

# Self-calibration technique for on-machine spindle-mounted vision systems

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**Abstract:** On-machine measuring (OMM) systems are being more and more applied in machine tools in order to measure workpieces on the machine itself. Many of these systems are directly mounted in the machine spindle, so the measuring uncertainty is affected by clamping positioning and orientation variations, especially when integrating optical systems based on machine vision. This paper presents a self-calibration technique for vision systems by using redundant information of on machine measurements, avoiding extra mechanical anchoring or calibration means. It has been applied to a vision system with the angular placement uncertainty of a tool holder coupling being the main uncertainty contributor. A milling machine pilot case has been selected for demonstration, showing an effective self-calibration capability both in laboratory and industrial conditions.

**Keywords:** Machine tool; Measuring; Uncertainty

## 1. Introduction

In the last years, due to the growth of sectors as aeronautics, energy generation, etc., an increasing need for manufacturing of large parts has been raised. This leads to new challenges regarding the design of manufacturing systems able to meet new requirements [1], including the development of new machine concepts. In addition, the efficient and effective verification of these large parts has also become a key issue.

Smaller parts are usually verified by using Coordinate Measuring Machines (CMM) when a tight measurement uncertainty is required. However, for these large parts, a large scale CMM is seldom available. Besides, taking the part out of the machine tool, preparing it at the CMM and correcting the possible errors back in the machine tool is a very time consuming process. Optical measurement systems such as laser trackers are an alternative in this case [2]. However, the resulting uncertainty, the cost of the system, the measurement time and the accessibility to the part are still an issue.

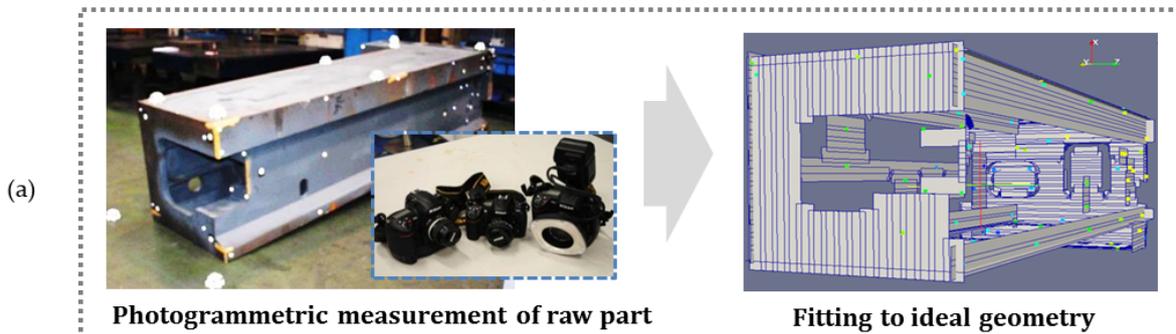
For these reasons the use of dimensional measurement systems directly integrated in the machine tool; i.e., on machine measurement (OMM) systems for the part [3]; is a relatively recent technology that helps to avoid most of the mentioned problems. These systems allow the integration of manufacturing and verification under the same boundary conditions, which speeds up the process at a relatively low cost.

However, it should be borne in mind that OMM cannot identify all the possible errors of large parts, since systematic errors of the machine itself will cause the repetition of the machining error during the verification process, and will not be detected [4]. The most influential errors in large machines are the static errors [5, 6] together with the thermo-mechanical errors [7]. This makes their compensation a key factor in large machines in order to obtain the required accuracy. In this context, an on-machine verification system allows both the detection of tool wearing effects and thermal and inertial deformations of the part caused by the large masses and machining time needed. In addition, on machine measurement allows a quick and more frequent dimensional verification of the workpiece and an immediate correction of the errors found, decreasing the probability of dismissing these very expensive parts.

47 Among the systems used for on machine verification of parts, touch probing is one of the most  
 48 classic ones [5, 8]. On the other hand, optical inspection based on cameras is becoming more and  
 49 more frequent due to its measurement speed and its more and more improved measurement  
 50 uncertainty [3]. For the case of touch probing, the system is not sensitive to errors in location of the  
 51 probe on the headstock, as long as rotational axes are not used during the inspection [9, 10]. On the  
 52 contrary, optical measurement based on cameras mounted directly in the spindle always needs a  
 53 good knowledge of the situation and orientation of the measuring systems. For that, the calibration  
 54 of the system is almost unavoidable. A possible solution to avoid it is the use of on purpose  
 55 developed interfaces between the optical probe and the machine spindle, which can be very  
 56 repetitive. However, most of the times, the tool holder itself (ISO, HSK ... taper) is directly used for it  
 57 due to the simplicity and availability of that solution.

58 It is well known that the most classic taper solutions (ISO, BTS ...) are prone to location errors,  
 59 especially when they have been used for some time and may present some wear [11]. The HSK taper  
 60 was developed to avoid some issues found with the classical tapers, mainly with high speed  
 61 interface deformation in mind, but at the same time obtaining much better static repeatability results  
 62 [12]. However, the angular orientation of the tool, or of the OMM system in this case, with respect to  
 63 the spindle axis (C-axis) may present high uncertainties – in the order of several degrees – due to the  
 64 backlashes of the kinematic chain from the motor to the main spindle [13]. This angular error makes  
 65 necessary the calibration of the optical system even when HSK tapers are being used. In order to  
 66 compensate for such clamping uncertainty, recent developments appeared in the market for 6D  
 67 on-machine calibration of OMMs in machine tool and robotic applications [14] by using infrared  
 68 sensors but with limitations in the field of work and not directly attached to the spindle.  
 69

### Out-of-machine



Optimal raw part location and orientation  
(ideal par frame,  $Op$ )

### On-machine



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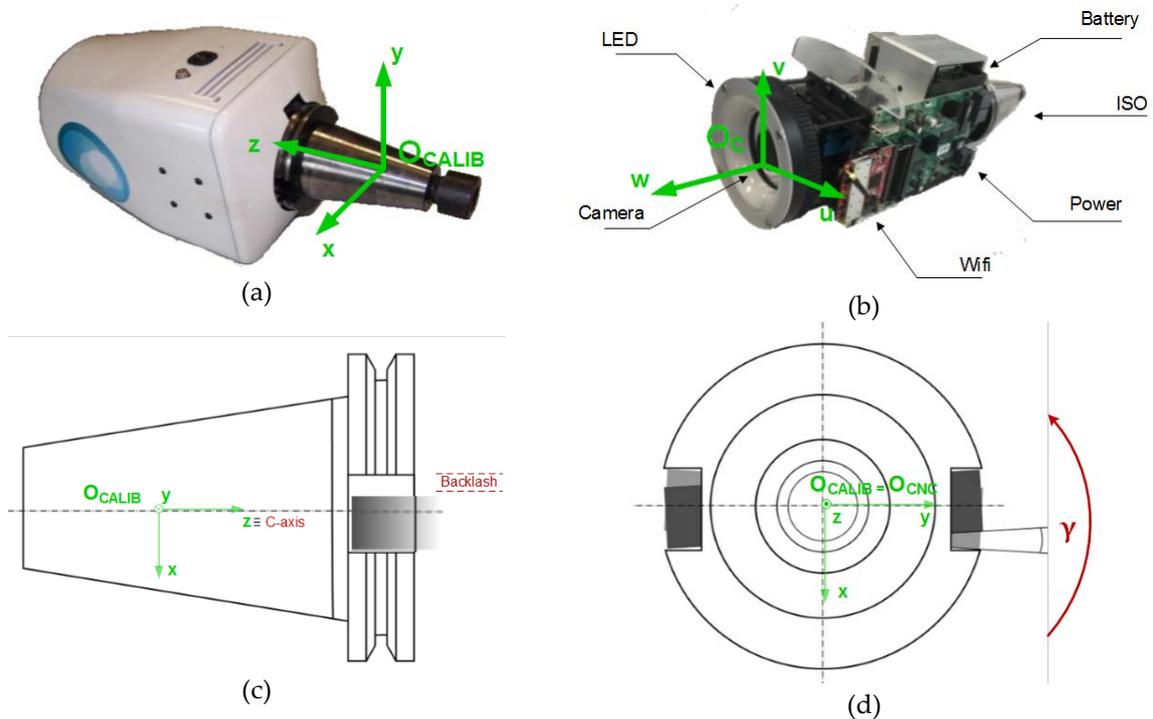
71 **Figure 1.** Vision OMM system for raw part alignment in milling. (a) Out-of-machine raw part  
 72 measurement by portable photogrammetry and fitting to ideal CAD geometry. (b) On machine  
 73 stereo-photogrammetric vision system for raw part location and orientation measurement.

74 The development shown in this paper is a step forward for precise operation of on machine  
 75 measuring systems based on machine vision. It has been applied to a portable vision OMM system  
 76 for the alignment of large raw parts in milling machines (Figure 1), coupled by an ISO taper into the

77 milling machine spindle (Figure 2). A self-calibration technique is presented by using redundant  
 78 information of on-machine measurements of the part by machine vision. A similar problem has been  
 79 addressed in previous works for different applications of active vision systems such those mounted  
 80 on robots [15,16], unmanned aerial vehicles [17,18], augmented reality [19], etc. The technique here  
 81 presented has been specifically optimized for a machine-tool application. Hence, the proposed  
 82 self-calibration method is based on redundant information given by a set of multiple camera views  
 83 taken by the OMM on the raw part from known CNC machine coordinates. It allows the  
 84 compensation of the coupling orientation error around the C-axis, which is the most important error  
 85 source in the location of the OMM system in the machine. This avoids extra mechanical anchoring or  
 86 calibration means for its precise operation every time the optical system is coupled into the spindle.

