ROBOTIC THREE-DIMENSIONAL MEASUREMENT SYSTEM FOR COMPLEX METAL PARTS USING STRUCTURED LIGHT

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ABSTRACT:

In thermal transformation processes for the production of metal parts of complex shape, shaping tools are frequently used. In die forging as an example, the tools are exposed to high mechanical and thermal loads and therefore subject to heavy wear. For fast feedback directly in the production process the accuracy to size of metal parts produced in such a way is at present frequently checked with groping measuring tools. This is unsatisfactory because of the complex forms, the broad product range and the thermal conditions. A 3D – measurement system for highest possible flexibility and industrial environment, conceived for this application and based on a 3D - sensor attached to an industrial robot for positioning is described here. The Structured – Light approach is used, i.e. the sensor consists of one or several CCD - cameras, combined with a programmable line projector. Two different calibration procedures of the line projector system are compared, on the one hand based on a polynomial model with a large number of coefficients, on the other hand based on a model targeted towards the actual optical / physical conditions with a significantly smaller number of coefficients. Finally a procedure for the solution of the Sensor to Hand calibration of the measuring robot is shown.

RESUME:

Dans les processus de transformation thermiques à l'aide d'outils formants visant à la fabrication de pièces métalliques de formes complexes, comme par exemple l'estampage, les outils sont soumis à des efforts mécaniques et thermiques élevés et par conséquent sont sujets à une forte usure. De manière à avoir un rapide retour d'information directement au niveau de la production, la précision des pièces produites doit être fréquemment examinée. La complexité des formes, la large gamme de produits et les contraintes thermiques rendent les mesures à l'aide d'outils tactiles peu satisfaisantes. Un système de mesure 3D permettant la plus grande flexibilité possible en environment industriel est décrit ici. Ce système est basé sur un senseur 3D positionné par un robot industriel. Un procédé à base de lumière structurée (Structured Light) est utilisé, la sonde se composant d'une ou plusieurs caméras CCD combinées à un projecteur de lignes programmable. Deux procédures de calibration du système sont comparées: l'une se basant sur un modèle polynômial de haut degré, l'autre sur les données opto-physicales nécessitant un nombre de coefficients significativement plus faible. Pour finir, une solution pour la calibration de la transformation entre la main du robot et le senseur est présentée.

KURZFASSUNG :

In thermischen Umformprozessen mit formgebenden Werkzeugen zur Herstellung komplex geformter Metallteile wie zum Beispiel beim Gesenkschmieden, sind die Werkzeuge hohen mechanischen und thermischen Belastungen ausgesetzt und unterliegen daher starkem Verschleiß. Um schnelle Rückmeldung direkt in der Produktion zu erhalten wird die Maßhaltigkeit von so produzierten Metallteilen gegenwärtig häufig mit tastenden Messwerkzeugen geprüft, was wegen der komplexen Formen, der breiten Produktpalette und der thermischen Belastung unbefriedigend ist. Ein für diese Anwendung konzipiertes 3D-Messsystem für höchstmögliche Flexibilität und industriellen Einsatz, basierend auf einem 3D-Messkopf und einem Industrieroboter zur Positionierung des Messkopfes wird hier beschrieben. Zum Einsatz kommt das Structured - Light Verfahren, der Sensor besteht aus einer oder mehreren CCD - Kameras, kombiniert mit einem programmierbaren Linienprojektor. Zwei verschiedene Kalibrierverfahren des Linienprojektorsystems werden verglichen, einerseits basierend auf einem Polynommodell mit einer großen Anzahl von Koeffizienten, andererseits einem an den optisch-physikalischen Gegebenheiten orientierten Modell mit einer signifikant geringeren Anzahl an Koeffizienten. Abschließend wird ein Verfahren zur Lösung der Sensor to Hand Kalibrierung des Messroboters dargestellt.

