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Assembly specific viewpoint generation as part of a simulation based sensor planning pipeline

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Abstract

Manual assembly often lacks process monitoring since information feedback is only generated by the worker. Machine vision systems thereby offer the possibility to automatically derive process states without intervening the work in progress. Recent approaches in the field of sensor planning and advances in sensor simulation allow automatic machine vision design but simultaneously require detailed knowledge of relevant object features which is difficult to obtain. Therefore, this paper introduces a novel method to derive task-specific viewpoints for the inspection of assembly states supporting a simulation-based pipeline to configure the inspection setup automatically.

Keywords: assembly monitoring; sensor planning; sensor simulation; machine vision; production automation

1. Introduction

Increasing complexity and variety of production processes enhances the demand for process control systems to reduce downtime, guarantee sufficient quality and avoid rejects. Where manufacturing processes are frequently automated and therefore already have a high density of information, assembly is mainly performed manually. For this reason, the feedback of information and assembly progresses is typically done by the worker. In this environment, visual inspection systems offer the possibility to automatically monitor assembly states and derive the required information without intervening with the actual working process [1].

With the trend of mass customization not only the assembly process itself, but also the inspection system has to be adaptable at short notice. With a flexible and easy-to-configure machine vision system, the applicability on small batch sizes would increase. Unfortunately most industrial visual inspection systems, as they are today, are commonly task-specific solutions and are therefore hard to be transferred to another inspection task. A generalized, adaptable off-the-shelf system is not available and hence custom solutions need to be designed specifically for single applications [2]. As the planning and configuration processes themselves are directly connected to the task constraints, even small variations in product, production process or environment can cause a repetition of the whole configuration procedure.

The performance of machine vision systems depends on the combination of sensing hardware, illumination techniques, object properties and image processing algorithms, which strongly enlarges the design space for the configuration of those systems [3]. Furthermore there exists no standardized pipeline to engineer such systems, but classically the tasks like *task analysis*, *hardware selection*, *sensor planning*, *software implementation* and *system validation* have to be fulfilled. This process can either be considered as an expert-based process chain or as an iterative trial-and-error process and can therefore be time-consuming and inflexible [4].

An approach to lower the barriers on applying machine vision into varying production systems by accelerating and simplifying the configuration process are (semi-)automated process chains. By modeling scene, object and sensor, possible viewpoints can analytically be calculated, before the performance of the machine vision system can be validated through sensor simulation leading to the prototype setup. Benefits are less downtime in the production system and no need for physical parts [4]. Figure 1 shows a semi-automated pipeline for a task-specific and simulation-based configuration of machine vision systems. The general idea is, that a detailed task description provides the basis for the following sensor pose generation (feature derivation and viewpoint generation) which is followed by a sensor

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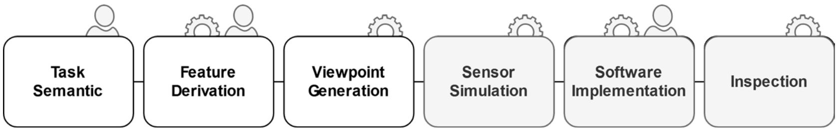

Fig. 1: Pipeline for task-specific and simulation based configuration of machine vision systems

simulation step to validate possible configurations, to select final viewpoints and to provide the necessary information for the software implementation. Research in the field of assembly specific machine vision is most commonly dedicated to the final processing steps of the pipeline (like AI-based assembly operation monitoring [1]) but lacks the previous configuration steps. A reoccurring problem during sensor configuration is the task specific definition of relevant features. Therefore, as a contribution to this pipeline, this paper presents a semi-automated procedure for the viewpoint candidate generation for assembly inspection based on 2D-images. Special focus of this publication is a method for viewpoint placement based on relevant features in assembly joints.