87 The vision OMM system is introduced under the scope of the raw part alignment solution in  
 88 Section 2. In Section 3 the measuring geometry of the OMM is described. Eventually, in Section 4, the  
 89 experimental validation on industrial applications and the repeatability results are presented  
 90 demonstrating its self-calibration capability.

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92

93 **Figure 2.** Portable OMM vision system with ISO coupling and positioning backlash  $\gamma_s$  around the  
 94 spindle C-axis. (a) Reference system of the vision OMM system,  $O_{CALIB}$ , joined to the taper. (b)

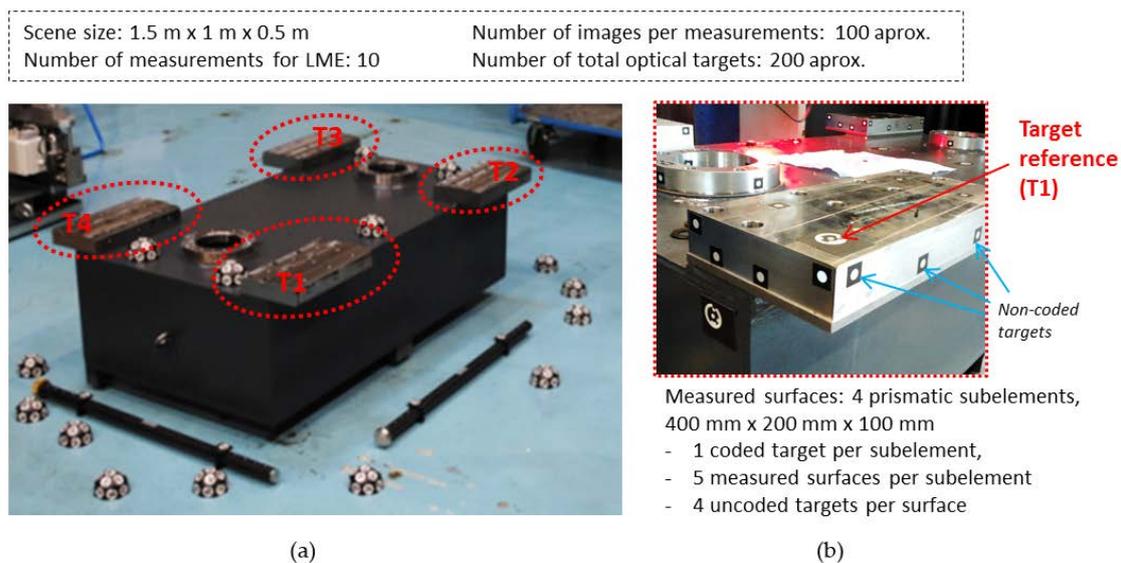
95 Camera reference frame,  $O_C$ , placed at the principal point. (c) Detail of the OMM system reference  
 96 frame on the taper. (d) Schematic view of the coupling backlash,  $\gamma_s$ , between the OMM system frame  
 97 and the spindle frame,  $O_{CNC}$ .

## 98 2. Materials and Methods

99 Large raw parts require a time consuming in machine alignment process prior to the machining  
 100 itself. With the aim of reducing it, a solution was developed in a previous work [3] based on two  
 101 machine vision systems: the first one for the raw part characterization, by means of out-of-machine  
 102 photogrammetry; and the second one, the pilot case under study in this paper (Figure 1); i.e., an  
 103 OMM system to determine the raw part location and orientation with a milling-machine  
 104 spindle-integrated portable vision system. Initially, with the out-of-machine photogrammetric  
 105 system (Figure 1a), the raw part is measured by using retroreflective coded and non-coded optical  
 106 targets. Images are taken around the part (a Nikon D300S, 3Mpixel, 24 mm camera is used) and the  
 107 photogrammetry system calculates target 3D coordinates. Non-coded targets are used to measure

108 the raw part surfaces. Coded targets are properly located as later references for the second system,  
109 the on-machine vision system.

110 Non-coded targets characterizing raw part surfaces are then fitted to the ideal part surfaces to  
111 be obtained after machining. The ideal geometry and the fitting reference frame are given by a CAD  
112 file (Figure 1a). Fitting algorithms play an important role in coordinate metrology [20-22]. In this  
113 work, positive and even overstock distribution is assumed as the fitting criteria [3]. As a result, the  
114 measuring frame is properly aligned to the ideal part frame, and corresponding 3D optimal  
115 coordinates of the coded references are determined in the ideal part frame. Once the optimum raw  
116 part setup is determined, the on-machine measuring system proceeds (Figure 1b). A single camera  
117 stereo-photogrammetric OMM solution (Imaging Source DMK 23GP031, 5Mpixel, 2592 × 1944  
118 format, 2.2 μm pixel size, 6 mm focal distance) is adopted for measuring the reference targets (Figure  
119 2a), determining the ideal part frame location and orientation with respect to the machine frame. If  
120 large deviations are observed, fixturing corrections are performed in order to properly align the raw  
121 part prior to its machining. The portable vision system is installed in the milling machine spindle by  
122 an ISO50 coupling (DIN 69871). Figure 2b shows a schematic view of the evaluated coupling  
123 backlash around the spindle C-axis. For the pilot case under study, orientation backlash ranged at  
124 6.15 mm/m (0.35 deg) according to nominal coordinates. As a result, every time the portable system  
125 was installed into the spindle, a time-consuming calibration procedure was required in the machine  
126 in order to compensate for coupling variations and enabling precise on-machine measuring.  
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128  
129 **Figure 3.** Reference part for the OMM system self-calibration evaluation. (a) Out-of-machine  
130 measurement of 4 prismatic sub-elements (T1 to T4) on the test part, showing scale bars and auxiliary  
131 coded targets for portable photogrammetry. (b) T1 prismatic sub-element showing both non coded  
132 targets in milled surfaces for evaluation and a reference coded target for on-machine part alignment.

133 In order to overcome this limitation, a self-calibration approach has been developed based on  
134 stereo-photogrammetry. A redundant measuring strategy of reference targets with known 3D  
135 optimal coordinates ( $X_i$  given by portable photogrammetry, see Section 3.2) is conducted from a set  
136 of images taken from known CNC machine spindle location and orientations ( $d_{cnc}$  and  $R_{cnc}$  in  
137 Section 3.3), enabling the simultaneous resolution of the raw part location and orientation ( $d_p$  and  
138  $R_p$  in Section 3.2) in machine coordinates, along with the C-axis coupling orientation,  $\gamma_s$ , of the  
139 vision system.

140 A test part has been used in order to evaluate the performance of the developed self-calibration  
141 approach. It is formed by four prismatic steel sub-elements screwed to a mechano-welded structure  
142 and milled to a nominal geometry (Figure 3). Reference targets were placed at the corner of each  
143 prismatic sub-element, to a total of 4 targets (T1 to T4). Part geometry given by optical target 3D  
144 coordinates was measured by photogrammetry and fitted to the nominal CAD geometry. The test

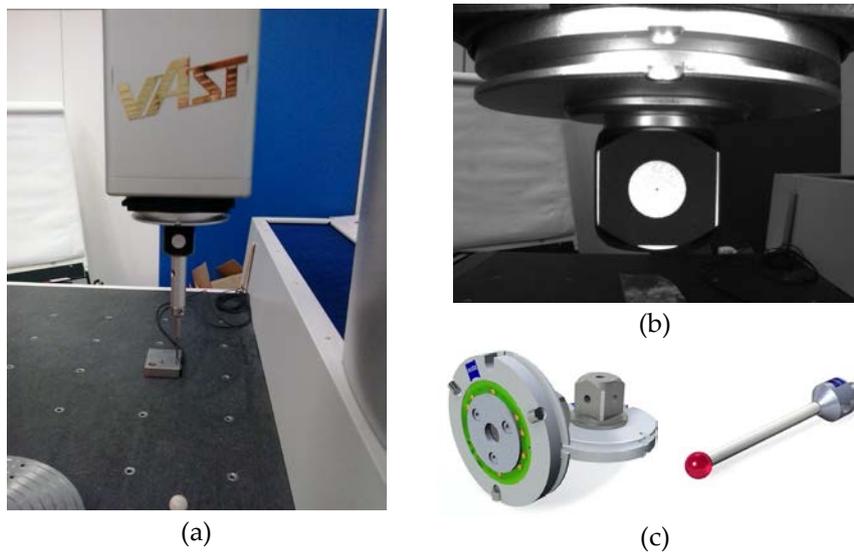
145 part was then located at a milling-machine and properly aligned to the machine axes to set it as the  
146 OMM performance evaluation reference.

