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Procedia CIRP 81 (2019) 968–973

www.elsevier.com/locate/procedia

52nd CIRP Conference on Manufacturing Systems

Free-Form Surface Analysis and Linking Strategies for High Registration Accuracy in Quality Assurance Applications

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Abstract

Robot-based optical inspection systems have become more affordable and show great potential for measuring geometric features of sheet metal parts in production sites. To deal with the lack of positioning accuracy of current industrial robots for the registration of range images, a stitching algorithm is often applied. This paper presents a concept to improve the fine registration accuracy in order to reduce the effect of error propagation. A geometric analysis of the surface is introduced to identify suitable regions for applying adapted texture projections onto the part. In addition, an approach to develop a corresponding linking strategy is described. The proposed concept promises to measure geometric features on both plane and highly featured surfaces with high accuracy.

Keywords: robot vision systems; robot-based inspection systems; range images; image processing; free-form surface analysis; manufacturing industries

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1. Introduction

Quality assurance plays a crucial role to ensure necessary quality standards of components in modern production sites. Hence, leading companies invest a lot of resources to monitor their products throughout the entire manufacturing process. Since quality assurance is usually not value-adding, effective and efficient inspection processes contribute to a competitive advantage in the global market and help to provide competitiveness for a sustainable future.

Current trends like individualized mass production and high cost awareness, yield new challenges. Beside the inherent requirement of high measurement accuracy, high data acquisition speed, more flexibility and low cost technology emerge [1]. As a consequence, robot-based inspection systems have become more popular over the last decade in comparison to state of the art coordinate measuring machines (CMM).

Robot-based inspection systems usually comprise of an industrial robot and an optical 3D sensor. The robot functions as a manipulator and carries the sensor through the working space in order to acquire a digital representation of the area of interest in the form of a point cloud respectively of a range image.

Since the field of view (FOV) of optical systems is limited, geometric features extending the FOV are captured by multiple images and merged afterwards. To integrate the data into a global coordinate system (CS), the proper transformation needs to be obtained. This process is usually referred to as registration.

Due to the lack of absolute position accuracy of robots, the transformation retrieved from the robot control can not be employed for quality assurance purposes.

Therefore, the concatenation of several point clouds for robot-based inspection systems was introduced by [2, 3] using the measurement data itself for obtaining a transformation. The approach exploits the high accuracy of state of the art optical 3D sensors without taking the industrial robot into the measurement chain. The results showed that the inaccuracy of the self-localization of the robot could be compensated. Furthermore, no expensive tracking systems,

10.1016/j.procir.2019.03.236

manual application of physical markers or time-consuming calibration programs of the robot are needed.

This approach uses the mutual area of range images acquired at two consecutive measurement poses, in the following referred to as the overlap area. In addition, intensity data provided by applied texture projections are encoded into the range image. The alignment is conducted subsequently by employing a 3D registration algorithm. This way, two or more range images can be linked and evaluated as a whole.

In this paper, we describe a new concept for 3D image stitching for robot-based inspection systems based on the work of [2, 3]. It focuses on identifying homogenous regions within the overlap area and using these as a carrier for texture projections. The data points in those regions as well as the encoded ones are later on employed for the subsequent registration process. The presented concept is considered as a standalone offline solution prior to the actual measuring process by introducing simulated measurement data.

The novel approach aims at achieving high registration accuracy independent of the shape of the overlap area while also providing sufficient robustness and an estimation of the resulting alignment error. The core aspect consists of automatically looking for the mentioned plane, featureless regions in a simulated range image of the overlap area and applying projections exclusively to those designated regions on sheet metal parts. Combined with a corresponding linking strategy, the enhancement through our concept promises great potential to cope with the current challenges in modern geometric quality assurance.

