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IN PROCESS IDENTIFICATION OF WORKPIECE/SYSTEM GEOMETRICAL DEVIATIONS BASED ON GENERAL PURPOSE ROBOTS AND LASER TRIANGULATION SENSORS – PART 1: CONCEPTUAL FRAMEWORK

Abstract: *This paper gives a conceptual framework of a new class of metrological systems based on integration of general purpose industrial robot with laser triangulation sensor for contactless dimensional metrology. The paper has two parts. Part one considers conceptual framework where the system architecture is given, key aspects of the interface between two subsystems are considered, as well as a new methodology frames for signal processing and generation of partial or complete 3D digital model of scanned object with complex spatial geometry. For verification of practical applicability, laboratory installation is developed and experiments and practical functional testings are carried out. This paper also gives recapitulation of two feasibility studies: huge assemblies welding process robotization and forging press serving in the scope of flexible manufacturing cell for forging on MAXI presses. Evaluation and practical implementation are in the second part of this paper.*

Key words: *Industrial robot, laser triangulation sensor, 3D digitalization*

1. INTRODUCTION

Nowadays product quality standards impose the need for identification of geometrical properties for practically every part/component, subassembly or final assembly which is assembled using an automated system, where the deflections from nominal values should be recognized and corrective interventions carried out when needed. In the scope of mass customization manufacturing which leads to extreme increase of product variations and decrease of batch size, the demand for metrology system high flexibility and applicability in plant conditions emerges.

Installation of an optical sensor on general purpose industrial robot, usually of an anthropomorphic configuration, gives a powerful metrology system with remarkable flexibility and high accuracy with potential for realization of huge class of technological tasks in dimensional metrology and inspection in industrial conditions, directly on manufacturing line. Obvious potential which emerges from this symbiosis opens up a series of engineering tasks and challenges. These tasks can be classified into following groups:

- The choice of optimal sensor system
- Planning of optimal trajectory and velocity profile, especially the development of interactive tools for trajectory generation based on virtual geometry model of the scanned object
- Creation of virtual metrology model of the robot-sensor-object-to-be-scanned system for simulation of robot and sensor system task
- Sensor signal processing and generation of planar or spatial model of scanned object
- Autonomous compensation of the position and orientation deflection of the scanned object
- Identification of metrological performances of the system, system calibration, mapping and compensation of robot deflections

Technology of contactless optical sensors suitable for observed application gives following possibilities: 1)spot CCD or PSD laser systems based on single or multiple optical triangulation, 2)confocal spot laser systems, 3)linear CCD or CMOS triangulation systems – profilometers, and 4)triangulation systems with structured (coded) light source. A review of specified sensor technologies is given in [1] and [2]. All of these systems have compact construction and are suitable for installation on robot. From metrological point of view, industrial robot in such a metrology system has a function of programmable platform for moving/manipulation of sensor system in workspace.

This paper, which consists of two parts, reports a part of results obtained within project MA14035 INTOSA[1] where the conceptual bases for one robotized system for 3D digitalization of objects with complex geometry based on CCD laser sensor with spot optical triangulation is developed. Practical applicability of this concept is verified and demonstrated in laboratory conditions in the Center for New Technologies at Faculty of Mechanical Engineering in Belgrade.

2. CONCEPT OF THE SYSTEM

Metrology system consists of: 1)universal industrial robot with appropriate kinematical configuration, 2)laser triangulation sensor and 3)acquisition system for data conditioning and acquisition (Figure 1). Sensor is attached to the robot end point *P* using appropriate adapter. Although generally it is possible to attach sensor arbitrarily, due to practical reasons it is appropriate to build in sensor in such a way that colinearity and/or orthogonality with main axes of symmetry of robot terminal plate is achieved.