147 In Section 3.1 the initial OMM calibration procedure performed in a CMM, needed only the first  
148 time the camera is going to be used and no longer required every time the OMM is clamped into the  
149 machine, is presented. Section 3.2 describes the on-machine multiple view geometry of the vision  
150 system used to solve the raw part location and orientation (6D) by stereo-photogrammetry,  
151 demonstrating the relevant influence of clamping backlash into test part measurement results.  
152 Accordingly, Section 3.3 describes how the self-calibration of the tool holder clamping error is  
153 integrated into the measuring chain (7D), enabling precise measurement of clamping backlash angle  
154 ( $\gamma_s$ ) along with raw part 6D. Section 4 presents the resulting joint uncertainty performance for the  
155 whole system, including both out-of-machine and on-machine vision systems for raw part  
156 alignment, along with evaluation results in an industrial scenario. Finally, Section 5 brings main  
157 conclusions of the presented work.

### 158 3. Machine Vision OMM for raw part alignment

#### 159 3.1. OMM calibration

160 A similar concept to Lu et.al [23] was adopted in the milling machine for calibrating the OMM  
161 system camera model extrinsic parameters ( $O_c$  camera principal frame) into the ISO taper reference  
162 frame used ( $O_{CALIB}$ ), along with camera intrinsic parameters given by the focal distance and lens  
163 distortion model according to Brown [24]. Although the process provided precise calibration every  
164 time the system was clamped into the spindle to compensate for the taper coupling uncertainty, the  
165 process lasted up to 1 hour, limiting the industrial usability of the solution. Moreover, the calibration  
166 is affected by the precision of the machine. This makes errors to be propagated in the calibration and  
167 consequently to the measurement. In order to overcome the accuracy and time limitations, the  
168 process has been taken out of the machine and a Zeiss Prismo Navigator CMM is used instead. Both  
169 extrinsic and intrinsic camera parameters are solved simultaneously and the calibration is  
170 performed only once, independently of the machine to be used.  
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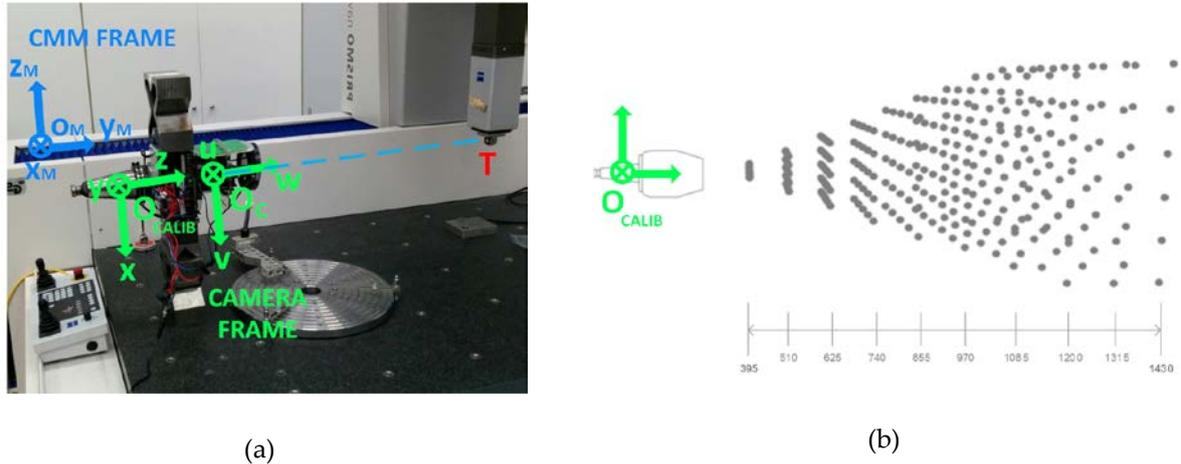


172 **Figure 4.** (a) ZEISS Prismo CMM probe head with integrated precalibrated cubic tip. (b)  
173 Retroreflective target on a surface of the tip. (c) Schematic view of the precalibrated tip and the  
174 adapter plate used (Courtesy of © Carl Zeiss).

175 The calibration process is based on generating a pyramidal grid structure where a single  
176 retroreflective target is captured in different images from different points of view. For this purpose,  
177 the CMM integrated target (Figure 4) is placed at different predefined spatial positions relative to the  
178 OMM reference frame ( $O_{CALIB}$ ) (Figure 5), which is properly probed to be referenced with respect to

179 the CMM frame ( $O_{CMM}$ ). The system is solved through a set of 2D image points and their  
 180 corresponding known 3D positions in the CMM frame ( $O_{CMM}$ ), following the same multivariable  
 181 optimization strategy as for the reprojection problem described in Sections 3.2 and 3.3.

182 The target is precalibrated to the tip frame using a ZEISS O-Inspect optical CMM. This  
 183 precalibration aims to know the 3D offset between the tip probe and the center of the target, so that a  
 184 pre-defined calibration grid can be programmed at the CMM frame (Figure 5b) with an uncertainty  
 185 ranging 0.001 mm all over the calibration grid volume.  
 186



187 **Figure 5.** OMM calibration in a CMM. (a) Calibration layout into a Zeiss Prismo CMM. (b)  
 188 Calibration grid with respect to the OMM frame at taper ( $O_{CALIB}$ ).

189 Calibration grid consists of planar dense point grids located at equidistant 10 positions along  
 190 camera main axis, from a minimum distance of 395 mm to a maximum of 1430 mm (Figure 5b). As a  
 191 result of all the above, the obtained calibration results are shown in Table 1:  
 192

193 **Table 1.** Camera calibration: extrinsic and intrinsic parameters.

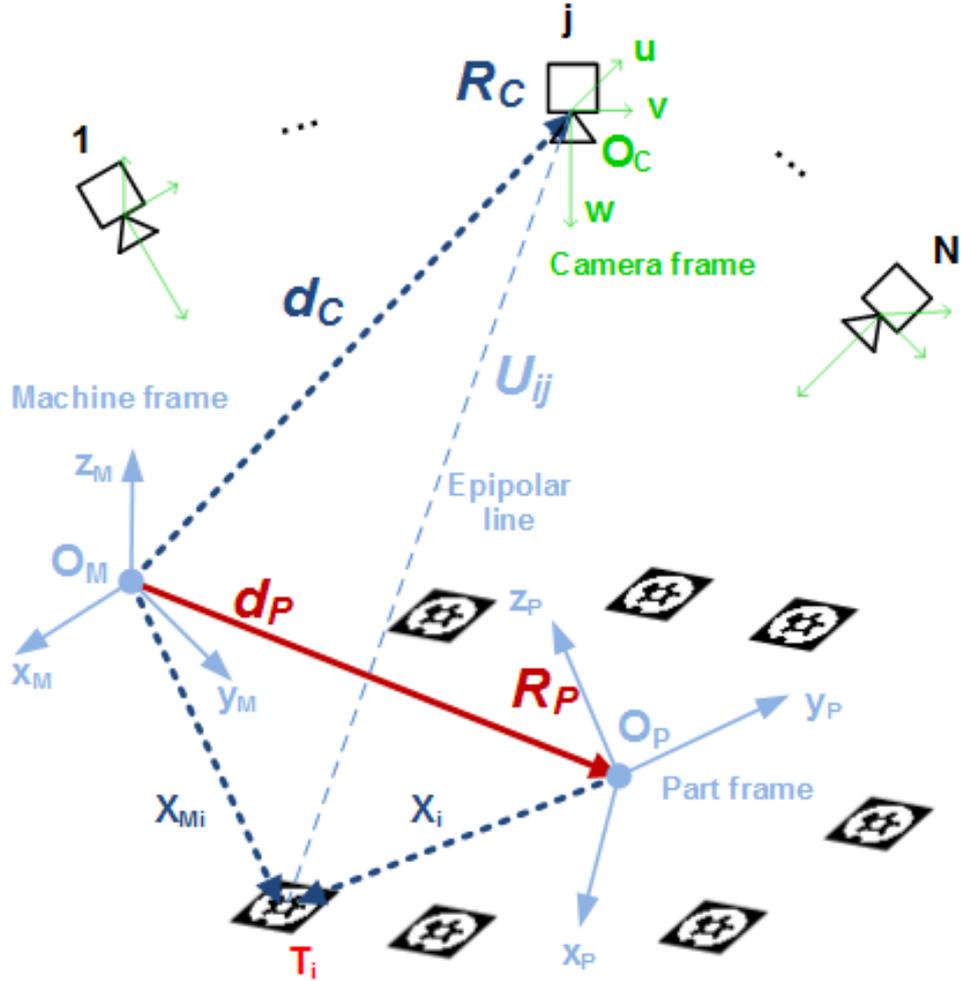
	$f$ (mm)	$cl_0$ (pixel)	$rw_0$ (pixel)	$k_1$ ( $pixel^{-2}$ )	$k_2$ ( $pixel^{-4}$ )	$\pi_1$ ( $pixel^{-1}$ )	$\pi_2$ ( $pixel^{-1}$ )
<b>Intrinsic parameters</b>	6.189	-8.732	27.52	2.997e-08	-1.937e-15	-6.188e-08	3.408e-07
	$d_x$ (mm)	$d_y$ (mm)	$d_z$ (mm)	$\alpha$ (rad)	$\beta$ (rad)	$\gamma$ (rad)	
<b>Extrinsic parameters</b>	-2.139	0.301	-3.203e+02	-0.003	-0.009	0.03	

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Being  $f$  the focal distance of the pin-hole projection model of the camera,  $k_1$  and  $k_2$  the radial distortion coefficients,  $\pi_1$  and  $\pi_2$  the tangential distortion coefficients,  $cl_0$  and  $rw_0$  the principal point decentering at the image plane,  $d_x$ ,  $d_y$  and  $d_z$  the 3D camera frame coordinates to the taper frame, and  $\alpha$ ,  $\beta$  and  $\gamma$  the Euler angles of the camera frame to the taper frame.