Nomenclature

CAD	Computer Aided Design
CMM	Coordinate Measuring Machines
CS	Coordinate System
ICP	Iterative Closest Point
FOV	Field of View

2. Motivation

Error propagation is an inherent problem of concatenated images by means of registration. Due to random errors emerging from influences like the environment, the measuring device, or the operator, the acquisition of perfect range images is not possible. With each additional link, the overall alignment error increases. Hence, minimizing the alignment error of links while reducing the overlap area are present goals in order to achieve high registration accuracy and to enlarge the measuring range of robot-based inspection systems.

In addition, a high flexibility of the measurement method is important to make it more accessible for various parts and different industries, accordingly a broad field of measurement applications. Therefore, high registration accuracy and robustness needs to be independent of the shape of the surface, i.e. the underlying overlap area.

Furthermore, the accuracy of a measurement method should not depend on the user. A method of 3D image stitching for robot-based inspection systems [2, 3] is preferred which is independent of experience and preknowledge of the measurement engineer in charge. In that regard, the possibility of automation of the desired method provides a lot of potential.

Our concept promises an enhancement for quality assurance applications, which require robot-based inspection systems with an optical 3D sensor due to, for example, large batch sizes, many features of interest, and high manufacturing tolerances. Typical examples are the inspection of car body parts in the automobile industry, components in the aviation sector or tool engineering. The variety of large sheet metal parts in automotive engineering, which need to be inspected automatically, reaches from parts with large homogenous regions, for example a hood or a car top, to highly featured surfaces as it can be found for instance at the inside of a side door. The main goal of the presented concept is to extent the existing 3D image stitching approach with texture projections [2, 3] to any kind of underlying surface and, therefore, to increase the applicability of this measurement method.

3. State of the art

3.1. Fine registration through Iterative Closest Point

In order to align two range images with an overlap area, various algorithms exist. It is distinguished whether or not an estimation of the transformation is needed in advance. In case that an initial transformation is required, the process is often referred to as fine registration.

Since the robot control provides a transformation between two poses – within the scope of the absolute pose accuracy of the robot –, fine registration algorithms can be applied.

The Iterative Closest Point (ICP) algorithm [4] is widely used and well-established for the fine registration of point clouds. Hereby, points are connected between both point clouds according to a certain metric. Afterwards, the corresponding transformation is calculated minimizing the error metric. The procedure is repeated iteratively until certain termination criteria are met.

Numerous modifications exist, since Besl and McKay presented the ICP algorithm in 1992 [4]. Also Chen and Medioni published a similar method using a point to plane error metric [5]. Segal et al. [6] integrate both error metrics of [4, 5] into one algorithm. [7] provide an additional possibility of including color information into the fine registration process. For a detailed review of current registration algorithms see [8, 9].

3.2. Multi-view registration for measurement applications

Beside applications in industrial quality assurance [10], multi-view registration is a common procedure in different disciplines like object reconstruction [11], cultural heritage preservation, e.g. archeology [12] or cultural relic packaging [13], or environment mapping, for example in autonomous driving [14] or navigation of micro aerial vehicles [15], to obtain a full digital representation of the entire object or surrounding of interest.

A flowchart of multi-view registration for geometric quality assurance is depicted in Fig. 1a. First, point clouds respectively range images are acquired by a 3D sensor at measurement poses covering the area or features of interest. If the proper alignment is found through the data itself by applying for example an ICP algorithm to the points in the overlap area, the term ‘data-driven registration’ is widely used. After all transformations are found, the data is transferred into a single CS. This process is often referred to as integration. Afterwards, a comparison of the actual dimensions of the features with a digital representation, for example a CAD model, is conducted. The concatenation of several images in an open-loop manner is often also described as image stitching, compare Fig. 1b.

Wu et al. [16] present a viewpoint planning concept for digitization or geometric assessment, but focuses on the pose planning with a defined size of the overlap area.

In [17], 3D fine registration is employed to link measured point clouds to a corresponding CAD model in order to improve the absolute pose accuracy of industrial robots for subsequent checking for form deviations of the part.

