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Robot-Based Inline 2D/3D Quality Monitoring Using Picture-Giving and Laser Triangulation Sensors

Chen-Ko Sung, Robin Gruna, Minzi Zhuge and Kai-Uwe Vieth
*Fraunhofer Institute IITB, Fraunhoferstrasse 1, 76131 Karlsruhe
 Germany*

1. Introduction

Robots with multiple intelligent sensors will be increasingly used in the future for demanding production and assembly tasks. A substantial reason for the hesitant use of picture-giving sensors for the monitoring of inspection is the insufficient flexibility of the used monitoring concepts in relation to changing setting of tasks. At present either one (user-specific) sensor or more sensors with static arrangement for a certain task of inspection are used (Malamas et al., 2003; Ranky, 2003). This rigid approach is unsuitable for the inspection of variant products.

An especially attractive area of application is the inline 2D/3D quality monitoring of complex, large-area production parts such as the aircraft fuselage or parts of the bodies of man-made objects. For example hundred different mounting parts on an aircraft fuselage (about 4 m x 10 m in size) must be inspected, whether proper parts have been attached correctly. A special transport system like a monorail conveyor will probably be needed for the transportation of large objects. Such transport systems do not allow a precise positioning. The test object is free-hanging over the ground. At present no existing inspection system can do automatically the total quality monitoring of such production parts well.

Another very important task for the quality monitoring in factories is the inspection of work piece surfaces and structural defects. Scratches, dents, pores, deformations, recesses, increases, slivers, blisters and other kinds of defects on or below the surface should be detected and classified. Different kind of hardware (sensors, light sources, grip systems, robots and so on) and software (models, algorithms, data bases and so on) at present must be used, in order to mastering this task. That is surely a wrong way that we use numerous robots and inspection station in different places for the quality monitoring of such products. For these reasons, we develop and examine a new concept for 2D/3D metric and logical quality monitoring with a more accurate, flexible, economical and efficient inspection centre. At the same time the measuring methods with the new modern technology are also improved. With the new concept the testing periods and investment in plants can be substantially decreased.

2. System overview

A four-step concept has been developed and realised at IITB for the flexible inline 2D/3D quality monitoring with the following characteristics (Fig. 1):

- Multiple short-range and wide-range sensors;
- Cost reduction of investment at plants without reduction of the product quality;
- Large flexibility regarding frequently changing test tasks;
- Low operating cost by minimisation of the test periods.

The robot-based system uses an array of test-specific short-range and wide-range sensors which make the inspection process more flexible and problem-specific. To test this innovative inline quality monitoring concept and to adapt it to customised tasks, a development and demonstration platform (DDP) was created (Fig. 2). It consists of an industrial robot with various sensor ports - a so-called "sensor magazine" - with various task-specific, interchangeable sensors (Fig. 3) and a flexible transport system.

All sensors are placed on a sensor magazine and are ready to use immediately after docking on the robot arm. The calibration of all sensors, robot calibration and the hand-eye calibration have to be done before the test task starts. The central projection for the camera calibration has been used.

Fig. 1. System overview: A four-step concept for the flexible inline quality monitoring.

The four steps for a flexible inline quality monitoring which are described in the following sections are:

- Localisation of unfixed industrial test objects;
- Automatic detection of test zones;

- Time-optimal dynamical path planning;
- Vision-based inspection.

Fig. 2. Quality monitoring of aircraft fuselages with wide- and short-range inspection sensors. Left: Inspection station and test environment. The movement of production pieces is carried out by monorail conveyors which do not allow precise positioning. Right: Development and demonstration platform (DDP).

Fig. 3. Sensor magazine.

2.1 Localisation of unfixed industrial test objects

As the first step of the presented quality monitoring chain, the exact position of a production piece is determined with a wide-range picture-giving sensor (Fig. 2), which is - depending on the object size - mounted in an adequate object distance, i.e. not necessarily fixed on an inspection robot's end-effector.

A marker-less localisation calculates the exact object position in the scene. This procedure is based only on a 3D CAD-model of the test object or at least a CAD-model which represents a composition of some of its relevant main parts. The CAD-model contours are projected into the current sensor images and they are matched with sub-pixel accuracy with corresponding lines extracted from the image (Müller, 2001).

