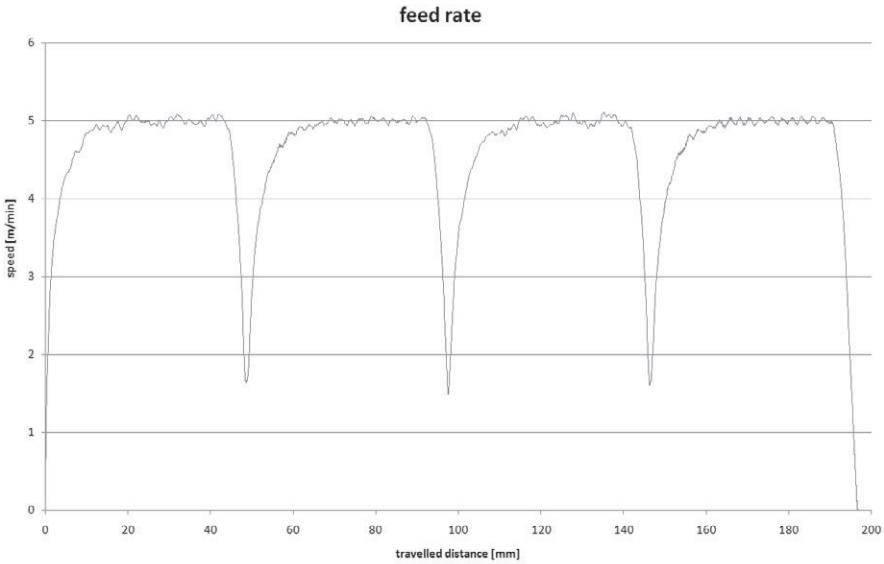



Figure 7. Measured feed rate (camera system) during test described in Figure .

For the same test, the actual feed rate is measured by the camera system (Figure ). The diagram shows travel speeds during the whole motion of the handling system.

In order to precisely calculate the measurement deviations between the camera system with applied optical flow algorithms (software-based) and the reference device, both measurements are started coevally and set to the same measurement rate of 1000 Hz.

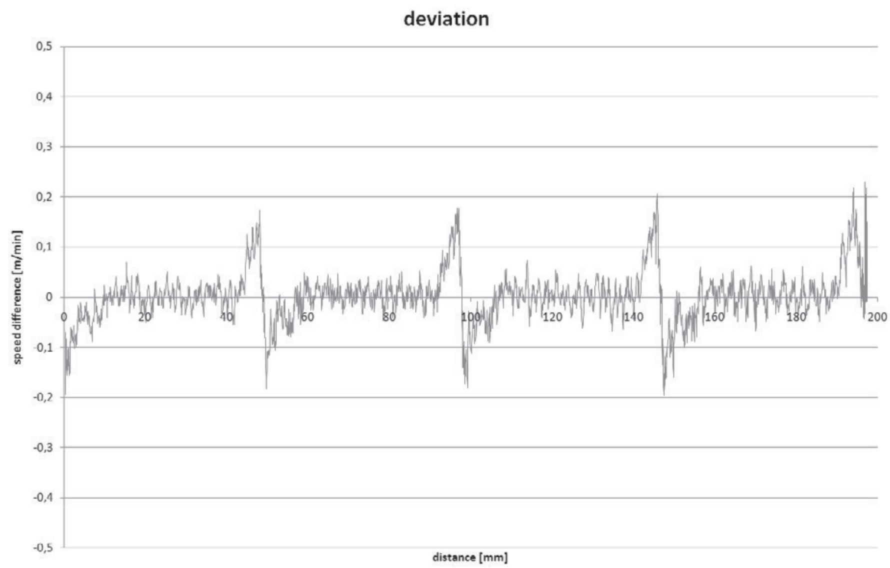



Figure 8. Measurement deviation (camera system to Heidenhain KGM) during test described in Figure .

The deviation of both signals is shown in Figure . As predicted in 1.3, slow motions lead to small pixel deviations from one image to another and thus imply high accuracy errors. During movement with the preselected processing speed (here 5 m / min), the accuracy of the measurement system improves according to 2.4. The deviation from the interferometrically measured speed is less than 0.05 m / min.

### *3.2. Online Process Control*

The capability of measuring the trajectory in real-time during the laser process is already validated for some applications. First tests show that the accuracy of measurement is affected only little by the process. Due to the implemented plausibility check, faulty vectors in the process zone do not affect the measurement. The correlation of the amount of valid vectors and the algorithms' accuracy has to be investigated.

A hardware-based implementation of the algorithm will enable manufacturers to measure at camera speeds of more than 1000 Hz in real-time as presented in [7]. Future studies will investigate on measuring the process speed online. These parameters will provide the capability to apply closed loop control in order to provide a stabilized energy input per unit length.

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