1. INTRODUCTION

Complexly formed alloy parts frequently are manufactured by thermal transformation processes with shaping tools. The tools thereby used are exposed to high mechanical and thermal loads and therefore are subject to strong wear. Furthermore processes of transformation in the crystalline structure during the cooling down of the parts cause variations in volume, which can lead to fluctuations in geometry and dimension of the final product. Therefore required is a measuring system, which can be used directly in the production process and that delivers fast feedback about the accuracy to size of the manufactured product. Because of the broad product range, the complex form of the object to be measured and the thermal load this task cannot be solved in a satisfactory fashion by conventional groping measurement tools. For this reason JOANNEUM RESEARCH works on a new measuring system, which is to solve this task. The following key specifications are required from the measuring system:

- maximal part size = up to 2m
- accuracy of measurement = tenth of mm
- duration of measurement = few minutes
- object temperature > 250°C
- utmost flexibility
- possibility of comparison with the CAD-Model
- environment: fabrication site, heat, dust

2. DESCRIPTION OF THE MEASUREMENT SYSTEM

Because of the demand for maximum flexibility and the harsh conditions on site the decision has been taken to employ a robot equipped with a 3D – measuring system. Figure 1 shows the prototype of the measuring system in a laboratory at JOANNEUM RESEARCH.

Figure 1: The lab prototype of the measurement system

Chosen is a six-axis robot and a line projector, the latter is supplied by an external cold light source mounted at the elbow joint of the robot. For avoiding shaded areas, two CCD cameras with resolutions of more than 1000 x 1000 pixels are used. For the acquisition of a part to be measured the robot steers to 10 to 20 positions depending on the item. The measurement data of each position is converted into a common coordinate system with the help of the kinematic parameters of the robot. For the further increase of the accuracy the overlap areas of the individual measurements are used, in order to enhance the overall result. Finally the final result is overlaid to a CAD model and the deviation is visualized.

3. COORDINATE SYSTEMS

Figure 2 shows the various coordinate systems and the relationships between them:

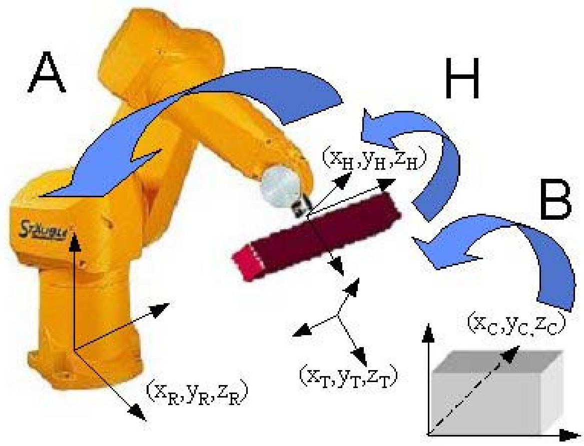

Figure 2: Coordinate systems

$X_R = [x_R, y_R, z_R]$ is the robot coordinate system (or world coordinate system) that is fixed in space and has its origin in the robot's base. It is the reference coordinate system of the assembled individual measurements.

$X_H = [x_H, y_H, z_H]$ is the hand coordinate system, which is fixed to the mounting flange of the robot's arm.

$X_T = [x_T, y_T, z_T]$, the sensor coordinate system (or tool coordinate system) is the reference coordinate system of the 3D - sensor. Origin and orientation of this coordinate system are defined by the position of the calibration target during the calibration of the sensor. As long as the calibrated sensor is mounted to the flange, there is a fixed but unknown relation to X_H.

$X_C = [x_C, y_C, z_C]$ is the reference coordinate system of the calibration piece (a cube – like object) for the hand to sensor calibration. It serves as an auxiliary system for the calculation of H. As long as the calibration piece remains fixed in space, this coordinate system has a fixed but unknown relation to X_R.

The relations A, H and B between two coordinate systems can be expressed by a congruence transformation of the form

$$X_2 = T \cdot X_1 \tag{1}$$

where X_1 resp. X_2 represent the extended coordinate vectors in both coordinate systems [x, y, z, 1] and T represents the 4x4 transformation matrix, which itself contains the orthogonal rotational matrix R and the translation vector t:

$$T = \left(\begin{array}{c|c} R & t \\ \hline (0,0,0) & 1 \end{array} \right) \tag{2}$$

4. SENSOR CALIBRATION

The sensor operates according to the principle of triangulation with structured light (Wolf, 1997; Wolf and Wolf, 1999). A line pattern which defines a phase value p continuously over the measurement range, is projected on the surface to be acquired. Ambiguities in the lines are resolved by the multiple phase-shift procedure, by which a sequence of patterns with closely related wavelengths is projected, whereby for each pixel [u, v] of the observing camera a unique phase value p can be found. The corresponding 3D-point of each pixel results as intersection of the straight lines through [u, v] and the main point of the camera with the plane p (Figure 3).