2. Related work

The topic of automated inspection planning is a part of research efforts from the 1990s on. It has gained attention especially in the fields of surface inspection [2], active robot vision [5] or public surveillance [6]. Where the focus of the early work is most commonly placed onto the definition of general visual constraints for sensor planning, it was slightly shifted along the years towards application-specific inspection planning and viewpoint optimization. Already in 1995 Tarabanis et al. [7] published a survey on sensor planning which classifies different approaches based on four introduced categories: *synthesis*, *generate-and-test*, *sensor simulation* and *expert systems*. All categories are based on a-priori known information regarding the object and sensors. Even current research can still be classified within these proposed categories.

Synthesis approaches model visibility constraints like visibility, concealment, perspective, field-of-view, resolution or depth-of-field as analytic functions. Sensor locations are then automatically calculated satisfying those constraints. Cowan et al. [8] contributed to the work of synthesis approaches by calculating independent continuous three dimensional exploration spaces for those constraints. The output of analytic, continuous approaches might diverge towards a global optimum but is - especially for complex objects - requiring a high computational effort.

In difference to those synthesis, the *generate-and-test* approaches generate sensor configurations by equally dividing the solution space and evaluate the single configurations. This procedure can be divided into two steps: Object space exploration which is the discrete computation of viewpoint candidates followed by the testing based on the introduced visibility constraints. First attempts in discrete viewpoint generation were made by Sakane [9] by surrounding the object with a sphere to restrict the possible sensor poses to be equally distributed over the sphere. As this approach quickly reaches its limit with complex or bigger objects, the topic of viewpoint generation moved into focus of research.

Sensor simulation and *expert system* differ from the previous categories as those approaches do not derive configurations automatically. The simulation can be used to evaluate viewpoints by visualizing the scene, within a framework to render sensor-real data based on configurations generated with either synthesis or generate-and-test approaches [4]. Expert systems can be considered as a set of rules which provides advice for the suitable sensor configuration based on input constraints, object, environment and sensing device [10].

As most work is based on the synthesis approach and the scope of this paper is the generation of assembly-specific features for inspection planning, current approaches for viewpoint candidate generation are presented in the following. Whereas the calculation of a sphere around on object of interest is a method which does not make use of the knowledge about the objects geometry, [11] uses the objects silhouette to create an offset mesh around the object. The offset is placed in the sensors depth of field. Viewpoint candidates are then distributed over the mesh and orientated towards the original objects cell.

An extension of this work is the active viewpoint candidate generation. The 3D model is therefore sampled based on the facets of its mesh and viewpoint candidates are then calculated in direction of the facets normal [12]. They are also placed in distance of the sensors depth of field. These approaches benefit from the fact, that the viewpoints are directly placed in the optimal viewing angle for surface inspections tasks, but - depending on the mesh resolution - produce a huge amount of viewpoint candidates which have to be optimized. Novel work by Mosbach et al. [13] is likewise based on an active approach, but uses geometric feature functionals to measure the relevance of object surface regions to perform a non-uniform viewpoint distribution. As a result the viewpoint candidates exist in larger numbers in regions of higher surface complexity, which lowers the number of viewpoints candidates going into the optimization phase. This work shows, that the sensor planning pipelines benefit from a task-specific feature derivation.

The presented work in viewpoint candidate generation has in common, that it uses the mesh of an object to distribute the candidates over the surface - even or uneven. In difference to that, the relevant features for assembly inspection are not directly related to the surface of the object but to geometrical features on its wire-frame. A viewpoint generation approach, which focuses on the semantic of how a completed assembly joint is geometrically described, has the potential to derive sensor poses with a high information density and reduces the number of viewpoints going into the optimization. Therefore in this paper such a task semantic and a viewpoint generation method is presented, fulfilling the first steps of a simulation based sensor planning pipeline for assembly inspections processes.

3. Task semantic

The overall goal of an assembly task is to join single parts or units to a final product or sub-assembly. Assembly tasks can thereby differ from positioning of single or multiple objects over connecting them via screws or rivets to welding or soldering [14]. The purpose of our assembly inspection system is the assembly state monitoring. Therefore the scope is to check the presence of parts and to verify the correct relationship between the the single parts within the assembly.