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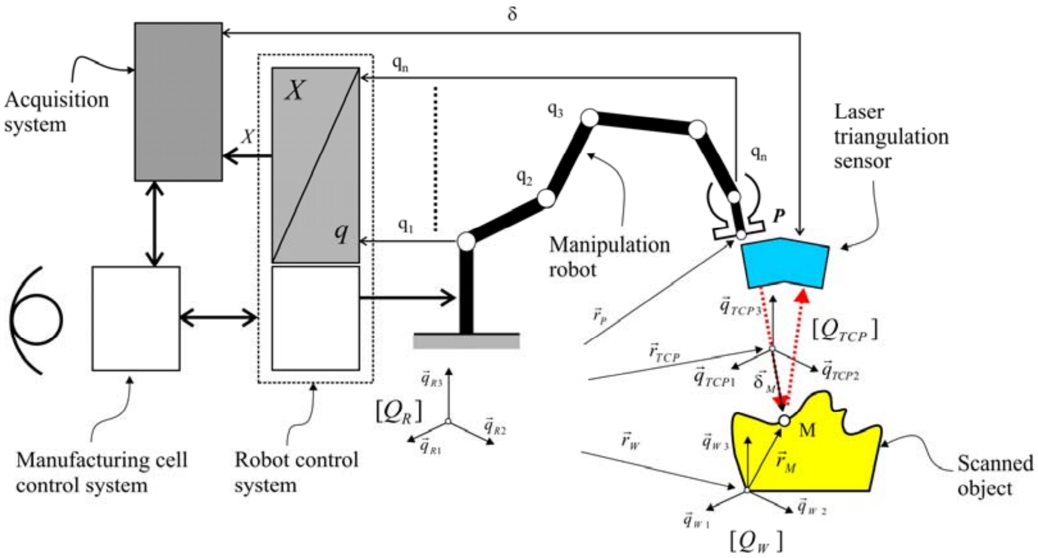

Fig. 1: Robotized measuring system concept

2.1. Triangulation sensor

Typical configuration of laser sensor with optical triangulation is shown in Figure 2. Semiconductor low power laser, usually with maximal power not higher then 1mW generates monochrome coherent light which is trough primary optical system collimated on the surface of scanned object. Optical axis of primary optical system is significant because one of the axes of local coordinate frame is coincident with it. Emitted light beam with diameter of 10 to 100μm is reflected in all directions according to Lambert's law of diffuse reflection [3]. One part of reflected light is reflected in the direction of optical axis of secondary optical system which focuses the overtaken part of light to optoelectrical transducer. The spot on which focused light falls depends on the distance of the surface of the scanned object. Applying triangulation geometry, based on information about location of this point in the local frame of linear transducer, the unknown displacement, i.e. momentary distance, is calculated:

$$\Delta d = f(\Delta z) \qquad (1)$$

Detail analysis of relation (1) is given in [3]. Appling linear CCD or CMOS digital transducers with high resolution together with appropriate algorithms for primary processing of sensor signal, the resolution of 14bits along measuring range (MR) is achieved. Scanning speed is in the range from a few hundreds of samples per second to a few tens of kHz. This kind of triangulation sensors is characterized by high robustness and metrology stability. Depending on the chosen optical system design characteristics, different measuring ranges as well as their projections from the sensor body (stand off distance) are achieved.

2.2. Robot TCP and triangulation sensor location

When robot TCP (Tool Center Point) is determined for particular application, it is convenient to coincide one of the axes with the principal axis of primary optical system and to choose the middle of the laser measuring range as the origin point of local laser sensor frame. This fact should be used when robot trajectory is planned – one should tend to keep TCP, that is origin of laser sensor local frame, always sliding over the surface of the scanned object, or to keep it as close as possible. Besides this one there are two additional requirements.

The first requirement, which is importanant for the accuracy of the measuring system as a whole, is connected to the constraint inflicted by the optical triangulation concept. Modeling and calibration of laser sensor are always carried out under the assumption that the principal axis of emitted laser beam is orthogonal to the surface of the object whose distance is measured – orthogonality requirement. The deflection of orthogonality degrades the accuracy of laser system which has its clear foundation in Lambert's law of diffuse reflection. Besides, measuring surface inclination puts down the energy of reflected light which in certain cases can have drastic repercussion to performance of sensor transducer set which due to insufficient excitation can stay without valid sample. Generally, inclination should be within interval of ±15º. This is especially important when object has highly reflective surface and/or surface with high texture. For the reference surface made of white paper inclination in given interval generates the error of 0.2% of measuring range, which is for the measuring range of 100mm as far as 200μm and can be regarded as significant error. If the inclination in both directions is in the interval of ±5º, than the error is not more then 0.12% of MR.

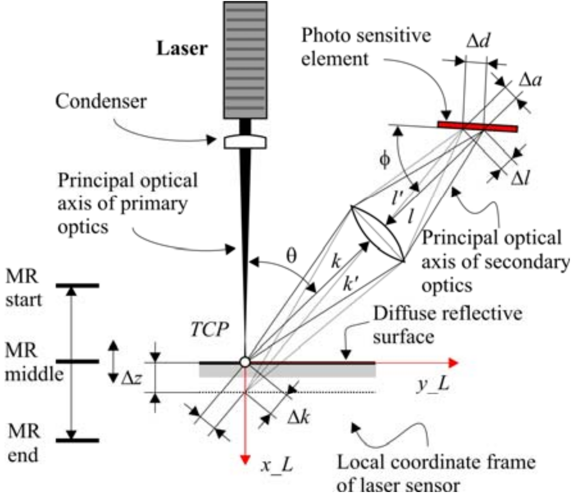

Fig. 2: Functional principle of laser triangulation sensor and definition of local coordinate frame

The second requirement refers to the problem of shadow, i.e., the occurrence of physical obstacle which totally or partially breaks the optical axis of secondary optical system - sensor can not generate valid result. **Optical visibility requirement** puts in additional constraint for the process of robot trajectory planning. Generally, this requirement can not be always fulfilled.