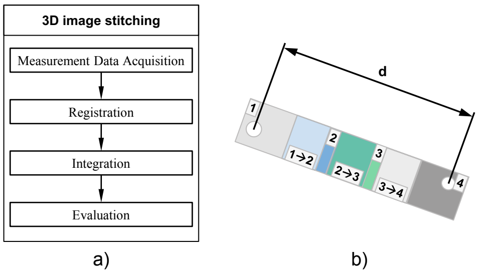

Fig. 1. a) Flowchart for geometric quality assurance through multi-view registration of range images. b) An illustration of four concatenated point clouds in an open-loop way for evaluating the distance d.

In the work of [2, 3] texture projections are used to artificially encode additional geometric features into the range image of the overlap area, in the following referred to as just *3D image stitching*. At detected edges of projected patterns, points are added in normal direction prior to the 3D registration. This method is addressing in particular sheet metal parts with mostly plane, featureless surfaces, i.e. homogenous surfaces. For parts with those characteristics, high registration accuracy was achieved. The method does not provide further information whether or not to apply texture projections to medium or highly featured surfaces and how to deal with the associated implications like changing lightning conditions and varying registration accuracies.

4. Concept overview

Varying registration accuracies, insufficient robustness, and the lack of predictability of the alignment error require an enhancement of the measuring method *3D image stitching*. Therefore, we introduce a new offline concept which comprises region-specific texture projections with a prior analysis of the free-form surface of the overlap area. The corresponding linking strategy contains experimentally predefined parameters and procedure guidelines. An overview of the modules of the concept and their integration into the entire measuring process is shown in Fig. 2.

Subsequent to the offline pose planning of the measurement task, our concept is executed prior to the actual measuring process. It consists of three modules: surface analysis, region-specific projection, and the linking strategy.

At each measurement pose of the 3D sensor, a simulated range image is retrieved from a CAD model. The image is cut down to the overlap area for computational performance purposes. After identifying homogenous regions in the remaining range image (module: surface analysis), a corresponding 2D projection image is derived (module: region-specific projection) containing projection primitives in the designated regions and positions according to the linking strategy. This process is repeated iteratively until each pose possesses a corresponding projection image. Afterwards, the actual measuring process gets initiated.

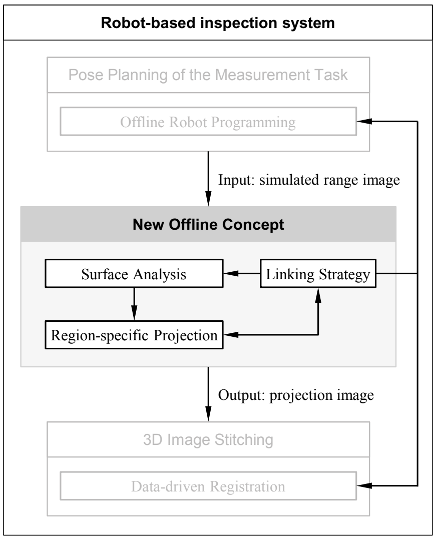

Fig. 2. The flowchart depicts our new concept and its modules between the prior offline robot programming and the subsequent measurement method 3D image stitching for robot-based inspection systems[1].

Fig. 3a shows an exemplary sheet metal part with two FOV and the resulting overlap area marked by the red circle. Fig. 3b depicts one of the trimmed range images with a full texture projection, as suggested in the work of [2, 3]. Fig. 3c illustrates our approach by applying projection primitives (yellow squares) only to homogenous regions.

First observations suggest that also for a highly featured surface, for example the inside of a side door of a car, the registration accuracy depends on the characteristics of those features in the overlap area with and without full projections. Significant deviations to the right measured value by a CMM were observed in both cases when slightly varying the overlap area for the measurement of an Euclidean distance between two bores. Since manufacturing tolerances of 0.1 mm are usually aimed at in automotive industry, an

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[1] Measuring method ‘3D image stitching’ based on the work of [2, 3].

enhancement is necessary to further increase accuracy and robustness of the existing measuring method.