In order to perform a sensor planning for assembly inspection tasks, a detailed knowledge about task, object and environment - a so called task semantic - is necessary. The information which describes the general task semantic, as shown in table 1, originates from different sources. Geometry and positions of the objects are defined by their CAD-data, where the secondary objects involve all parts which are mounted to the primary object of interest for the inspection task. Different to the presented work in surface inspection planning the relevant features to decide whether an inspection result is positive or negative is not solely dependent on the surface of the objects geometry but on the relationship between the objects. Therefore the feature description is an important information for the viewpoint planning process. Feature descriptions are not a-priori available but need to be analyzed individually.

Table 1: Task semantic for assembly inspection planning

information	source
assembly type	design
geometry of primary and secondary objects	CAD
positions	CAD
feature description	inspection planning
sensor hardware	inspection planning
visibilty restrictions	environment
sensor placement restrictions	environment

Beside those visibility demands there may also be visibility restrictions inside the environment. These are areas or objects (e.g. humans) which must not be visible within the sensor data. Sensor placement restrictions are positions where sensors can not be mounted because of interference of the assembly process. The task semantic allows to model the scene within the sensor planning and viewpoint simulation processes.

4. Feature derivation

Providing a basis for feature description, a tool-set of basic features needs to be derived. Consisting of fundamental geometries and constraints it represents an amount of features which can be detected with classical 2D image processing algorithms.

4.1. Basic geometries and constraints

A geometric feature describes a generic shape or characteristic part of a workpiece with an engineering background. While designing products, different workpieces are related with constraints referred to their features. [15] Identifying these features indicates the semantic of whether an assembly task is completed or not.

As CAD-data is classically represented as a boundary representation, these objects can be modeled using a limited amount of basic geometrical elements. These basic geometrical elements can be categorized as surface, curve and point, where points arise as intersections from surfaces and curves. Stroud [15] defines a reasonable set of basic geometrical elements to create random geometrical objects as following:

1. **Surface:** planes, spheres, cylinders, cones, general quadratics, toroids, free-form surfaces
2. **Curve:** straight lines, circles, ellipses, parabolas, hyperbolas, free-form curves

To create defined geometries through a combination of these elements, constraints are needed which define the relationship between the elements. A basic constraint can create a relationship between planes, lines and points. They do not relate complex geometries, as they are always to be decomposed into their basic geometrical elements. The basic constraints for following analysis are:

1. Angular relationships
2. Distance relationships

The scope of this paper is to provide inspection planning for 2D image processing. To identify the majority of the elements from the surface category, 3D input data would be necessary. Therefore the category of curves represents the relevant basic features for the following analysis. Research on of the the transferability of the features for 3D-processing and extending the analysis to 3D features are reasonable steps and is the scope of future publications.

4.2. Geometrical features in assembly joints

The classical assembly operation groups are joining, handling, testing and assistance operations like cleaning or sealing. Most relevant for the manual assembly are joining and handling tasks. A handling task is the positioning two or more parts either just by gravity or using the surfaces of the secondary object to further reduce the object's degree of freedom [16]. The group of joining tasks can again be categorized into nine different groups which differ in the way the task is performed but have similarities in the way the objects are related to another [16]. Therefore this paper presents as an extract the analysis of two very common task for industrial assemblies and for manual assembly in particular - positioning tasks and bolted joints.

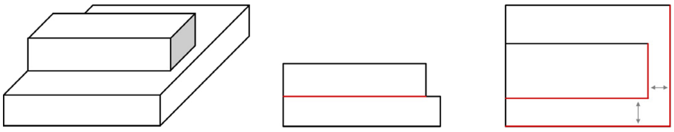

Fig. 2: Representation of a common result of a handling task with relevant features (red lines) from different viewing positions and two distance constraints (grey arcs) related to the secondary object

A representation of a common handling task is shown in Figure 2. In this case the correctly finished task can be geometrically described with the above mentioned groups of feature and constraints. The middle shows a single straight line between the two objects which indicates a direct contact between their two surfaces. From the top down perspective two pairs of parallel lines and one distance relationship each generates a complete description of their position and thus a correctly finished assembly step.