### 201 3.2. OMM by stereo-photogrammetry

202 Once the camera has been calibrated it can be attached to the spindle to carry out the  
 203 on-machine measurement of the workpiece. Figure 6 shows the multiple view geometry of the  
 204 on-machine vision system for measuring part location and orientation. It is defined as the translation  
 205 ( $d_p$ ) and rotation ( $R_p$ ) of the ideal part frame ( $O_p$ ) with respect to machine frame ( $O_m$ ). Raw part  
 206 geometry is defined by the 3D coordinates ( $X$ ) of reference coded targets obtained by the out of  
 207 machine photogrammetry and fitting, expressed at the ideal part frame ( $O_p$ ).  
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**Figure 6.** Measuring geometry of the OMM vision system by stereo-photogrammetry. A set of epipolar lines  $U_{ij}$  given by detected  $T_i$  targets on images with known points of view ( $d_C$  and orientations  $R_C$  camera extrinsic) at machine frame enables on machine raw part location and orientation (6D) measurement ( $d_P$  and  $R_P$ ).

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The process consists in solving the base where the point cloud with known  $X_i$  coordinates is located with respect to the machine system  $X_{M_i}$  points.

$$X_{M_i} = R_P X_i + d_P \quad (1)$$

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where the rotation matrix  $R_P$  is composed by the multiplication of the 3 elementary rotation matrices through the so-called Euler angles  $\alpha_p$ ,  $\beta_p$  and  $\gamma_p$ . This transformation follows the x, y and z rotation sequence

$$R_P = R_\gamma R_\beta R_\alpha \quad (2)$$

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On-machine measurement is conducted by taking a set of images to a set of reference targets ( $T_i$ ), each image taken from different CNC positions ( $d_C$ ) and orientations ( $R_C$ ). Each reference target ( $X_i$ ) observed in an image ( $O_{C_j}$ ) defines a so called epipolar line, that is to say, the direction at which that reference target lies in machine frame coordinates ( $X_{M_i}$ ). With a minimum set of 3 linearly independent epipolar lines over a set of different reference targets, part location and orientation can be determined.

According to Equation (1), for a specific camera location ( $d_C$ ) and orientation ( $R_C$ ), target coordinates ( $X_i$ ) can be expressed into each camera frame ( $O_{C_j}$ ) as:

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$$\begin{aligned} X_{M_i} &= R_C U_{ij} + d_C \\ U_{ij} &= R_C^T (X_{M_i} - d_C) \end{aligned} \quad (3)$$

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This way, the former equations are combined into a single one as

234

$$U_{ij} = R_C^T (R_P X_i + d_P - d_C) \quad (4)$$

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Each target 3D coordinate  $U_{ij}$  can be then projected into the corresponding camera 2D image plane as  $p_{ij}$  and  $q_{ij}$  coordinates (Figure 7), following the widely assumed pin-hole model in machine vision [25] as:

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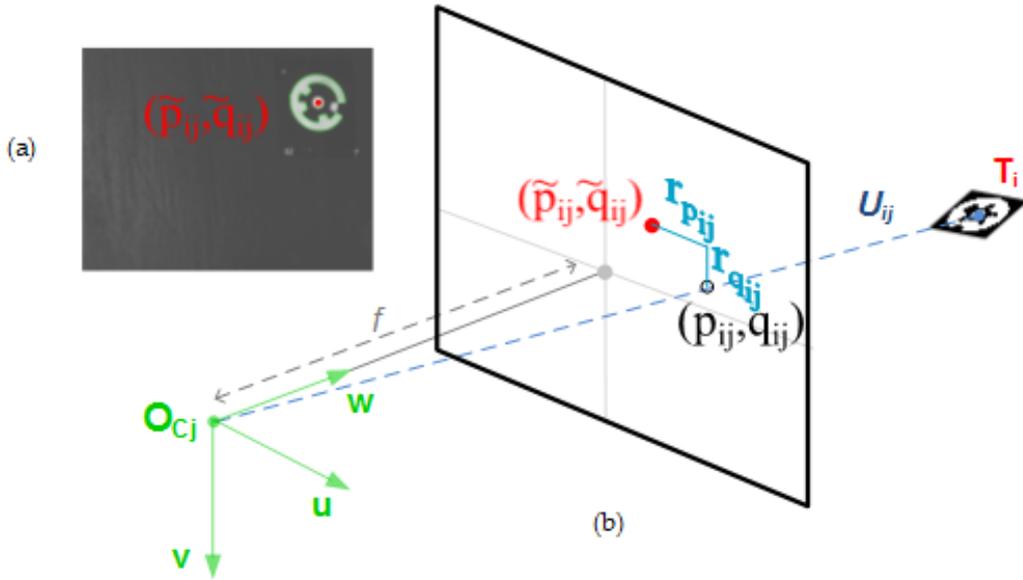
$$\begin{bmatrix} p_{ij} \\ q_{ij} \end{bmatrix} = f \begin{bmatrix} u_{ij}/w_{ij} \\ v_{ij}/w_{ij} \end{bmatrix} \quad (5)$$

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where  $U_{ij} = [u_{ij} \ v_{ij} \ w_{ij}]^T$  and being  $f$  the focal distance of the camera lens.



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**Figure 7.** Target 2D detection and conic projection. (a) Example of reference target coordinate detection ( $\tilde{p}_{ij}$  and  $\tilde{q}_{ij}$ ) at image plane. (b) Conic projection ( $p_{ij}$  and  $q_{ij}$ ) into image plane of the 3D coordinate  $X_{ij}$  corresponding to  $T_i$  optical target, with the corresponding projection error contribution ( $r_{p_{ij}}$  and  $r_{q_{ij}}$ ) to the joint residual minimization problem.

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Residual errors  $r_{p_{ij}}$  and  $r_{q_{ij}}$  can be then defined for every target observed at an image (Figure 7) as the difference between detected target coordinates  $\tilde{p}_{ij}$  and  $\tilde{q}_{ij}$  and projected target coordinates  $p_{ij}$  and  $q_{ij}$ , which directly depend on the part location ( $d_P$ ) and orientation ( $R_P$ ) to be solved. A single joint residual vector  $\vec{r}$  can be defined with the residuals  $r_{p_{ij}}$  and  $r_{q_{ij}}$  corresponding to the complete set of images of the on machine measurement according to the following structure:

255

$$\vec{r} = \begin{bmatrix} r_1 \\ \vdots \\ r_N \end{bmatrix} \quad (6)$$

256 where each  $r_j$  vector contains the residual vectors of the error-projection for the detected  
 257 markers ( $m = \sum_{j=1}^N m_j$ ) in the  $j$  photograph:  
 258

$$r_j = \begin{bmatrix} r_{p_{1j}} \\ r_{q_{1j}} \\ \vdots \\ r_{p_{ij}} \\ r_{q_{ij}} \\ \vdots \\ r_{p_{mj}} \\ r_{q_{mj}} \end{bmatrix} = \begin{bmatrix} p_{1j} - \widetilde{p}_{1j} \\ q_{1j} - \widetilde{q}_{1j} \\ \vdots \\ p_{ij} - \widetilde{p}_{ij} \\ q_{ij} - \widetilde{q}_{ij} \\ \vdots \\ p_{mj} - \widetilde{p}_{mj} \\ q_{mj} - \widetilde{q}_{mj} \end{bmatrix} \quad (7)$$

259  
 260 In order to define the residual minimization problem, it is necessary to group all the parameters  
 261 into a  $\theta$  vector. In short, there are 6 parameters to solve

$$\theta = [\alpha_p \ \beta_p \ \gamma_p \ X_p \ Y_p \ Z_p]^T \quad (8)$$

262  
 263 The process is essentially the calculation of the optimal vector of parameters  $\hat{\theta}$  which  
 264 minimizes the objective function:  
 265

$$\hat{\theta} = \arg \min_{\theta} \frac{1}{N} \|\tilde{r}\|^2 \quad (9)$$

266  
 267 The resolution is defined as the non-linear optimization problem solved by the Gauss-Newton  
 268 method [26] which minimizes the residual vector  $\|\tilde{r}\|^2$  norm. These resolution methods are based  
 269 on a first-order Taylor approximation of the objective function around a given point of the  
 270 parameters vector  $\hat{\theta}$ . It is assumed that a small increase of the parameter vector  $\Delta_{\theta}$  produces a  
 271 change in the residual vector that can be well estimated by a lineal approximation as following  
 272

$$r(\theta + \Delta_{\theta}) = r(\theta) + J(\theta)\Delta_{\theta} + \theta(\Delta_{\theta}) \quad (10)$$

273  
 274 The Jacobian  $J$  matrix contains the partial derivatives of each component of the residual vector  
 275 respect to the parameters to optimize  
 276

$$J(\theta) = \begin{bmatrix} \frac{\partial r_1}{\partial \theta_1} & \dots & \frac{\partial r_1}{\partial \theta_6} \\ \vdots & \dots & \vdots \\ \frac{\partial r_N}{\partial \theta_1} & \dots & \frac{\partial r_N}{\partial \theta_6} \end{bmatrix} \quad (11)$$

