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High-Precision Calibration of a Weld-On-The-Fly-System

Claus Emmelmann[a], Kerstin Schenk[a]*, Jörg Wollnack[b], Marc Kirchhoff[a]

[a]*Institute of Laser and System Technologies (iLAS), University of Technology Hamburg-Harburg (TUHH), Hamburg, Germany*
[b]*Institute of Production Management and Technology (IPMT), University of Technology Hamburg-Harburg (TUHH), Hamburg, Germany*

Abstract

Since 20 years the importance of laser based material processing increases constantly due to its significant higher process speed in comparison to conventional processing technologies. A scanner system for laser-remote-welding mounted on a robot hand to achieve more freedom in positioning the laser spot has been investigated. Additionally the scanner head contains two fixed cameras for measurements and process monitoring. To perform required measurements with maximum accuracy the allover system has to be calibrated precise. Therefore a combination of video metric measurement system and a laser tracker has been used. This paper depict this high-precision calibration process and shows reachable accuracies.

Keywords: system calibration; video metric measuring; camera; laser tracker; laser beam; laser remote welding

1. Motivation

In recent years laser beam welding has become more and more important in the field of joining materials. In comparison to conventional processing technologies it allows high welding speed, slender welding seams and moderate thermal distortion of the material. Due to a large distance between optic and joining area as well as mounting the scanner head on a robotics hand the non-productive time is significant shortened and the system possess high flexibility in positioning. This enables to weld large pieces, as they are processed in the ship or railway construction. To use the full potential of the system, the motions of the robot and the scanner have to be synchronized (weld-on-the-fly). The robot angels the pose (position and orientation) of the scanner head, while the scanner adjusts the exact position of the laser spot on the work piece as function of the scanner head pose.

Precise welds require an accurate positioning of the laser spot. Thus, because the repeatability of a robot is typical one magnitude smaller than the absolute positioning, the offline programmed trajectory from CAD data is fitted to the actual work piece. So far this step is done manually by teaching. In serial production this is a reasonable amount of time. But for small lot sizes, not negligible tolerances or prototypes it is not economical.

* Corresponding author. Tel.: +49 (0)40-42878-2980; Fax: +49 (0)40-42878-4076.
E-mail address: schenk@tu-harburg.de.

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To automate this step the scanner-robot system was upgraded with a video metric measurement system. It allows an accurate measurement of the position and the orientation of the work piece as well as the seam pattern. For high-precision measurement the overall system has to be calibrated exactly. This includes adjustment of robot and video metric sensor calibration with a laser tracker as well as calibration of the laser scanner system. The following passages give an overview of the laser remote system and the calibration process.

2. System Setting

For the experiments the laser remote system “Dragon” developed at Institute of Laser and System Technologies (iLAS) has been used [7]. It mainly consists of an optical system for beam shaping and a movable mirror for positioning the laser spot focus. The working space of this system is limited by the maximum mirror deflection. To expand the working space and get more flexibility in positioning the laser spot the scanner system was mounted at a robot. Additional two cameras and a green laser were fixated at the scanner base for performing measurements and monitor the welding process. The green measurement laser is coupled into the optical path of the infrared process laser. So it is possible to mark and check welding points and implement 3D/6D (D stands for “dimensional”) measurements.

The evaluation of measurement data and controlling occur with a computer-aided system. By analysing primary image data for corresponding areas with mathematical algorithm it calculates the 3D/6D information for component and generates the trajectories for welding process. For correct calculation results the exact position and orientation of the scanner head is required. Therefore the system has to be calibrated.

3. Calibration Problem

There are a number of coordinate systems and models corresponding to Figure 1 to be used in videometrically guided robotic remote laser scanner systems. Multi-camera models or two-camera models are used for 3D videometry. The camera model on which these models are based is derived from the work of Tsai and Lenz [6]. The relations between the Cartesian coordinate systems are described using homogeneous coordinate transformations **T** with six degrees of freedom of the pose, three in the position and three in the orientation.

The robot model should be characterized using Denavit-Hartenberg axis models or other suitable models depending on axis transition [1, 2, 3, 4, 5, 10, 12, 16]. Instead of serial kinematics, parallel kinematics also can be used. However, with parallel kinematics, calibration is performed via the kinematic inverse transformation.

The laser remote model describes the relation between machine coordinates and focused laser spot position.

Thus based on the problem definition the following situation exists:

- 3D camera system uncalibrated (two-camera system)
- Transformation from laser tracker measurement frame to TCP COOS unknown (TCP := tool center point, COOS := coordinate system)
- Transformation from Laser-Scanner to TCP COOS unknown
- Robot and Laser controller partially calibrated or uncalibrated
- Transformation from Object to robot COOS unknown
- Pose of local object characteristics unknown (production tolerances) or pose of the object unknown

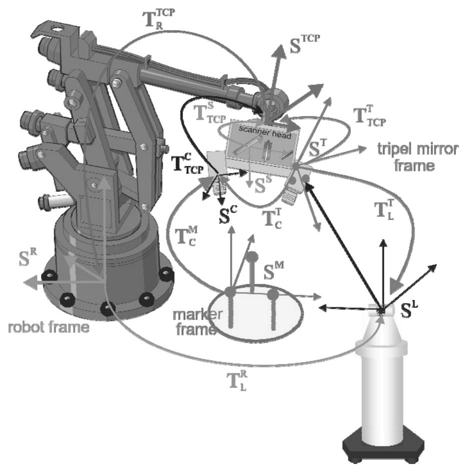

Figure 1. System model

In this context means unknown or uncalibrated that the parameters of the model cannot be derived from the design engineering data with the required accuracy. In general, a reduction of production tolerances is technically or economically not purposeful.