Fig. 4 shows a localisation example. The CAD-model projection is displayed in yellow and the object coordinate system in pink colour. The red pixels close to the yellow projection denote corresponding image line pixels which could automatically be extracted from the image plane. The calculated object pose (consisting of three parameters for the position in 3D scene space as well as three parameters for the orientation, see the red text in the upper part of the figure) can easily be transformed into the global scene coordinate system (displayed in green colour).

Known test zones for detail inspection as well as associated sensor positions and orientations or required sensor trajectories (cf. section 2.2 and 2.3) can be defined with respect to the object coordinate system in an inspection preceding step. All the object based coordinates will be transformed online into the global scene coordinate system or the robot coordinate system with respect to the localisation result, i.e. with respect to the position and orientation of the test object in the scene. The red, T-shaped overlay in Fig. 4 shows an example for an optimal 3D motion trajectory (see the horizontal red line which is parallel to the object surface) together with the desired sensor's line of sight with respect to the object surface (the red line which points from a position in the middle of the trajectory towards the test object).

Fig. 4. Localisation of an object to be inspected and computation of an initial optimal inspection trajectory.

2.2 Automatic detection of test zones

Two approaches can be applied to find automatically anomalies on a test object. One is model-based comparison between the CAD-model projection and the extracted image features (edges, corners, surfaces) to detect geometric differences (Veltkamp & Hagedoorn, 2001). Another one resembles probabilistic alignment (Pope & Lowe, 2000) to recognize unfamiliar zones between view-based object image and test image.

In this second step, we used purely image-based methods and some ideas of the probabilistic alignment to achieve a robust inline detection of anomalies under the assumption that the object view changes smoothly. The same wide-range camera for object localisation was used for this step.

Using the result of object localisation to segment an object from an image, a database with 2D object images can be built up in a separate learning step. We postulated that the views were limited either of the front side or the back side of the test object with small changes of viewing angles and furthermore postulated that we had constant lighting conditions in the environment.

We used the calibration matrix and the 2D object images to create a 3D view-based virtual object model at the 3D location where an actual test object was detected. The next process was to project the view-based virtual object model into the image plane. The interesting test zones (anomalies, Fig. 5) where detailed inspections were needed (see section 2.3 and 2.4) were detected within the segmented image area by the following steps:

- Comparison between the projected view-based object image and the actual test image;
- Morphological operations;
- Feature analysis.

Fig. 5. Left: One of the segmented object images in the learning step. Only the segmented area in an image is relevant for the detection of anomalies. Right: The automatic detected test zones are marked with red rectangles (overlays).

2.3 Time-optimal dynamical path planning

In the third step, an optimised inspection path plan is generated just in time, which is then carried out using various inspection-specific short-range sensors (e.g. cameras, feeler, etc.).

All the interesting test zones or the regions of interest (ROIs) have been found in the second step, but the path plan is not perfect yet. A time-optimal path has to be found from the supervising system.

The problem is closely related to the well known travelling salesman problem (TSP), which goes back to the early 1930s (Lawler et al., 1985; Applegate et al., 2006). The TSP is a problem in discrete or combinatorial optimisation. It is a prominent illustration of a class of problems in computational complexity theory which are classified as NP-hard (Wikipedia, 2009).

The total number of possible paths is calculated by: $M = (n-1)!/2$. The definition of the TS-problem is based on the following assumptions:

- Modelled as a graph with nodes and edges;
- Graph is complete, this means that from each point there is a connection to any other point;

- The graph can be symmetric or asymmetric;
- The graph is metric, that means it complies the triangle inequality $C_{ij} \leq C_{ik} + C_{kj}$ (e.g. Euclidian metric, maximum metric).

Looking at the algorithms for solving TS-problems, there exist two different approaches: Exact algorithms which guarantee a global optimal solution and heuristics, where the solution found is only locally optimal.

The most accepted exact algorithms which guarantee a global optimum are Branch-and-Cut Method, Brute-Force and Dynamic Programming. The major disadvantage of the exact algorithms mentioned above is the time consuming process finding the optimal solution. The most common heuristic algorithms used for the TSP are:

- Constructive heuristics: The Nearest-Neighbour-Heuristic chooses the neighbour with the shortest distance from the actual point.