277  
 278 If all the columns of  $J$  are linearly independent, the Hessian matrix will be definite positive and,  
 279 therefore, the  $L(\Delta_{\theta})$  will have a unique global minimum obtained from  
 280

$$J^T J \Delta_{\theta} = -J^T r \quad (12)$$

281  
 282 The core of the Gauss-Newton method is the resolution of the former equation, which is in fact,  
 283 the system of Gauss's normal equations. For each iteration, the resolution of the system is followed  
 284 by an update of the vector of parameters  
 285

$$\theta \leftarrow \theta + \Delta_{\theta} \quad (13)$$

286  
 287 Based there on, part location ( $d_p$ ) and orientation ( $R_p$ ) is defined as the non-linear optimization  
 288 problem. Likewise,  $J$  matrix is composed by each  $J_j$  jacobian of each image.  
 289

$$J_{2m \times 6} = \begin{bmatrix} J_1 \\ \vdots \\ J_N \end{bmatrix} \quad (14)$$

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where  $J_j$  contains the partial derivatives of the projection parameters respect to the  $\alpha$ ,  $\beta$  and  $\gamma$  rotation angles:

$$(J_j)_{2 \times 6} = D_P D_{U_P} \quad (15)$$

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$D_P$  contains the derivatives respect to the projection parameters of each point in the image (see Equation (5))

$$(D_P)_{2 \times 3} = f \begin{bmatrix} 1 & 0 & -\frac{u_{ij}}{w_{ij}^2} \\ \frac{1}{w_{ij}} & 0 & \frac{-v_{ij}}{w_{ij}^2} \\ 0 & \frac{1}{w_{ij}} & \frac{-v_{ij}}{w_{ij}^2} \end{bmatrix} \quad (16)$$

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and  $D_{U_P}$  refers to the partial derivatives from Equation (4) respect to  $\alpha$ ,  $\beta$  and  $\gamma$  rotation angles.

$$(D_{U_P})_{3 \times 6} = R_C^T [D_A X_i \quad D_B X_i \quad D_C X_i \quad I_{3 \times 3}] \quad (17)$$

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where  $D_A$  is the partial derivative respect to  $\alpha$  rotation angle,

$$D_A = \frac{\partial R_P}{\partial \alpha} = R_\gamma R_\beta \frac{dR_\alpha}{d\alpha} \quad (18)$$

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$D_B$  respect to  $\beta$  rotation angle,

$$D_B = \frac{\partial R_P}{\partial \beta} = R_\gamma \frac{dR_\beta}{d\beta} R_\alpha \quad (19)$$

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and  $D_C$  respect to  $\gamma$  rotation angle.

$$D_C = \frac{\partial R_P}{\partial \gamma} = \frac{dR_\gamma}{d\gamma} R_\beta R_\alpha \quad (20)$$

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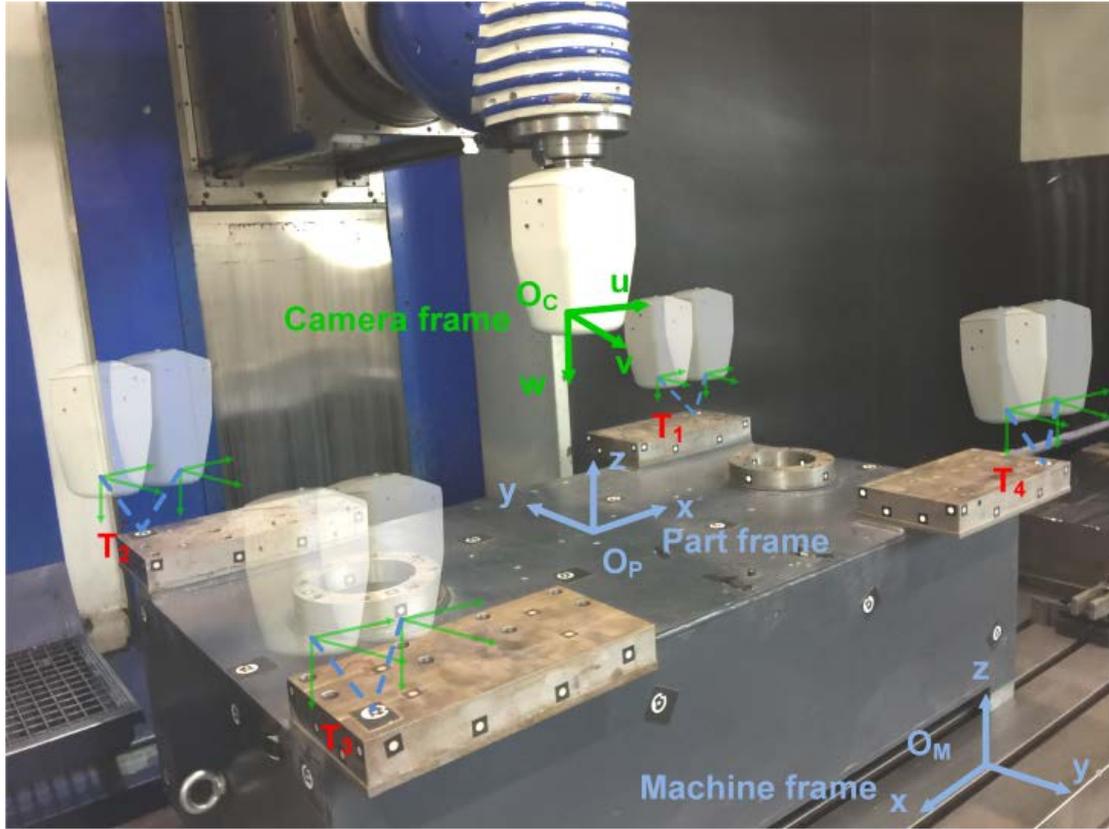
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As introduced in Section 2, a test part was then taken into a milling machine and properly aligned to be used as a precise reference object for the vision OMM performance evaluation (Figure 8). A spindle integrated contact probe was used in the machine as a reference for aligning the test part to the machine frame. Once the test part was aligned, a set of 10 consecutive measurements was performed by the vision OMM (Figure 8), at a measuring distance of 300 mm to each reference target, including system clamping-unclamping between each measurement set, with 2 images per target, to a total of 8 redundant images per set in order to solve part location and orientation (6D).



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**Figure 8.** Testing scenario for the vision OMM self-calibration. Schematic view of the stereo-photogrammetric layout, with 2 images taken at each reference target placed at the XY plane, with the OMM measuring direction being Z axis.

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Table 2 summarizes the repeatability results obtained for each measuring variable, having a common and constant OMM system calibration (see Table 1) and assuming that there is no misalignment between the OMM calibration frame ( $O_{CALIB}$ ) and the spindle frame ( $O_{CNC}$ ), given a constant  $\gamma_s = 0.0$  mm/m for all measurements. As expected, without a specific calibration every time the vision OMM system is clamped,  $X_p$  and  $Y_p$  machine coordinates (forming a perpendicular plane to C-axis, parallel to  $Z_p$  axis), and  $\gamma_p$  coordinate (twist around  $Z_p$  axis) are directly affected by the coupling uncertainty around C-Axis ( $\gamma_s$ ), ranging above 0.05 mm and 0.05 mm/m, respectively.

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**Table 2.** Measurement repeatability  $\sigma(k = 2)$  for part location ( $X_p$ ,  $Y_p$ ,  $Z_p$  in mm) and orientation ( $R_p$  rotation matrix expressed by Euler angles  $\alpha_p$ ,  $\beta_p$ ,  $\gamma_p$ , in mm/m).