Considering these requirements/constraints in the application of laser triangulation sensors, the application of robots gets its full significance. Inherent manipulability properties enable to, choosing the right trajectory, one can always provide optimal metrology conditions: 1)location of the TCP on the surface of scanned object, 2)orthogonality of the principal optical axis to the surface of the scanned object, and 3)elimination of shadow problem always when it is physically feasible. The possibility to fulfill given three prerequisites makes the symbiosis of robot and laser triangulation sensor a technology entity of a high value.

2.3. Acquisition system

Integration of robot and laser sensor is carried out trough acquisition system. Acquisition system, i.e. PC or another microprocessor system supplied with corresponding interfaces and acquisition software must have the function of communication with robot control system and laser sensor microprocessor system. Acquisition system conducts synchronous acquisition of robots internal coordinates (values of actuator encoders) and measured distance to the scanned object. In successive time sampling instants acquisition system gets and memorizes the vector with (n+1) elements where n denotes the number of active robot DOFs. Position vector of arbitrary point M r_M on the scanned object, presented in local workspace coordinate frame is computed using relation:

$$\vec{r}_M = \vec{r}_{TCP} + \vec{\delta}_M - \vec{r}_W \qquad (2)$$

where r_{TCP} denotes robots TCP position (from robot control system), δ_M is the vector of measured distance generated by laser triangulation sensor, and r_W is the vector of position of the scanned object in workspace (Figure 1). Deflection (deviation) η of point M nominal position r_{Mo} defined by digital 3D CAD model from the real position obtained by measuring is then:

$$\vec{\eta} = \vec{r}_M - \vec{r}_{Mo} \qquad (3)$$

Point M position vector contains inherent error of manipulation robot end point position which comes as a consequence of imperfections of robots mechanical and control system. This error consists of stationary and nonstationary component (oscillation of robot end point, processes of stochastic nature and slow processes caused by nonstationary temperature field and wearing/deformation of kinematics chain elements). In the most cases stationary component has dominant influence and metrological performances of robotized measurement system can be significantly improved if this component is identified and memorized for total robot workspace or only for a part significant for application at hand. Reading the values of identified stationary component of robot end point positioning error from look-up table together with interpolation relations gives the values of current correction e_M and corrected values of point M position vector is given by:

$$\vec{r}_M^{\,k} = \vec{r}_M + \vec{e}_M \qquad (4)$$

This approach significantly improves metrological properties of robotized scanning system.

Scanning task is, as a rule, comprised of the sequences made of subsequences of scanning and subsequences of robot repositions. Each of these sequences gives, as a result, a vector of one contour, usually as continuous time series. This working principle assumes the existence of bidirectional communication between acquisition system on one side and robot control system and laser sensor on the other one. Acquisition system is required to have the function of discontinuous withdrawal of encoder signal and adjoined measured distance whenever it is demanded by measuring plan. Acquisition system can be a part of cell controller or it can be located in the layer right beneath it. Anyway it is superior to the microprocessor system of laser sensor and it is in hierarchy sense parallel to the robot control system.

A set of measured point position vector time series calculated from equations (2) and (4) by superposition, generates so-called nonstructured points cloud which caries the complete or partial information about real geometry of visible surface of scanned object.

3. SENSOR SIGNAL PROCESSING

Time series for each of scanned contours demands the appropriate processing before synthesized output, in the form of points cloud suitable for digital 3d model generation in CAD modeler, is generated. Primary signal processing assumes four tasks: 1)Removing the noise and microgeometry texture details in time domain; 2)Transformation of time into spatial domain; 3)Contour resampling in spatial domain and the reduction of number of points; 4)Compensation of robot positioning errors

Secondary signal processing is guided by concrete application, i.e. by the task put to the robotized measuring system. Here, two basic cases are possible:

1. Object is partially scanned and only a location of certain points or profiles of characteristic cross sections is checked. In this case from primary processed sensor readings the coordinates of required points or vectors of required cross section contour are extracted.
2. Object is totally scanned and corresponding point cloud is generated, and by further polygonization (Delaunay triangulation etc.) its virtual geometry model is generated [4]. In this case a synthesis of contours generated during primary signal processing is carried out, the redundancies are eliminated and virtual model of object is generated in the form of point cloud.