The Nearest-Insertion-Heuristic inserts in a starting path additional points;

- Iterative improvement: Post-Optimisation-methods try to modify the actual sequence in order to shorten the overall distance (e.g. k-opt heuristic).

A heuristic algorithm with the following boundary conditions was used:

- The starting point has the lowest x -coordinate;
- The Nearest- Neighbour-Constructive heuristics look for the nearest neighbour starting with the first node and so on;
- The iterative improvement permutes single nodes or complete sub graphs randomly;
- Terminate, if there was no improvement after n tries.

The optimised path planning discussed above was tested at the DDP with a realistic scenario. Given a work piece of 1 by 0.5 square meter, the outputs of the second step (see section 2.2) are 15 detected ROIs, which belong to the same error class. This would lead to a total number of about 43.6 billion possible different paths.

Starting with a 1st guess as outlined with an associated path length set to 100 %, after 15 main iteration loops the path lengths drops down to nearly 50 % of the first one, and no better achievement could be found (Fig. 6). The calculation time for the iterated optimal path was less than 1 s. on a commercial PC, Intel Pentium 4 with 3 GHz, and took place while the robot moved to the starting position of the inspection path.

2.4 Vision-based inspection

In the fourth step, the robot uses those sensors which are necessary for a given inspection path plan and guides them along an optimal motion trajectory into the previously-identified ROIs for detailed inspection. In these ROIs a qualitative comparison of the observed actual topography with the modelled target topography is made using image-processing methods. In addition, quantitative scanning and measurement of selected production parameters can be carried out.

For the navigation and position control of the robotic movement with regard to the imprecisely- guided production object as well as for the comparison of the observed actual topography with the target topography, reference models are required.

These models, using suitable wide-range and short-range sensors, were scanned in a separate learning step prior to the generation of the automated inspection path plan. Two sensors have been used for our work: A laser triangulation sensor is used (Wikipedia, 2009) for the metric test task (Fig. 7) and a short-range inspection camera with a circular lighting is

used for the logical test task. For a fuselage, for example, it can be determined if construction elements are missing and/or if certain bore diameters are true to size.

Fig. 6. Left: initial path; Right: final path.

Fig. 7. A laser line scanning technique captures the structure of a 3D object (left part) and translates it into a graphic model (right part).

By using the proposed, robot-based concepts of multiple sensor quality monitoring, the customary use of expensive 3D CAD-models of the test objects for high-precision CNC controlled machine tools or coordinate inspection machines becomes, in most instances, unnecessary. The quality of the results of the metric test task is therefore strongly dependent on the quality of the calibration of the laser triangulation sensor which will be discussed next in chapter 3.

An intelligent, sensor-based distance-control concept (Visual-Servoing-Principle) accurately controls the robot's movements with regard to the work piece and prevents possible collisions with unexpected obstacles.

3. 3D Inspection with laser triangulation sensors

The test objects like aircraft fuselages consist of a large ensemble of extended components, i.e., they are 3D objects. For inline 3D quality monitoring of so-called metric objects, the sensor magazine contains a laser triangulation sensor. The sensor presented here is currently

equipped with two line laser projectors but is not necessarily reduced to two light sources. The usage of two or more sources yields a predominant shadow-free quality monitoring for most inspection tasks. Thus, the inspection path of the sensor can be reduced for metric objects principally by a factor of two or more compared to the usage of one line laser. Before going into details, a short overview of 3D measurement techniques is given as the sensor magazine could also contain other 3D sensors, of course. Depending on the requirements of the inspection task the corresponding optical technique has to be chosen.

3.1 From 2D towards 3D in-line inspection

As described in the previous Section, 2D computer vision helps to roughly localize the position of the object to be inspected. Then the detailed quality inspection process starts which can be performed and actually should be performed with 2D image processing where possible. For many inspection tasks, traditional machine vision based systems are not capable of detecting defects because of the limited information provided by 2D images. For this reason, optical 3D measurement techniques have been gaining an increased importance in industrial applications because of their ability to capture shape data from objects.