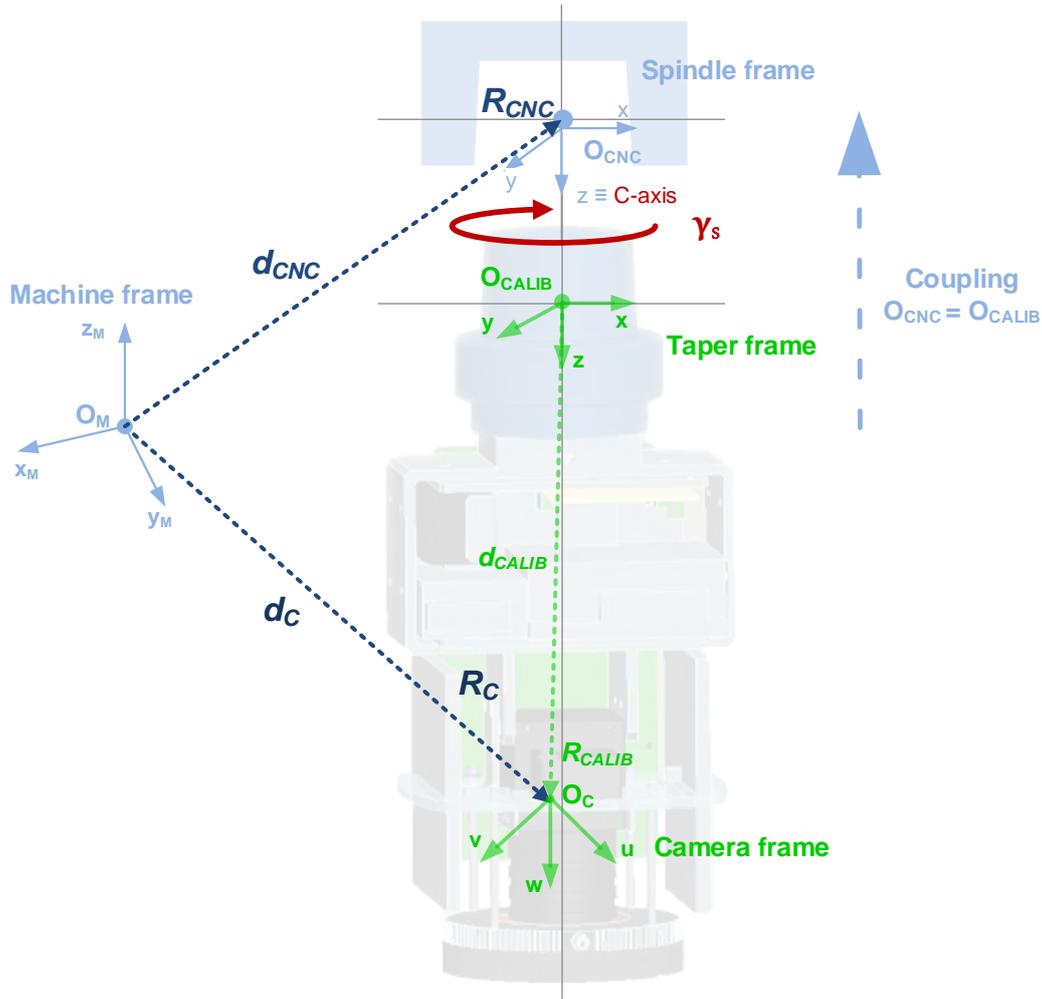
	$X_p$	$Y_p$	$Z_p$	$\alpha_p$	$\beta_p$	$\gamma_p$
6D	0.136	0.056	0.026	0.039	0.056	0.070

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### 334 3.3. Clamping self-calibration

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In order to include self-calibration capabilities to the portable OMM vision system, coupling errors to be compensated have to be properly included into the measuring chain. Figure 9 shows the adopted geometry for considering the coupling positioning uncertainty around the C-axis ( $\gamma_s$ ) for the ISO taper interface into the milling machine spindle.



340

341 **Figure 9.** Coupling geometry of the vision OMM system, showing the complete chain for expressing  
 342 camera extrinsic ( $d_C$  and  $R_C$ ) at machine frame, given by spindle location and orientation by  
 343 machine CNC ( $d_{CNC}$  and  $R_{CNC}$ ), OMM calibration to taper joined frame ( $d_{CALIB}$  and  $R_{CALIB}$ ), and  
 344 coupling positioning ( $\gamma_s$  angle between spindle and OMM frame z axes).

345 Vision OMM geometry is defined as the camera frame ( $O_C$ ) location ( $d_{calib}$ ) and orientation  
 346 ( $R_{calib}$ ), obtained during on machine calibration. An error  $\gamma_s$  is defined as the coupling orientation  
 347 difference between the OMM positioning during calibration and during the actual measuring  
 348 process. As a result, camera frame position ( $d_C$ ) and orientations ( $R_C$ ) can be expressed as:

349

$$\begin{aligned} d_C &= R_{CNC} R_S d_{CALIB} + d_{CNC} \\ R_C &= R_{CNC} R_S R_{CALIB} \end{aligned} \quad (21)$$

350

351 being  $d_{cnc}$  and  $R_{cnc}$  the CNC programmed spindle position and orientation for each image,  
 352 respectively. And  $R_S$  consist in a rotation matrix where the  $\gamma_s$  is only taken into account:

353

$$R_S(\gamma_s) = \begin{bmatrix} \cos(\gamma_s) & \sin(\gamma_s) & 0 \\ -\sin(\gamma_s) & \cos(\gamma_s) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (22)$$

354

355 Accordingly, residual projection vector  $\vec{r}$  can be expressed dependant to the  $\gamma_s$  and included  
 356 in the minimization problem. Therefore, in this case  $\theta$  vector is composed by 7 parameters.

357

$$\theta = [\alpha_p \ \beta_p \ \gamma_p \ X_p \ Y_p \ Z_p \ \gamma_s]^T \quad (23)$$

358

359

Consequently, the Jacobian matrix  $J$  from Equation (14) has a new column

360

$$J_{2m \times 7} = \begin{bmatrix} J_1 \\ \vdots \\ J_N \end{bmatrix} \quad (24)$$

361

because each  $J_j$  from Equation (15) contains the partial derivatives which correspond to the spindle  $\gamma$  rotation angle.

362

363

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In short,  $J_j$  is redefined as  $J_s$  which includes the new column for spindle angle:

365

$$(J_s)_{2 \times 7} = D_p D_{U_s} \quad (25)$$

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The partial derivatives respect to the projection parameters are not affected by the inclusion of this new term, so  $D_p$  remains constant. Furthermore, since the  $U_{ij}$  is modified, its partial derivatives are declared as follows

$$(D_{U_s})_{3 \times 7} = (R_{CNC} D_s R_{Calib})^T [X_i - (R_{CNC} R_s d_{Calib} + d_{CNC})] - (R_{CNC} R_s R_{Calib})^T (R_{CNC} D_s d_{Calib}) \quad (26)$$

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374

where  $D_s$  contains the partial derivatives associated to the  $R_s$  rotation matrix with respect to the spindle  $\gamma$  rotation angle:

$$(D_s(\gamma_s))_{3 \times 3} = \begin{bmatrix} -\sin(\gamma_s) & \cos(\gamma_s) & 0 \\ -\cos(\gamma_s) & -\sin(\gamma_s) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (27)$$

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As a result, OMM calibration ( $d_{Calib}$ ,  $R_{Calib}$ ) is no longer required every time it is mounted into the spindle, and self-calibration can be accomplished along with determining part location ( $d_p$ ) and orientation ( $R_p$ ) if redundant measurement is conducted.

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**Table 3.** Measurement repeatability  $\sigma(k = 2)$  for part location ( $X_p$ ,  $Y_p$ ,  $Z_p$  in mm) and orientation ( $\alpha_p$ ,  $\beta_p$ ,  $\gamma_p$ , in mm/m), along with coupling positioning angle ( $\gamma_s$ , in mm/m).

	$X_p$	$Y_p$	$Z_p$	$\alpha_p$	$\beta_p$	$\gamma_p$	$\gamma_s$
6D	0.136	0.056	0.026	0.039	0.056	0.070	---
7D	0.032	0.030	0.020	0.028	0.024	0.010	3.840
Factor	4.2	1.9	1.3	1.4	2.3	7.0	---

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Table 3 summarizes the repeatability results obtained for each measuring variable in the testing scenario, comparing the results obtained with and without self-calibration (7D and 6D, respectively). With the self-calibration of coupling positioning uncertainty around the C-axis ( $\gamma_s$ ), all measured values lay at a better and even repeatability figures, ranging below 0.04 mm and 0.03 mm/m for part position and orientation measurement, respectively. Indeed, a coupling positioning repeatability of 3.84 mm/m  $\sigma(k = 2)$  is measured and compensated for. Assuming a uniform distribution to the

389 C-axis positioning stochastic process, it would correspond to a backlash of 6.65 mm/m given by  
 390  $\sqrt{3} \sigma (k = 2)$ , close to the expected nominal value of 6,15 mm/m (see Section 2).

#### 391 4. Uncertainty estimation for the whole system

392 Once the repeatability of the on-machine system has been evaluated and improved thanks to  
 393 the self-calibration process presented (case 7D in Table 3), it is possible to assess the measurement  
 394 uncertainty of the system. In order to evaluate the on-machine calibration and measurement process  
 395 uncertainty, the test part is located back into the machine and properly aligned to the machine axes  
 396 by gauging along all milled surfaces (Figure 8). Again, a set of 10 consecutive measurements was  
 397 performed, with 2 images per reference marker (M1 to M4), to a total of redundant 8 images, but  
 398 measuring distance was optimized from 300 mm to 150 mm, so that the size of the reference target at  
 399 image plane was maximized and image coordinate uncertainty was correspondingly minimized.  
 400 Additionally, a set of 10 consecutive camera model calibrations were conducted in the CMM. In this  
 401 scenario, for a constant measuring system and measurand geometries, two contributors are  
 402 analyzed,  $u_{ip}$  and  $u_{it}$ .