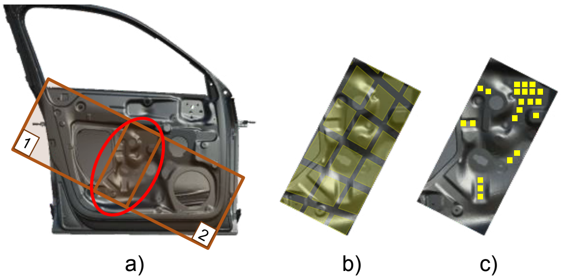

Fig. 3. a) Sheet metal part with a depicted overlap area of two range images. b) Texture projection applied to the entire overlap area. c) Projection primitives (yellow squares) applied exclusively to homogenous regions in the overlap area.

The main idea of the concept consists of deliberately selecting homogenous regions with applied region-specific texture projections for registration over featured free-form surfaces with or without full projections. Projecting over the entire overlap area, as proposed by [2, 3], is covered by our concept in the case that the entire area is evaluated as one coherent homogenous region. But in contrary to the work of [2, 3], it is not intended to apply distorted projection primitives as artificial features, i.e. virtual references.

5. Free-form surface analysis

In data-driven registration, high accuracy is connected to the shape of the surface that two concatenated range images share. While homogenous surfaces have no stable alignment configurations, areas with a high degree of geometric features tend to provide significantly better results [11].

Since the shape of the overlap area depends on the part as well as the chosen FOV, each time the shape changes the registration process faces different conditions resulting in varying alignment errors.

Considering free-form surfaces with features like holes and edges, anticipating their influence on the corresponding alignment errors opens up a highly complex mathematical task. Therefore, we choose a different approach: homogenous regions tend to not converging to the right local minimum during 3D matching. However, with the aid of providing additional information, i.e. applied texture projections, this circumstance is bypassed, and high registration accuracy is achieved, cf. [2, 3]. Hence, our concept identifies homogenous regions and exclusively provides projection primitives to those designated regions.

Furthermore, measurement data quality of optical systems varies at regions with high curvatures or at edges. This also impacts the accuracy of data-driven registration.

This module analyses the free-form surface of the overlap area in relation to homogenous regions. Hereby, we assume that some sort of homogenous regions are present within the overlap area respectively the sheet metal part. The inspected parts comprise mainly test objects originating from the automobile industry. Geometric dimensions, features, and shape of those parts exceed multiple times the dimensions of the projection primitives and mostly show some homogenous regions. Therefore, we take the assumption as justified.

Fig. 4 shows the module of the surface analysis and its components. It comprises the surface descriptor, the surface feature, and the surface classification.

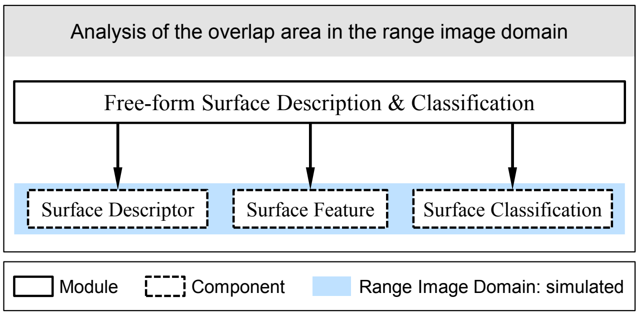

Fig. 4. The module "Surface Analysis" classifies random free-form surfaces into homogenous regions by calculation of a predefined surface descriptor and surface feature.

By means of a suitable surface descriptor, a certain surface feature can be determined for each discrete point of a surface. In addition, a classification scheme is established to specify whether or not a point of a range image is considered being part of a homogenous region. For that purpose, a measure of plane homogeneity is introduced, see section 7, which describes the degree of deviation of the predefined feature to an ideal homogenous plane.

Table 1 shows a small selection of potential approaches for quantitatively detecting homogenous regions. An evaluation is currently under investigation regarding the applicability of a suitable surface descriptor and surface feature in the context of the proposed concept.

Table 1. A preselection of potential surface descriptors, features, and classifiers to identify homogenous regions of random free-form surfaces.