Geometry or shape acquisition can be accomplished by several techniques, e.g., shape from shading (Rindfleisch, 1966), phase-shift (Sadlo et al., 2005), Moiré-approach, which dates back to Lord Rayleigh (1874), Stereo-/Multi-View-Vision (Breuckmann, 1993), tactile coordinate metrology, time-of-flight (Blanc et al., 2004), light sectioning (Shirai & Suwa, 1971), confocal microscopy (Sarder & Nehorai, 2006), interferometric shape measurement (Maack et al., 1995).

A widely adopted approach is laser line scanning or laser line triangulation. Because of its potentiality low cost and the ability to optimize it for high precision and processing speed, laser triangulation has been frequently implemented in commercial systems which are then known as laser line scanners or laser triangulation sensors (LTSs). A current overview about triangulation based, optical measurement technologies is given in (Berndt, 2008).

The operating principle of laser line triangulation is of actively illuminating the object to be measured with a laser light plane, which is generated by spreading out a single laser beam using a cylindrical lens. By intersecting the laser light plane with the object, a luminous laser line is projected onto the surface of the object, which is then observed by the camera of the scanning device. The angle formed by the optical axis of the camera and the light plane is called angle of triangulation. Due to the triangulation angle, the shape of the projected laser line as seen by the camera is distorted and is determined by the surface geometry of the object. Therefore, the shape of the captured laser line represents a profile of the object and can be used to calculate 3D surface data. Each bright pixel in the image plane is the image of a 3D surface point, which is illuminated by the laser line. Hence, the 3D coordinate of the illuminated surface point can be calculated by intersecting the corresponding projection rays of the image pixels with the laser light plane.

In order to capture a complete surface, the object has to be moved in a controlled manner through the light plane, e.g. by a conveyer belt or a translational robot movement, while multiple laser line profiles are captured by the sensor. In doing so, the surface points of the object as seen from the camera can be mapped into 3D point data.

3.2 Shadow-free laser triangulation with multiple laser lines

There are, however, certain disadvantages shared by all laser scanners and which have to be taken into account when designing a visual inspection system. All laser line scanning systems assume that the surface of an inspection object is opaque and diffusely reflects at least some light in the direction of the camera. Therefore, laser scanning systems are error-prone when used to scan shiny or translucent objects. Additionally, the object colour can influence the quality of the acquired 3D point data, since the contrast of the projected laser line must be high enough to be detectable on the surface of the object. For this reason, the standard red HeNe laser (633 nm) might not always be the best choice, and laser line projectors with other wavelengths have to be considered for different inspection tasks. Furthermore, the choice of the lens for laser line generation is crucial when the position of the laser line should be detected with sub-pixel accuracy. Especially when the contrast of the captured laser line is low, e.g., due to bright ambient light, using a Powell lens for laser line generation can improve measurement accuracy, compared to the accuracy obtained with a standard cylindrical lens (Merwitz, 2008).

An even more serious problem associated with all triangulation systems is missing 3D point data due to shadowed or occluded regions. In order to measure 3D coordinates by triangulation, each surface point must be illuminable by the laser line and observable by the camera. Occlusions occur if a surface point is illuminated by the laser line but is not visible in the image. Shadowing effects occur if a surface point is visible in the image but is not illuminated by the laser line. Therefore, both effects depend on the camera and laser setup geometry, and the transport direction of the object. By choosing an appropriate camera-laser geometry, the amount of shadowing effects and occlusion can be reduced, i.e., by choosing a smaller angle of triangulation. However, with a smaller angle of triangulation also measurement accuracy decreases and in most cases, shadowing effects and occlusion cannot be eliminated completely without changing the setup of camera and laser.

To overcome this trade-off and to be able to capture the whole surface of an object without the need of changing the position of camera or laser, various methods can be applied. One solution is to position multiple laser triangulation sensors in order to acquire multiple surface scans from different viewpoints. By aligning the individual scans into a common world coordinate system, occlusion effects can be eliminated. Obviously, the main disadvantage of this solution is additional hardware costs arising from costly triangulation sensors. In the case of robot-based inspection, missing 3D data can also be reduced by defining redundant path-plans, which allows capturing multiple surface scans from different points of view of a single region to be inspected. This approach would make path-planning more complex and would lead to a longer inspection time.