- 403 • The former ( $u_{ip}$ ) corresponds to the contribution both due to the camera model calibration  
 404 (Figure 5) and the part measuring process (Figure 6), integrating the joint contribution of  
 405 gauging, machine positioning and image coordinate uncertainty during calibration and  
 406 measuring processes. First, machine uncertainty in reference target coordinates is estimated,  
 407 given by the standard deviation observed in the joint set of 100 calibration and measurements  
 408 (10 x 10), estimated in 3.5  $\mu\text{m}$  for X, 14.3  $\mu\text{m}$  for Y and 15.5  $\mu\text{m}$  for Z. Since reference target  
 409 coordinates determine the measured machine part location and orientation their uncertainty  
 410 must be propagated to the whole working volume. A Monte Carlo analysis was carried out for  
 411 that, incorporating as well the repeatability results for part location and orientation with  
 412 calibration (case 7D in Table 3). Final results show maximum values for contributor  $u_{ip}$  of  $u_{ip,X}$   
 413  $=20.1 \mu\text{m}$ ,  $u_{ip,Y} = 27.4 \mu\text{m}$  and  $u_{ip,Z} = 23.5 \mu\text{m}$  for X, Y and Z coordinates, respectively, in a scene  
 414 size of 0.75 m<sup>3</sup> (1.5 m x 1 m x 0.5 m, see Figure 3 and 8).
- 415 • The later ( $u_{it}$ ), accounts for the uncertainty contribution by the dimensional expansion of the  
 416 workpiece due to temperature uncertainty during measurements. The maximum values of  $u_{it}$   
 417 obtained for the working volume with a temperature variation of  $\pm 1 \text{ }^\circ\text{C}$  were 9.5  $\mu\text{m}$  for X, 6.4  
 418  $\mu\text{m}$  for Y and 3.2  $\mu\text{m}$  for Z.

420 From these contributors the expanded measurement uncertainty of the OMM system ( $U_{OMM}$ )  
 421 can be calculated by Equation (28), with a coverage factor  $k=2$ , for X, Y and Z. Results are shown in  
 422 Table 4.

$$424 U_{OMM} = k \times \sqrt{u_{ip}^2 + u_{it}^2} \quad (28)$$

426 **Table 4.** Main uncertainty contributors and OMM system estimated maximum expanded uncertainty ( $k=2$ ) for  
 427 the coordinates of any point in the scene volume.

	X [ $\mu\text{m}$ ]	Y [ $\mu\text{m}$ ]	Z [ $\mu\text{m}$ ]
$u_{ip}$	20.1	27.4	23.5
$u_{it}$	9.5	6.4	3.2
$U_{OMM} (k=2)$	44.5	56.3	47.4

428  
 429 If the whole process is analyzed and both, out-of-machine and on-machine measuring processes  
 430 are put together, the total uncertainty ( $U_{total}$ ) can be then calculated by Equation (29) (with  $k=2$ ) for X,  
 431 Y and Z. As mentioned in Section 2, part geometry given by optical target 3D coordinates was  
 432 measured by photogrammetry and fitted to the nominal CAD geometry by the out-of-machine  
 433 measuring system (Figure 1). This process results in an additional contributor ( $u_{out}$ ). Joint  
 434 uncertainty evaluation of the out-of-machine measuring and fitting processes, including the

435 non-coded targets, was evaluated according to the Length Measurement Error (LME) evaluation  
 436 guideline by VDI 2634 [27]. Contributions due to the scale factor and temperature changes were also  
 437 included in the analysis, resulting in values around 70  $\mu\text{m}$  for contributor  $u_{out}$  for the X, Y and Z  
 438 coordinates of the photogrammetric targets at the test part as shown in Table 5.  
 439

$$440 \quad U_{total} = k \times \sqrt{u_{out}^2 + u_{ip}^2 + u_{it}^2} \quad (29)$$

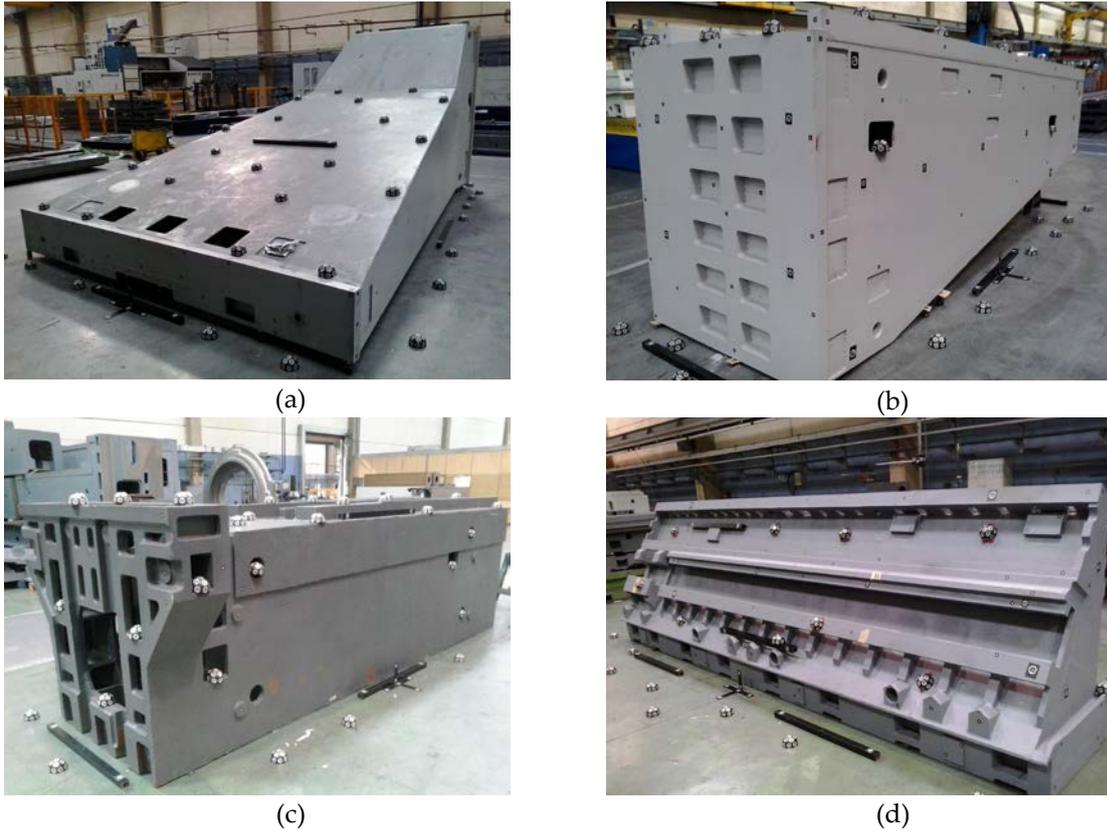
441  
 442 Table 5 summarizes the set of analyzed uncertainty contributors, and a total uncertainty of  
 443  $U_{total,X} = 148.5 \mu\text{m}$ ;  $U_{total,Y} = 151.8 \mu\text{m}$ ;  $U_{total,Z} = 148.4 \mu\text{m}$  is estimated for the machine coordinates of  
 444 non-coded targets characterizing part geometry in a scene size of  $0.75 \text{ m}^3$  ( $1.5 \text{ m} \times 1 \text{ m} \times 0.5 \text{ m}$ , see  
 445 Figure 3 and 8). This uncertainty is one order of magnitude smaller than the one obtained in the  
 446 previous work [3] where no specific self-calibration capability was included in the OMM.  
 447

448 **Table 5.** Main uncertainty contributors and total (out-of-machine plus on-machine measuring systems)  
 449 estimated maximum expanded uncertainty ( $k=2$ ) for the coordinates of any point in the scene.

	X [ $\mu\text{m}$ ]	Y [ $\mu\text{m}$ ]	Z [ $\mu\text{m}$ ]
$u_{out}$	70.9	70.5	70.3
$u_{ip}$	20.1	27.4	23.5
$u_{it}$	9.5	6.4	3.2
$U_{total} (k=2)$	148.5	151.8	148.4

450  
 451 In order to evaluate the estimated total uncertainty in the test-bench scenario, a spindle  
 452 integrated contact probe was used for gauging a minimum set of 10 non coded targets distributed in  
 453 3 directions and at extreme and opposite surfaces of the test part. Each target was gauged according  
 454 to the contact probe tool offset given by the OMM raw part location and its expected location  
 455 according to its ideal 3D coordinates given by the out-of-machine photogrammetric and fitting  
 456 process. A gauging process was conducted after each OMM measurement of the set of 10 described  
 457 in Section 3.2 for measurement repeatability evaluation, and  $10 \times 10$  probing errors were observed  
 458 between the ideal gauging coordinate and actual no coded target placement in machine coordinates.  
 459 A probing repeatability of 0.10 mm was observed, homogeneously distributed in three X, Y and Z  
 460 gauging directions, given by the  $\sigma(k = 2)$  of the probing error distribution, with all probing errors in  
 461 all surfaces being below +/- 0.15 mm. An overestimation at Table 5 can be observed, where total  
 462 uncertainty estimations range at 0.15 mm ( $U_{total} (k=2)$ ), 0.05 mm above the 0.10 mm ( $\sigma(k = 2)$ )  
 463 resulting from the probing error evaluation. The main contribution is given by the out of machine  
 464 portable photogrammetry process. According to LME evaluation results reported in literature [28],  
 465 typical LME errors could also be estimated as  $50 \mu\text{m} + 20 \mu\text{m}/\text{m}$  for portable photogrammetry, which  
 466 will result in an uncertainty estimation ( $u_{out}$ ) of  $40,4 \mu\text{m}$  for 1 m long scene in the test-bench scenario,  
 467 given that  $u_{out} = LME/\sqrt{3}$ , pointing out a possible uncertainty overestimation in the LME error  
 468 evaluation conducted in the present work following the VDI2634 guideline, where LME errors up to  
 469  $121,4 \mu\text{m}$  were observed in the worst case scenario.