Surface Descriptor	Surface Feature	Surface Classification
Normal	Angle	Intervals of Angle Deviation
Normal	Curvature	Intervals of Curvature Deviation
Plane	Distance	Intervals of Mean Square Error Deviation

After calculating the value of the surface feature, each individual point is classified according to a threshold of the plane homogeneity measure. As a result, the overlap area is now limited to points belonging to homogenous regions. The modified range image is passed on to the next module: "Region-specific Projection".

6. Region-specific texture projection

This module derives a projection image from the modified range image. By knowing the regions to apply texture projections on, the challenge arises how to map points in the range image domain to projector pixels in the projection image domain. Moreover, an additional model becomes necessary to embed projection primitives into the permitted regions. An overview of the individual components is provided in Fig. 5.

The projection model mathematically maps each point in the overlap area to a corresponding pixel of the projector. Current studies are using the principle of a pinhole camera combined with oblique projection. In the end, a 2D image with the resolution of the projector is derived indicating which pixel functions as a potential transmitter of a texture projection and which pixel needs to be suppressed, resulting in a binary image representing homogenous regions.

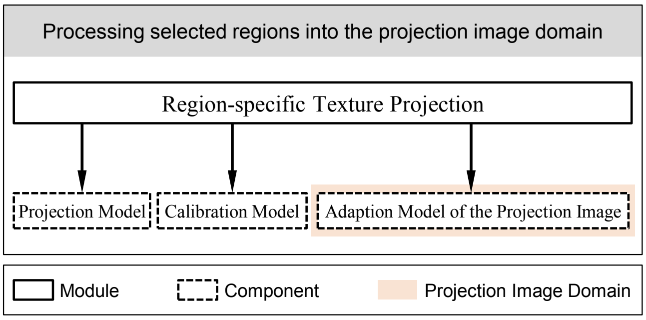

Fig. 5. Region-specific texture projection designs an individualized 2D projection image for each measurement pose based on the results of the surface analysis.

By means of a developed calibration model, the actual dimensions of the calibration volume in size and position can be determined within the working space in order to adapt the mathematical model to the real-world application. Within the calibrated volume, the projection model remains valid. To extent the calibrated working space, auxiliary kinematics for the projector can be deployed.

The calibration model is executed in the form of a certain procedure with step-by-step instructions which allows applicability to other setups. The accurateness of the calibration procedure has an impact on the actual projection position on the part. By fitting the projection primitives into the permitted regions with an additional predefined surrounding space—limiting the minimum distance to the next primitives and/or the borders, cf. next paragraph—procedural flaws can be compensated for.

Subsequently, the computed binary image is enhanced by projection primitives. Hereby, one or more primitives are embedded into the permitted regions of the image in a predefined manner considering various aspects of the linking strategy, see section 7. The final projection image represents the underlying free-form surface at each corresponding measurement pose reduced to its homogenous regions enriched by virtual references.

Since the quality of data acquisition and registration conditions stay assessable, sufficient robustness and predictability of the alignment error are expected, too.

7. Linking strategy

In a broader sense, the linking strategy provides a parametrization to the modules of the presented offline concept. The individual components are shown in Fig. 6: defining of the applicable projection primitive, determining of the corresponding alignment error in dependence on the chosen surface feature, selection of an admissible projection configuration, and the procedure guideline to interact with the prior offline robot programming unit and the subsequent data-driven registration, compare Fig. 2.

In the context of this paper, a projection primitive is understood as a single unit of a virtual reference applied for the measuring method *3D image stitching*. The primitive usually comprises of simple geometries, i.e. points, lines, polygons or circles. More complex structures, like optical labels, nested geometries or gradient patterns, are also possible. Dealing with different lighting conditions, both the kind of projection primitives and the employed detection algorithms of the later image processing promise to show impact on the localization accuracy and robustness, so on the registration accuracy as well. Hence, a projection primitive and detection method are determined capable of coping with those conditions.