In order to avoid the aforementioned disadvantages, a 3D measurement system with single triangulation sensor but multiple laser line projectors is presented, which keeps inspection time short and additional costs low. Due to new advances in CMOS technology, separate regions on a single triangulation sensor can be defined. Each one is capable of imaging a single projected laser line. Furthermore, processing and extracting image coordinates of the imaged laser profiles is done directly on the sensing chip, and thus extremely high scanning frame rates can be achieved. The scan data returned from such a smart triangulation sensor is organised as two-dimensional array; each row containing the sensor coordinates of a captured laser line profile. Thus, the acquired scan data has still to be transformed into 3D

world coordinates, using the calibrated camera position and laser light plane orientation in a common world coordinate system (see Section 3.4).

In the presented system, such a smart triangulation sensor is used in combination with two laser line generators, where each laser line illuminates a separate part of the sensor's field of view. Therefore, by scanning the surface of an object, scans from the same point of view but different light plane projection directions are acquired. By merging the individual scans of each laser, shadowing effects can be minimised and the 3D shape of a measurement object can be captured with a minimised amount of missing 3D data. This step is performed for both, the creation of a reference model and the subsequent inline inspection of the production parts.

3.3 3D inspection workflow

Fig. 8 gives an overview of the steps required for a 3D inspection task. In the following, the individual steps of the data acquisition and processing workflow are described in more detail.

3.4 Sensor calibration and 3D point data acquisition

As mentioned before, the scan data returned by the triangulation sensor are related to sensor coordinates, describing the position of individual laser line profiles which were captured during the scanning process. In order to get calibrated measurements in real world coordinates, the laser triangulation sensor has to be calibrated. This yields a transformation from sensor coordinates (x, y) into world coordinates (X, Y, Z) which compensates for nonlinear distortions introduced by the lens and perspective distortions caused by the triangulation angle between laser plane and the optical axis of the sensor. Therefore, the calibration procedure can be divided into the following steps:

- Camera calibration;
- Laser light plane calibration;
- Movement calibration of the object relative to the measurement setup.

For camera calibration, extrinsic and intrinsic parameters have to be determined. Extrinsic parameters define the relationship between the 3D camera coordinate system and the 3D world coordinate system (WCS). For example, the z-axis of the camera coordinate system coincides with the optical centre of the camera, i.e., with the optical axis of the lens.

The intrinsic parameters are not dependent on the orientation of the camera expressed in world coordinates. Moreover, the intrinsic parameters define the transformation of the 3D camera coordinate system (metric) and the 2D image coordinate system (ICS) (pixel). Thus, they describe the internal geometry like focal length f , optical centre of the lens c , radial distortion k , and tangential distortion p . The effect of parameters k and p are visualised in Fig. 9.

Fig. 8. The 3D inspection workflow depicts the major elements described in this chapter.

Fig. 9. The left pattern depicts the effect of radial distortion, whereas the right pattern shows the effect of tangential distortion.

We perform the calibration according to Zhang (2000) which is based on the pinhole camera. For this method an image of a planar chess board is taken with at least two different positions. The developed algorithm computes the projective transformation of the 2D image coordinates of the extracted corner points of the chess board by using the n different images and its 3D coordinates. Therewith, the extrinsic and intrinsic parameters of the camera are gained with a linear least-square method. Afterwards a non-linear optimisation is applied based on maximum-likelihood criteria using the Levenberg-Marquardt algorithm. By doing

so, the error of back projection is minimised. The distortion coefficients are determined according to Brown (1971) and are optimised as mentioned above. Zhuge (2008) describes that a minimum of 2 images are required depicting a 3x3 (4 corners) chess board. Improving numerical stability a chess board with more squares and more pictures is to be recommended. We used a 7x9 chess board (48 corners, Fig. 10) and checked the change of the parameters as a function of the number of images used as input for computing the intrinsic and extrinsic parameters. The extrinsic parameters are expressed in terms of rotation and translation in order to put into coincidence point of origins of image coordinates and world coordinates.

Fig. 10. Images for the camera calibration.

Table 1 shows the exemplary results using 7, 12, and 20 images as input for calculating the intrinsic and extrinsic parameters. The results, for example with arbitrarily selected 7 pictures, are totally wrong. If the positions and the views of the chess board are well distributed in selected pictures, the results become then better and better. The best choice for the current investigation is marked in Table 1 with red. It is not necessary to use 20 pictures for the camera calibration. For low measuring accuracy or for a smaller sensor chip the number of pictures can be reduced to 12 or less.