470 Finally, the system has been evaluated in an industrial scenario (Figure 10) demonstrating fast  
 471 and precise raw part geometry control and on machine alignment guided by the self-calibrated  
 472 vision OMM system presented in this paper. Four representative part models were adopted for the  
 473 evaluation, all of them included in a maximum prismatic working volume of  $10 \text{ m} \times 3 \text{ m} \times 5 \text{ m}$ ,  
 474 according to their first machining set-up in machine X, Y, and Z axes, with a maximum scene volume  
 475 ranging  $150 \text{ m}^3$ .  
 476



477 **Figure 10.** Evaluation test of the system at end-user (Goimek, Elgoibar, Spain) in Soraluze milling  
 478 machines. 4 components are adopted for evaluation under a maximum working volume of 10 m x 3  
 479 m x 5 m. (a) Milling machine structural gantry (b) Grinding machine vertical column. (c) Milling  
 480 machine travelling column. (d) Lathe bed. Reference targets placed at XZ plane for all cases, with  
 481 OMM measuring direction being Y axis.

482 The out-of-machine photogrammetry and fitting process took an overall time of 2 hours per  
 483 part, determining the optimal 3D coordinates of 4 reference coded target per part. Four reference  
 484 coded targets were placed at XZ plane, located at extreme raw part positions. Reference coded  
 485 targets were measured in the machine by the OMM integrating self-calibration capability,  
 486 resembling the same measuring strategy as described previously, with 2 images per target up to a  
 487 total of 8 images from different machine positions. Raw part was then aligned manually by the  
 488 machine operator by adjusting the corresponding fixturing tools, guided by the OMM measuring of  
 489 raw part orientation ( $\alpha_p$ ,  $\beta_p$ ,  $\gamma_p$ , in mm/m). A set of 10 consecutive measurements was performed by  
 490 the vision OMM following same approach as shown in Figure 8, but being Y machine axis the OMM  
 491 measuring direction since reference targets are located at XZ plane, with a measuring distance of 150  
 492 mm to each reference target, including system clamping-unclamping between each measurement  
 493 set. Same image detection quality was expected both in laboratory and industrial scenarios, given by  
 494 the active LED illumination integrated by the vision OMM, same measuring distance and reference  
 495 target size. Indeed, similar repeatability figures were observed in the industrial scenario for raw part  
 496 location (dp) ranging 0.02 mm ( $k=2$ ). Correspondingly, a reduction of one order of magnitude was  
 497 observed in raw part orientation measurement (Rp), with angle measurement repeatability ranging  
 498 below 0.005 mm ( $k=2$ ), proportional to the larger relative distance between measured reference  
 499 targets (at XZ plane, 10 m x 3 m) comparing to the test bench scenario (XY plane, 1.5 m x 1 m),

500 Again, assuming a constant measuring system and measurand geometries, three contributors  
 501 are estimated for the industrial scenario,  $u_{ip}$ ,  $u_{it}$ , and  $u_{out}$ :

- 502 • Assuming a constant image detection uncertainty in both scenarios, laboratory (1.5 m x 1 m x  
 503 0.5 m) and industrial (10 m x 3 m x 5 m), and given a similar measuring geometry for  
 504 measuring each reference target, measurement uncertainty on reference target machine

505 coordinates can be assumed independent to scene size, previously estimated in for the test  
 506 bench scenario. 3.5  $\mu\text{m}$  for X,  $\mu\text{m}$  for Y 15.5 and 14.3  $\mu\text{m}$  for Z. Note that estimations for Y and  
 507 Z are correspondingly interchanged due to the change of OMM measuring direction from Z in  
 508 the test bench scenario (Figure 8) to Y in the industrial scenario. A Montecarlo analysis was  
 509 conducted to propagate reference target uncertainty in the industrial scene volume of 10 m x 3  
 510 m x 5 m, showing maximum values for contributor  $u_{ip}$  of  $u_{ip,X} = 57.6 \mu\text{m}$ ,  $u_{ip,Y} = 140.2 \mu\text{m}$  and  
 511  $u_{ip,Z} = 134.9 \mu\text{m}$  for X, Y and Z coordinates, respectively.

- 512 • Maximum temperature uncertainty during measurement was  $\pm 1 \text{ }^\circ\text{C}$  for the industrial  
 513 scenario, resulting in an uncertainty contribution by dimensional expansion ( $u_{it}$ ) of the  
 514 workpiece of 64.0  $\mu\text{m}$  for X, 19.2  $\mu\text{m}$  for Y and 32.0  $\mu\text{m}$  for Z.
- 515 • Uncertainty contribution due to out of machine photogrammetry ( $u_{out}$ ) is estimated according  
 516 to [28] for the 10 m x 3 m x 5 m scene volume, resulting in 144.3  $\mu\text{m}$  for X, 89.3  $\mu\text{m}$  for Y and  
 517 112.4  $\mu\text{m}$  for Z, given the scale dependent LME error contributor of 20  $\mu\text{m}/\text{m}$ .

519 Table 5 summarizes the set of estimated contributors for the industrial scenario, and a total  
 520 uncertainty of  $U_{total,X} = 336.1 \mu\text{m}$ ;  $U_{total,Y} = 334.6 \mu\text{m}$ ;  $U_{total,Z} = 356.9 \mu\text{m}$  is estimated for the  
 521 machine coordinates of non-coded targets characterizing part geometry in a scene size of 150 m<sup>3</sup> (10  
 522 m x 3 m x 5 m, see Figure 10).  
 523

524 **Table 6.** Main uncertainty contributors and total uncertainty estimation in the industrial scenario for the  
 525 machine coordinates of any point at raw part surfaces.

	X [ $\mu\text{m}$ ]	Y [ $\mu\text{m}$ ]	Z [ $\mu\text{m}$ ]
$u_{out}$	144.3	89.3	112.4
$u_{ip}$	57.6	140.2	134.9
$u_{it}$	64.0	19.2	32.0
$U_{total} (k=2)$	336.1	334.6	356.9

526  
 527 In order to evaluate the estimated total uncertainty, the same probing error evaluation  
 528 methodology was adopted on the four part models under study (Figure 10), as previously described  
 529 for the laboratory test bench. In this case, a probing repeatability of 0.34 mm was observed, with a  
 530 difference ranging 0.01 mm to the estimated figures in Table 6. Again, homogeneously distributed  
 531 probing errors were observed in three X, Y and Z gauging directions, assuming  $\sigma(k = 2)$  for the  
 532 probing error distribution, with all probing errors in all surfaces ranging below +/- 0.50 mm,  
 533 demonstrating the adequate accuracy of the system for large raw part alignment processes with tight  
 534 overstock allowances.

535 The capability of the measurement process can be determined in accordance with Berndt's  
 536 principle ("golden rule" of metrology) [29,30] that states that the measurement uncertainty shall be  
 537 less than 20% of the tolerance. In the presented case the tolerance is established in  $\pm 1 \text{ mm}$ , as a tight  
 538 overstock allowance to be controlled in up to 10 m long raw parts. According to the results shown in  
 539 Table 6, the ratio U/T shows values of 17% for both X and Y and 18% for Z. Therefore, the  
 540 measurement process can be considered capable for the required tolerance in accordance with  
 541 Berndt's principle.

542 Along with the demonstrated accuracy due to developed self-calibration capability, under the  
 543 analyzed industrial scenario, comparing to the conventional manual means for on machine raw part  
 544 alignment by using contact probes, the OMM vision system has shown the potential of reducing  
 545 alignment time from up to 1 hour to less than 15 min, as a result of the fast and efficient  
 546 measurement by vision stereo-photogrammetry of a minimum set of optical reference targets.  
 547 Additional benefits of the proposed system can be pointed out, such as process cost savings since  
 548 enables the application of a common alignment methodology in production regardless to the part  
 549 geometry since reference targets can be similarly place for different part models, digital traceability  
 550 of adopted raw part location and orientation prior to each machining, and increased reliability since  
 551 alignment process brings lower dependence to machine operator skills.

552 **5. Conclusions**

553 A self-calibration technique by using redundant information of on-machine measurements by  
554 machine vision has been presented. It has been applied to a machine vision system directly mounted  
555 in the machine tool spindle with an ISO taper. The out-of-machine calibration process for the camera  
556 model extrinsic and intrinsic parameters and the OMM mathematical model have been presented.  
557 The self-calibration technique developed to avoid the calibration of the system every time it is  
558 mounted into the spindle has been described. The system has been tested on a milling machine used  
559 as test scenario and evaluated on other milling machine in an industrial scenario. The results show  
560 that the application of this technique reduces the uncertainty due to the angular placement of the  
561 taper with no need of extra anchoring or further calibration of the probe with respect to the spindle.  
562 It is based on the integrated resolution of the position and orientation of the part together with the  
563 placement uncertainty.

564 By using it, the measurement repeatability has been improved for the portable vision OMM,  
565 ranging below 0.05 mm and 0.05 mm/m for part position and orientation measurement in laboratory  
566 conditions (working volume 1.5 m x 1 m x 0.5 m), respectively. The final measurement uncertainty  
567 has been improved from the range of 1 mm, that the system presented in laboratory conditions  
568 without the specific self-calibration here shown [3], to the range of 0.15 mm. Under industrial  
569 conditions (working volume 10 m x 3 m x 5 m) the measurement process showed an uncertainty  
570 ranging 0.3-0.4 mm, assuring its performance for the in-machine alignment of large raw parts with  
571 tight overstock allowances of up to  $\pm 1$  mm.

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