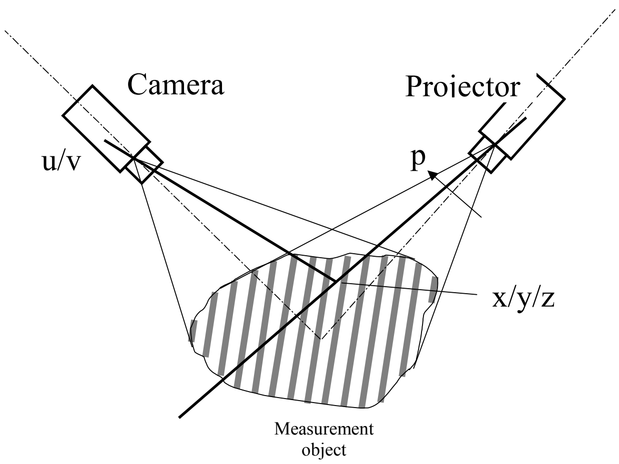

Figure 3: Measurement principle of the line projection

The sensor calibration serves to determine the parameters of the projection equations, where different physical or mathematical models can be applied. In the case discussed here, two different models have been compared:

ABW - Method:

This method, offered and implemented by the manufacturer of the projector, models the projection by means of polynomials. The model does not have a physical interpretation, it just is assumed that polynomials of sufficiently high order can adapt to the conditions of the projection. In mathematical formulation the model writes:

$$z = \sum_{i=0}^{n_u} \sum_{j=0}^{n_v} \sum_{k=0}^{n_v} a_{ijk} \cdot u^i \cdot v^j \cdot p^k \tag{3}$$

$$x = \sum_{i=0}^{n_u} \sum_{j=0}^{n_v} \sum_{k=0}^{n_z} b_{ijk} \cdot u^i \cdot v^j \cdot z^k \tag{4}$$

$$y = \sum_{i=0}^{n_u} \sum_{j=0}^{n_v} \sum_{k=0}^{n_z} c_{ijk} \cdot u^i \cdot v^j \cdot z^k \tag{5}$$

where typically $n_z = 2$ and $n_u = n_v = n_p = 4$ is used, resulting altogether in 275 coefficients.

JR-Method

This method is based on projection equations of central projection (e.g. Zhang, 1998; Reid, 1996). They describe the projection in a camera respectively a line projector by

$$s \cdot \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = A \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \tag{6}$$

respectively

$$t \cdot \begin{pmatrix} p \\ 1 \end{pmatrix} = B \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \tag{7}$$

where s and t are random scalars, which are eliminated by division after the matrix multiplication. A and B can further be divided in extrinsic and intrinsic parameters, delivering precise physical interpretations of the parameters such as special position of camera and projector, principal point and focal length. Combining (6) and (7) and solving for (x, y, z) leads to a similar system of equations:

$$r \cdot \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = C \cdot \begin{pmatrix} u \cdot p \\ v \cdot p \\ u \\ v \\ p \\ 1 \end{pmatrix} \tag{8}$$

To be determined in the calibration are the 23 parameters of the 4 x 6 matrix C (the last element can be assumed to be one without loss of generality). Since it has been discovered that the lens of the projector owns a non-negligible distortion, a radial correction of the form $dr = k * r^2$ has been added for correction of the projected pattern before the calibration step, while the camera model was left unchanged .

Results compared

First the striking difference in the number of free parameters of both models is noticeable. The high number of degrees of freedom of the ABW method raises the suspicion that the polynomials are inclined to oscillations and instabilities at the edge and in particular outside of the calibrated area. For the comparison of both procedures identical input data have been used. The calibration equipment consisted of a calibration plate with a matrix of approx. 400 ring shaped labels, which was moved by a linear unit to three different positions. The [x, y] coordinates are determined by the point matrix, the z-positions by the linear drive. For each centre of the labels the corresponding [u, v, p] values were calculated with sub-pixel accuracy. Considering the 23 coefficients of C in (8) being the unknowns to be determined in the calibration procedure, one corresponding pair of known [x, y, z] and [u, v, p] values delivers three linear equations. Thus the 1200 corresponding points deliver a highly over-determined system of equations, which is solved by least square error minimization.