In order to test the quality of the estimated camera parameters, the 3D world coordinate corners of the chess board are projected onto the image with the computed camera parameters. The smaller the deviation is between the 2D coordinates of the back projected corners and the 2D coordinates that correspond to the 3D world coordinates the better is the computation of the parameters. To determine the extrinsic parameters it is recommended to use images where the chess board is centred. Finally the x- and y-axis of the ICS are brought into line with the X- and Y-axis of the WCS if the camera parameters are perfectly calculated. In Fig. 11 the first row and the first column of the green dots depict the X- and Y-axis of the WCS. If the camera parameters would have been computed perfectly, the WCS axes and the ICS axes would coincide.

After lens correction, image coordinates can be mapped to world coordinates using the orientation of the light plane in the world coordinate system, and the relative movement of the object between two acquired scans. Since the robot-based inspection system allows for an accurate tracking of the triangulation sensor in any scanning direction, no calibration of

the linear positioning by the robot is needed. To determine the orientation of the light plane, several methods have been proposed (Deutsch, 2007), which essentially use at least three data points from the projected light plane to approximate a best-fit plane into the obtained points.

No. of pictures	Intrinsic camera parameters					
	c_x, c_y [Pixel]	f_x, f_y [Pixel]	k_x, k_y [a.u.]	p_x, p_y [a.u.]		
7(03-09)	622, 160	576, 575	-0.014, -0.001	0.003, 0.001		
12(¹)	725, 229	2940, 2930	0.041, -3.034	0.005, 0.003		
20(01-20)	718, 240	2933, 2924	0.041, -2.974	0.006, 0.003		
No. of pictures	Extrinsic camera parameters					
	θ_x [rad]	θ_y [rad]	θ_z [rad]	t_x [mm]	t_y [mm]	t_z [mm]
7(03-09)	0.01	0.01	0	-134.3	-35.0	120.3
12(¹)	0.04	0.02	0	-154.6	-49.2	617.0
20(01-20)	0.05	0.02	0	-153.0	-51.4	615.4

Table 1. Compare the exemplary results of the estimated camera parameters with different positions and views of the chess board used for the camera calibration. The best one is marked with red. f : focal length; c : optical centre of the lens; k : radial distortion; p : tangential distortion; t_x, t_y, t_z : shift to the X-, Y- or Z-direction; $\theta_x, \theta_y, \theta_z$: rotation to the X-, Y- or Z-axis.
¹: the selected pictures were 1, 3, 6, 8, 12, 13, 14, 15, 16, 17, 18 and 19.

Fig. 11. Back projection of the world coordinate system into image coordinate system.

3.5 Laser calibration, pre-processing, and data merging

In this work, a laser calibration method is used that maps scan data acquired with different lasers to a common world coordinate system in two steps. In doing so, the orientations of the light planes of the lasers are not determined explicitly but are given implicitly by two 3D projective transformations, one for each laser. First, the scan data of each laser is augmented by a third coordinate, which comprises the translational movement of the object between two single laser line scans. This yields two perspective-distorted 3D point data sets for each laser. In a second step, perspective transformations are applied to the data sets, which correct for the perspective-distortions and align the data in a common world coordinate system (see lower Fig. 12).

These perspective transformations are modelled by systems of linear equations which can be solved by established 3D point correspondences. To identify corresponding 3D point pairs in the common world coordinate system and in the perspective-distorted 3D point data of each laser, a pyramid-shaped calibration target is used. Since planes are mapped to planes by perspective distortions, the faces of the pyramid can be easily identified in the distorted 3D point data. To this end, surface normals are computed for each 3D point in a local neighbourhood. By comparing the direction of the surface normals, the 3D points can be segmented into four point sets, each belonging to a pyramid face. For each point set, a least-square best-fit plane is computed. By intersecting the pyramid planes and the measurement plane, five intersection points are obtained which serve as feature points for establishing point correspondences.

From the obtained point correspondences, two perspective transformations are computed by solving the system of linear equations for each laser. Since the point correspondences are established from the same feature points in the world coordinate system, both transformations compensate for the perspective distortion and align the 3D point data sets into the world coordinate system (see Fig. 12).