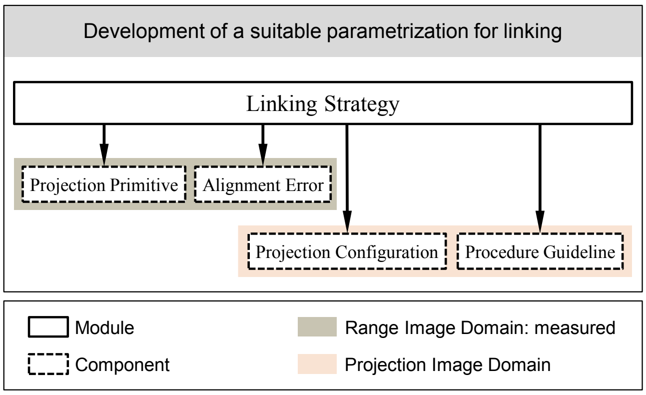

Fig. 6. The linking strategy provides experimentally determined parameters and instructions to other modules.

Since the shape of the underlying surface influences the functionality of the applied virtual references, it is investigated how a surface feature and related parameters, e.g. number of added points, ratio between measured and synthetic data, point spacing, affect the registration accuracy of a single projection primitive. Following this, we experimentally determine a measure of plane homogeneity indicating the decrease of registration accuracy, and derive a tolerable limit, which serves as a classifier for identifying homogenous regions in section 5.

The component “projection configuration” deals with the issue of all possible projection configurations resulting from successively adding a projection primitive to the binary image, cf. section 6. With each admissibly added primitive, a new configuration exists, i.e. a potential projection image for the later measuring process. During the fitting, certain requirements need to be implemented like expanding a primitive by an additional surrounding space to compensate for procedural flaws during calibration and avoid ambiguities in the registration process due to insufficient pose accuracy of the robot. Furthermore, different aspects of the projection configuration are considered and corresponding requirements are derived: First, the influence of symmetric or asymmetric arrangements of a set of primitives is investigated in relation to the convergence behavior of the ICP algorithm. Second, experiments will be conducted to find a minimum number of points needed to obtain reliable registration results. Third, the spatial distribution of primitives in the overlap area will show impact on the registration results. Based on the determined requirements, a final set of admissible projection configurations are available which all describe a valid projection image for the later measuring process.

The procedure guideline selects the final projection configuration. In the case of more than one valid configuration, the procedure guideline brings additional objective functions into action. Beside registration accuracy, minimizing the overlap area to enlarge the overall measuring range or optimization in regard to computational performance are possible options. The opposite scenario with no valid configurations is dealt with by defined instructions, for example, reducing the size of the primitives or enlarging the homogenous regions by adjusting the classifier. Ultimately, if no acceptable projection configuration is available, the procedure guideline component communicates in the form of a feedback-loop with the pose planning module to change the current measurement pose—i.e. the overlap area. Finally, the procedure guideline provides a preselection of points for the data-driven registration module.

This way, *a priori* investigated point collections of designated regions are employed during registration. It promises higher robustness and a better possibility to estimate quantitatively the resulting alignment error.

8. Conclusion

In this paper, we address the problem of varying registration accuracies at different shapes of surfaces with the measuring method 3D image stitching for robot-based inspection systems according to the work of [2, 3].

Therefore, we present a new concept, which promises to achieve high registration accuracy with sufficient robustness independent of the underlying surface. The goal is to reach a measurement uncertainty that is similar to one at an ideal homogenous plane with full projections. First tests at such a plane showed an uncertainty of approximately 50-60 µm for one link. The concept also promises the possibility of estimating the expected alignment error, which makes it more accessible for real-world quality assurance applications.

The proposed concept comprises a surface analysis module, region-specific texture projections, and a linking strategy. The standalone offline solution is integrated into a feedback-loop with the offline robot programming and communicates with the data-driven registration module by specifying a set of applicable points.

Since the entire concept is executed offline after the pose planning for the measurement task, an improvement of the actual required computational performance after the measurement data acquisition is also expected. This pushes the measuring method *3D image stitching* through data-driven registration towards shorter cycle times.