For this reason, calibration of the parametric models is required. Therefor the task of non-linear parameter identification is formulated as a minimization problem. The linearization of the vectorial residuum leads directly to the general Newton method. The numerical implementation of this algorithm can occur with the Powell method, for example [8, 9]. However, these methods have to be modified in such a way that the parameters which are to be used for the minimization [16] can be selected via an index table.

Parameters to be optimized are initialized with (design engineering) nominal values or with values from a previous minimization run, and those not to be optimized are filled with nominal values. This approach enables a structured hierarchical calibration of the models. In this way, the structures of the system models can be extended stepwise and calibrated hierarchically. The hierarchical calibration is used if there are incomplete models with poor condition and/or numerical rank defects (camera/sensor model). Here first the linear independent parameters were minimized which have the greatest influence on the model behaviour. Then further parameters were released sequentially. After all, complete models are subordinated, because not all (systematic) physical effects can be modelled and therefore structural model errors will exist.

Finding the successful strategy requires a mixture of systematic procedure and a heuristic approach. In this regard the knowledge of the models, the parameters ordered according to sensitivity and the singular value decomposition (SVD) values of the Jacobi matrix of the model parameters as well as the collected experience for the hierarchical minimization (first minimize important parameters without rank defects, then important parameters with rank defects, and after that include additional parameters in the minimization successively according to their significance) [16] is used. Then, the successful strategy can be applied without further ado to a series of systems or in practice so that the basic difficulty is not perceived by the user.

If the user changes the calibration scenario, the numerical analysis can be used to determine whether the modified scenario leads to the objective and give appropriate information fully automatically.

4. Fully automated sensor, robot and laser scanner calibration

The fully automated sensor, laser scanner and robot calibration utilizes the possibilities of structured hierarchical model calibration successively. Starting from a sufficient number of measured poses and measured remote laser spot positions, the entire system can be calibrated completely automatically, using numerical rank analyses to lead the user without a deeper understanding of the relationships to a useful movement strategy.

The following fully automated sequence can be implemented this way:

- After the calibration button is pressed, the robot moves to the defined or "taught" poses for calibration. If the movement concluded, the robot controller sends a measurement command to the sensor systems which causes the measurement marker coordinates to be measured in the RAM (random access memory) coordinate system and the triple mirror markers to be measured in the laser tracker frame. The data for the TCP poses, measurement marker coordinates in the RAM coordinate system, measurement triple coordinates in the laser tracker frame and the machine coordinates including the robot and sensor names and their unambiguous IDs are used for calibration. These data are saved in a data file for documentation. The first two movements are to be performed in such a way that analytical identification is possible in the third step (translation and two non-linear dependent rotations).
- Subsequently, the hierarchical identification of the internal camera parameters of the first camera as well as of the internal and external camera parameters of the second camera is started using the distance measurements (initial values are design engineering nominal values) of three non-collinear measurement markers. After this process is completed, a 3D position measurement in the first camera frame can be implemented. If the achieved accuracy work for this process in the application, further structural variation of the calibration model is not required, so the following process step can be omitted.
- The measurement marker coordinates in the sensor coordinate system of the first camera can be calculated with the previous process steps. A pose measurement can be implemented at the three or more non-collinear measurement markers, with which the analytical identification of the transformation of the measurement coordinate system to the TCP coordinate system via the first two TCP movements or three TCP poses is possible [17, 11]. The laser tracker is used as a reference system here. Now the transformations from triple frame to TCP and sensor frame to TCP are well-known.
- After performing the previous step, an analytical identification of the transformation of the reference coordinate system to the robot controller coordinate system can already be calculated from one measured pose via the TCP pose. Here, the laser tracker serves as reference system, too, analogous to step three.
- Up to this step, the important constant coordinate transformations are known. Thus, the sensor model can be calibrated using pose measurement based on three measurement markers. For this, the parameters identified in the previous process steps can be used as high-quality estimates of the initial values for the minimization, which is why a hierarchical recalibration of the sensor system is possible.
- Further the robot model can be calibrated via the measured data. The model parameters identified in the previous steps can be considered high-quality estimates of the initial values for the minimization, which is why a hierarchical recalibration of the entire system is possible. This leads generally to a significant increase in accuracy with respect to systematic errors.
- In order to calibrate the remote laser scanner model a sufficient number of laser spot positions are necessary. These are measured with the calibrated 3D sensor system. The points should be equidistant in the remote laser scanner working space. Using these measured 3D laser spot positions and the corresponding remote laser scanner machine coordinates the hierarchical calibration of the scanner model can be done. Hence an improved estimation of the transformation from remote laser scanner to the sensor frame is obtained. The parameters of the models of the previous steps are used as initial values of the minimization.

5. Results and Discussion

A method for calibrating a sensor guided remote laser scanner robot system was developed. Hence with the described system measurements can be performed with maximum precision. This is an important step to automate the calibration of work pieces and fit welding trajectories to the offline programmed data. Altogether it opens up various remarkable industrial application potentials. But now the weld-on-the-fly process can be performed with required accuracy. Beam and focal position can be regulated precisely and thus i.e. temperature drifts can be compensated. Form and position tolerances of components are no problems any more. And modifications of scanner components and other relations do not require teaching the product range again. Last but not least CAD CAM systems can use logical and geometrical information.

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