Before the perspective transformations have been computed, the acquired scans of each laser should be mapped in real world 3D point data in a common world coordinate system. However, the 3D point data of both lasers is maintained in separate data structures. In order to take advantage of the complementary missing data regions in the 3D point data sets, it is desirable to merge the aligned point data into a unified data structure. Due to the sequential nature of the laser line scanning process, captured 3D point data for each laser are sorted by their acquisition direction. Since most point data processing techniques, e.g., methods for surface reconstruction, take advantage of sorted data, this property should be maintained while the data is merged.

The problem of merging the two 3D point data sets therefore reduces to merging two sorted sequences into a single sorted sequence (FUSION, 2008). By stepwise comparing and choosing 3D points from the data sets, it is ensured, that the merged list is still sorted. Furthermore, 3D points whose coordinates do not agree with their acquisition direction are identified and dropped. These 3D points are assumed to stem from interreflections of the projected laser lines and the surface of the object, and therefore might lead to wrong measurements.

In most cases, dropping 3D data points does not significantly decrease data quality for subsequent processing steps since the acquired raw 3D point data are very dense. However, there exist surface regions where data acquisition is very difficult due to interreflections and

larger regions of missing data can occur. In such regions, bilinear interpolation is used to estimate missing surface data. Fig. 13 shows how missing data gaps are closed.

Fig. 12. 3D point data of a scanned mould. Upper: Unaligned 3D point data acquired with two laser lines, projected from the left (green) and right (red) side of the mould. Lower: By calculating and applying perspective transformations to the perspective-distorted 3D point data of each laser, the data becomes aligned in a common world coordinate system.

Fig. 13. Upper: Green dots are the missing scan data. Lower: The missing scan data gaps are closed.

3.6 Model building

The final goal of the data acquisition of the 3D laser triangulation sensor is to compare either CAD data or a reference model based on scanned data with acquired data of the test object. Therefore, this step is depicted at the end of the inspection pipeline (Fig. 8). Once a model is

created in the sense that it meets the requirements for being comparable with the test object it can be saved in a data base to be picked up from there if needed. The usefulness, i.e., meeting of requirements of the model depends on the task of the quality check. A task could be to determine the volume of a complete object or to determine the volume only at a certain location of an object. Another task could be to scan the surface of an object with a position-dependent precision. Hence, the model includes locally varying tolerances. Here we follow the creation of a model, a so-called reference model, yielded by scanning a good test object which is later compared with a test object having an artificial error.

The transformation matrix of the calibration of the reference measurement is used for the comparison of future test scans. Additionally, a registration of the reference measurement and the test scans are performed and needed for comparison. The registration corresponds to the alignment of the reference model and the test data. The data of the two lasers, as supplied by the camera, could have identical indices associated with different 3D coordinates. Thus, the point cloud is re-indexed in the WCS and assigned to a new mesh. An interpolation is performed for all points of each square of the mesh in order to compute the value of the centre point. In accordance to the resolution of the camera, the size of the mesh is adjusted. On the one hand, it has to be taken into account that small meshes contain less or no data points which results in an increasing number of data gaps. On the other hand, if the meshes are too big, the determination of the volume becomes less precise.

Fig. 14. The pyramid was scanned with and without the red artificial error.

We used for the data acquisition a sample rate of 0.2 mm along all coordinate axes and each mesh square had a size of 0.4x0.4 mm. The test object was a pyramid (Fig. 14) which is 150 mm wide at the basis and a maximal height of 20 mm. The sensor has got 1500x500 pixels. During the data acquisition signal noise was observed which was not negligible. Due to observations, it can be stated that the noise caused an uncertainty of less than ± 0.1 mm. Hence, a threshold of ± 0.1 mm is applied for a cluster process.