Primary research will focus on the question which surfaces are suitable to project on and how to parameterize them in order to reduce registration errors. Different projection primitives will also be tested in order to compensate variations in intensity and how they contribute to accuracy. Furthermore, experimental investigations need to be conducted to employ the right configurations of projection primitives complying with the mentioned goals. The concept is intended to be tested with sheet metal parts from the automotive industry. Future work could also incorporate a second robot for spatial manipulation of the projector to further enhance the measurement method.

Acknowledgements

The concept presented above is being investigated and validated within the scope of the research project ‘CyMePro’ (Cyber-physical measurement technology for 3D digitization in the networked production). The grant is kindly funded by the Bavarian Ministry of Economic Affair, Energy and Technology and coordinated by the VDI / VDE-IT (funding code ESB036 / 001). In addition, we like to thank our research partners AUDI AG and ZEISS Optotechnik GmbH for their continuous work and constructive support.

References

[1] Berthold J, Imkamp D. Looking at the future of manufacturing metrology: roadmap document of the German VDI/VDE Society for Measurement and Automatic Control. Journal of Sensors and Sensor Systems (JSSS), 2 (1) (2013), p. 1–7.

[2] Ulrich M, 3D-Image-Stitching für roboterbasierte Messsysteme. Dissertation Technische Universität München, München, 2018.

[3] Ulrich M, Forstner A, Reinhart G. High-Accuracy 3D Image Stitching for Robot-Based Inspection Systems. 2015 IEEE International Conference on Image Processing (ICIP), Québec City, Canada (2015), p. 1011–1015.

[4] Besl P.J, McKay N.D. A Method for Registration of 3-D Shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14 (2) (1992), p. 239–256.

[5] Chen, Y, Medioni, G. Object Modeling by Registration of Multiple Range Images. IEEE International Conference on Robotics and Automation, Sarcamento, California, USA, 3 (1991), p. 2724–2729.

[6] Segal A, Haehnel D, Thrun S. Generalized-ICP. Proceedings of Robotics: Science and Systems, Seattle, USA (2009).

[7] Park, J, Zhou, Q.-Y, Koltun, V. Colored Point Cloud Registration Revisited. 2017 IEEE International Conference on Computer Vision (ICCV), Venice, Italy (2017), p. 143–152.

[8] Maiseli B, Gu Y, Gao H. Recent developments and trends in point set registration methods. Journal of Visual Communication and Image Representation, 46 (2017), p. 95–106.

[9] Pomerleau F, et al. Comparing ICP variants on real-world data sets. Autonomous Robots, 34 (3) (2013), p. 133–148.

[10] Li T, et al. Free-form surface parts quality inspection optimization with a novel sampling method. Applied Soft Computing, 62 (2018), p. 550–570.

[11] Salvi J, et al. A review of recent range image registration methods with accuracy evaluation. Image and Vision Computing, 25 (5) (2007) p. 578–596.

[12] Stavroulakis P, et al. Digital Preservation of the Nottingham Ichthyosaur Using Fringe Projection, In: Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection, 7th International Conference, EuroMed 2018, Nicosia (2018) p. 38–44.

[13] Song L, et al. Structured-Light Based 3D Reconstruction System for Cultural Relic Packaging. *Sensors,*18 (9) (2018), p. 1–13.

[14] Mutz F, et al. Large-scale mapping in complex field scenarios using an autonomous car. Expert Systems with Applications, 46 (2016), p. 439–462.

[15] Engel J, Stuckler J. Cremers, D.: *Large-Scale Direct SLAM with Stereo Cameras*. 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, Germany (2015), p. 1935–1942.

[16] Wu Q, Zou W, Xu D. Viewpoint Planning for Freeform Surface Inspection Using Plane Structured Light Scanners. International Journal of Automation and Computing, 13 (1) (2016), p. 42–52.

[17] Shi, Q, Xi N. Automated Data Processing for a Rapid 3D Surface Inspection System. IEEE International Conference on Robotics and Automation, Pasadena, CA, USA (2008), p. 3939-3944.