The key requirement for the choice of technique for primary processing of generated time series is the phase correctness and possibility of multiresolution analysis. Techniques based on wavelet transform fulfill both requirements including the possibility of partial or total reconstruction of starting vector.

Using discrete wavelet transform (DWT) [5] signal f is presented as sum of its approximation $A_J f$ at certain resolution J and details $D_j f$, $j \in [1, J]$ taken from it during passing from higher resolution to lower one:

$$f = A_J f + \sum_{j=1}^{J} D_j f = \sum_n a_n^j \phi_{j,n} + \sum_j \sum_n d_n^j \psi_{j,n} \quad (5)$$

Ajf and *Djf* are represented by approximation a_n^J and detail d_n^j coefficients which represent the share of scaling functions $\phi_{j,n}$ and wavelets $\psi_{j,k}$ in signal. These coefficients are computed using fast onepass hierarchical algorithm –subband filtering scheme which enables reversibility of filtration and algorithm for inverse discrete wavelet transform (IDWT).

Using subband filtering scheme shown in Figure 3, d_n^j are computed from a_n^{j-1} by filtering it with highpass filter $\bar{G}$, and then downsampling by 2. Similarly, a_n^j are computed from a_n^{j-1} by filtering it with lowpass filter $\bar{H}$, and then downsampling by 2. Filters H, G, $\bar{H}$ and $\bar{G}$ are conjugate mirror FIR filters defined by selected wavelets. Algorithm for IDWT can be described by subband filtering scheme given in Figure 3b. a_n^{j-1} are computed by upsampling a_n^j and d_n^j by 2, convolving obtained sequences with filters H and G and summing it. Algorithm for IDWT can be used for computation of signal approximation at resolution (DWT level) J – $A_J f$ if detail coefficients d_j^n, $j \in [1, J]$ during computation are zeroed. Details *Djf* can be computed similarly.

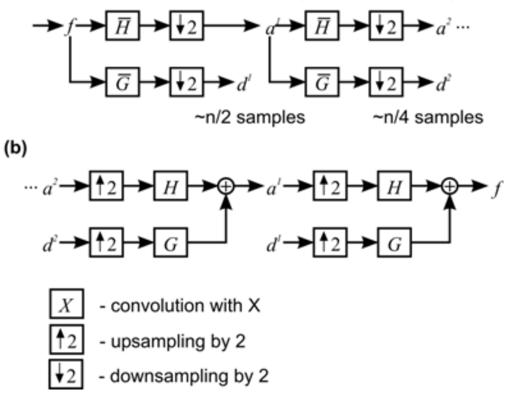

Fig. 3: Subband filtering scheme for: a)DWT, b)IDWT

The existence of IDWT is extremely significant for decoupling the noise, microgeometry of scanned object surface texture and its macrogeometry [6]. Adequate choice of wavelet used for DWT, as well as the choice of transformation level *J*, can lead to recognition of given components at certain levels of signal approximations or details.

Transition from time to spatial domain generally brings up the problem of contour spatial discretization uniformity. Depending on the shape of scanning trajectory as well as on the local properties of scanned object surface, the uniformity of sensor signal discretization in time domain is more or less deteriorated leading to cumulation of points in certain parts of contour and their rarifying in other parts. The problem is solved in such a way that initial contour vector in spatial domain is discretized again using interpolation algorithms [7]. This area is studiously researched for decades in the context of geometrical modeling of spatial objects and it is not the subject of research presented in this paper. Having the ringing in of developed concept as a goal, zero order interpolators are used living the room for application of advanced techniques in the phase of digital 3D model generation in CAD environment.

4. CONCLUSION

This paper gives a concept of a system for robotized digitalization of spatial objects with complex geometry based on application of spot laser sensors. The structure of system is shown and critical metrology details of symbiosis of general purpose manipulation robot and laser triangulation sensor are discussed. The concept of acquisition system is described and basic geometric equations for the synthesis of 3d digital model of scanned object in the form of unstructured point cloud are given as well as the relations for identification of deviation of empirical model from nominal digital model created in 3d CAD modeler. Basic definitions of laser triangulation sensor are given and it is shown that manipulation robot has very desirable properties, providing that, when working with complex geometry parts, orthogonality and optical visibility requirements can be fulfilled. For the primary sensor information processing, the application of DWT is suggested because it provides phase correct signal decomposition, gives the freedom in choice of time or spatial signal approximation in accordance to application conditions at hand and enables real-time applicability.

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