In the cluster process the model data and the test data are compared with the aim to suppress data which result from measurement uncertainty, and hence to get the volume difference of the model and the test object. The cluster in Fig. 15 is bounded by bold lines and does not exist in the beginning, but is generated after the comparison. If the criteria described below are fulfilled a cluster is the outcome. For this comparison the neighbours of a data point are taken into account and two criteria determine the clustering:

- If two of eight neighbours (red dots in Fig. 15) of the data point considered (green dot in Fig. 15) and the data point itself have a height difference that is larger than the absolute value of 0.1 mm, the data point is assigned to a cluster and not regarded as measurement uncertainty. Fig. 15 shows on the left the model data (blue dot) used for comparison. The cluster is depicted by bold black borders.
 - If the height difference of one neighbour and the considered data point is larger than the absolute value of 0.1 mm and the neighbour belongs to the cluster area, the data point is assigned to the cluster to be built. This situation is shown in Fig. 15 on the right. Fig. 16 shows the difference plot of the model data and the test data, i.e., the difference of the pyramid with and without red coding dot label. Red depicts positive deviations whereas green shows negative deviations.
- Fig. 17 shows the result of the difference plot after clustering of the model data and the test data. The red coding dot label stands out clearly due to clustering.
- The computation of the volume yields a good result for the red coding dot label on one side of the pyramid. Fig. 17 shows the result in detail in graphical form from a side view and from a top view.

Fig. 15. Left: Model data. Middle: Cluster with at least two neighbours. Right: Cluster with a neighbour in the cluster.

Fig. 16. Difference plot of model and test object.

Fig. 17. Difference plot of model and test object after clustering.

4. Conclusions

This paper has presented a robot-based inspection centre that uses wide-range sensors and an array of test-specific short-range which make the logical quality monitoring and the metric inspection process more accurate and flexible. Path optimisation and use of a sensor magazine supplement the robot-based inspection centre such that its flexibility yields problem-specific application coupled with economical and efficient improvements; these improvements are methodologically and operationally inherent. Specifically, using multiple projected laser lines the inspection time can be strongly reduced, additional costs kept low, and the quality of the inspection results is even still higher.

As Fraunhofer has got a strong focus on applied research, one of our main goals for the creation of the development and demonstration platform is to investigate, to optimize and to demonstrate to our potential cooperation partners how the inspection centre can be applied to reduce effort and to increase accuracy and flexibility. It can be used in the robot-based coordination of short and wide-range monitoring, for the introduction of learning capable evaluation processes, as a tool for visualizing results and for user interaction, as well as for the flexible networking and integration of various wide and short-range sensors. Depending on the test task the presented four steps can be used completely or partly in a meaningful combination. Its modular and hence flexible structure is a modern basis for future requirements and/or add-ons. This structure is especially needed, because nowadays fabrication is characterised by continuous, flexible product change.

Further inspection sensors, which are based on other measurement principles, will be developed on the sensor magazine and made available for the inspection on and below the surfaces. Due to other research work at our institute the sensor magazine especially could be equipped with devices used for deflectometric methods (Werling et al., 2007) as it is a promising inspection technique for shiny and mirror-type surfaces.

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This book is a collection of 18 chapters written by internationally recognized experts and well-known professionals of the field. Chapters contribute to diverse facets of contemporary robotics and autonomous systems. The volume is organized in four thematic parts according to the main subjects, regarding the recent advances in the contemporary robotics. The first thematic topics of the book are devoted to the theoretical issues. This includes development of algorithms for automatic trajectory generation using redundancy resolution scheme, intelligent algorithms for robotic grasping, modelling approach for reactive mode handling of flexible manufacturing and design of an advanced controller for robot manipulators. The second part of the book deals with different aspects of robot calibration and sensing. This includes a geometric and threshold calibration of a multiple robotic line-vision system, robot-based inline 2D/3D quality monitoring using picture-giving and laser triangulation, and a study on prospective polymer composite materials for flexible tactile sensors. The third part addresses issues of mobile robots and multi-agent systems, including SLAM of mobile robots based on fusion of odometry and visual data, configuration of a localization system by a team of mobile robots, development of generic real-time motion controller for differential mobile robots, control of fuel cells of mobile robots, modelling of omni-directional wheeled-based robots, building of hunter- hybrid tracking environment, as well as design of a cooperative control in distributed population-based multi-agent approach. The fourth part presents recent approaches and results in humanoid and bioinspirative robotics. It deals with design of adaptive control of anthropomorphic biped gait, building of dynamic-based simulation for humanoid robot walking, building controller for perceptual motor control dynamics of humans and biomimetic approach to control mechatronic structure using smart materials.

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