Lacking an other precise calibration object the verification took place with the calibration points themselves, whereby the standard deviation of the residual errors was consulted as comparison criterion in each case. In the first comparison the ABW method resulted in a sigma of 0,11 mm, the JR method however in a sigma of 0,22 mm. A closer analysis of this result showed that the calibration plate indicated biased errors in the order of magnitude of some tenths of millimeters. The polynomials could adapt at least partially to these errors, the projective model however could not. This is nevertheless a unique case of over-fitting, thus an adaptation of a balance function to incorrect points and the obtained higher accuracy thus only a pseudo accuracy. In the next attempt the calibration target was therefore measured exactly by an external measurement device and the accurate data was taken as basis. The comparison resulted in 0,08 mm for the ABW - method and 0,07 mm for the JR method, thus approximately the same result, which means that also the polynomials could adjust to the errors of the calibration plate only partly. In order to test the behaviour of the two procedures also outside of the calibration area, for further attempts consulted were only the internal 80% of all points for the calibration, the verification however was carried out on all points. This resulted in a value of 0,16 mm for the ABW - method and 0,08 mm for the JR method, thus as expected a clearly higher stability of the projective model at the edge and outside of the calibrated area is demonstrated.

5. HAND TO SENSOR CALIBRATION

For the conversion of the measuring data into a common Cartesian coordinate system the data points must be transformed from sensor coordinates to the absolute Cartesian coordinate system with A*H. The matrix A is defined by the kinetics of the robot. These are the Denavit - Hartenberg parameters including the six joint angles J1... J6, which describe the relative positions of the robot axes to each other and thus the configuration of the robot (Gong, Yuan, Ni, 1999). The conversion of these parameters in A (forward kinetics) respectively the determination of J1... J6 out of A (reverse kinetics) is taken over by the robot controller. The determination of the position of the sensor to the robot flange (matrix H) is determined in the hand to sensor calibration. This is carried out with the help of a cube-like calibration target, which is measured by the sensor from several robot positions – one view from each of the 8 corners. By fitting the measurement result of the three visible cube-sides of one view against the model of the target, each of the 8 measurements delivers a relative orientation of the calibration target to the sensor (matrix B). Since the calibration target however remains fixed in space, A * B * H = constant must be valid for all of these measurements. Two such measurements thus allow to set up the following set of equations;

$$A_1 * H * B_1 = A_2 * H * B_2 \qquad (9)$$

$$(A_2)^{-1} * A_1 * H = H * B_2 * (B_1)^{-1} \qquad (10)$$

$$A' * H = H * B' \qquad (11)$$

Out of each two additional measurements further equations are resulting, which can be solved by means of error minimization calculation, whereby the additional constraint of the orthogonality of R (R x R. = E) inside of H has to be considered.

6. EXAMPLE

Figure 4 shows a result of the assembled measurement data from two positions of the robot.

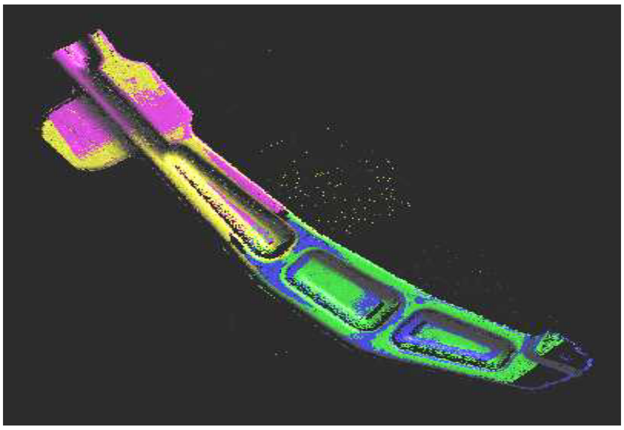

Figure 4: Measurement result assembled from several partial measurements (Courtesy of BÖHLER SCHMIEDETECHNIK GmbH & Co KG)

The four partial results (two positions, two cameras) are coded by colour, deviations in the overlapping areas lie in the range of few tenth of a millimeter.

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