The bolted joint is defined in a similar way. Looking directly from the side on the correctly assembled parts, two linear features are relevant for the description. The bottom line of the washer indicate that the washers bottom surface is in contact with the plate while its top line indicates the contact with the screw's head. An example of an incorrect assembly shows a third parallel line with a distance relationship to the two previous mentioned features (see Fig. 3).

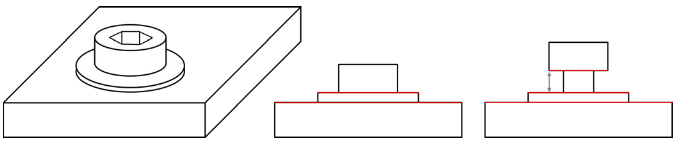

Fig. 3: Simplified representation of a bolted joint with the highlighted features for a correct assembly and the analog features with their distance relationships for an incorrent assembly

While designing a product with a common CAD software the designer uses exactly these geometries and relationships to reference his objects in order to reduce the assembly's degree of freedom. The facts that the mentioned, relevant features are all within the contact surfaces of the primary and secondary objects and that the relationships are defined orthogonal to the respective contact faces of the objects are the basis for the viewpoint generation pipeline.

5. Generation of viewpoint candidates

Section 2 has shown, that the previous work is viable for tasks which mean to cover the entire object. To reduce the amount of viewpoint candidates and to targeted viewpoints for the assembly inspection tasks, a pipeline is presented to derive contours from the assembly's 3D-model and to generate relating viewpoint candidates.

1. Generate intersection points: The contact plane between primary and secondary object is calculated. On this surface the intersection points are derived. These points represent outer or inner part edges intersecting with the contact plane.

2. Filter Contours: Continuous two dimensional contours are generated out of the derived intersection points. Having 3D-models, a minimum of two contours lie on one contact plane. Therefore the contours have to be filtered. The first filter generates coherent regions while the second filters them from the inside to the outside of the object. Inner contours are not visible for the inspection system, so the outer contour(s) are selected. Every remaining contour represents a relevant feature of the assembly inspection and is simultaneously one of the geometrical objects described in 4.1.

3. Distribute points on contour: For the generation of viewpoint candidates, the start points have to be generated on the contours. Possible procedures are uniformly, randomly or depending on the contours geometry. A random placement could lead to spatial concentrated viewpoint candidates where a uniform procedure might generate more than necessary for the present contour. The selected procedure distributes the points based on the geometry's curvature. The distance between the points on a straight line is bigger than on a curve, as the resulting viewpoint candidates would have the same orientation regarding the object. Therefore the concentration of points is higher in areas with different resulting orientations. This procedure can be parameterized to either increase or decrease the overall amount of viewpoint candidates for each feature.

4. Define the relative constraint plane: With section 4.1 showing that constraints are generally defined on a plane which is orthogonal in relation to the contact plane. If constraints exist for the respective contours, besides the contact plane, the constraint plane is relevant for the generation of the orientation angle. It is generated through a 90-degree-rotation of the contact plane in the respective contour point around a vector which is orthogonal to the line connecting the point and the contours center.

5. Define orientation angle: Having the contact and the constraint plane, a minimum of one orientation angle has to be defined. Analogous to the point distribution this is a parameterizeable process, which means the amount of orientations per point can be customized, which will directly increase the amount of emerging viewpoint candidates. The orientation angle is responsible for the amount of information which can be derived from an image. If the angle between a feature and the normal of the sensor is 90 degree, a detection is not possible even though a the feature is mathematically visible [17]. Therefore, this angle is restricted to a maximum of 45 degree on both sides of the contact plane.

6. Place viewpoint candidates: Having the contour points and the oriantation angle, a set of viewpoint candidates is then placed in distance of depth-of-field around the object. A raytracing using the sensor parameters is performed to exclude viewpoints due to self-occlusion or occlusion from a secondary object. The orientation of the viewpoint candidates is pointing towards the respective contour points.

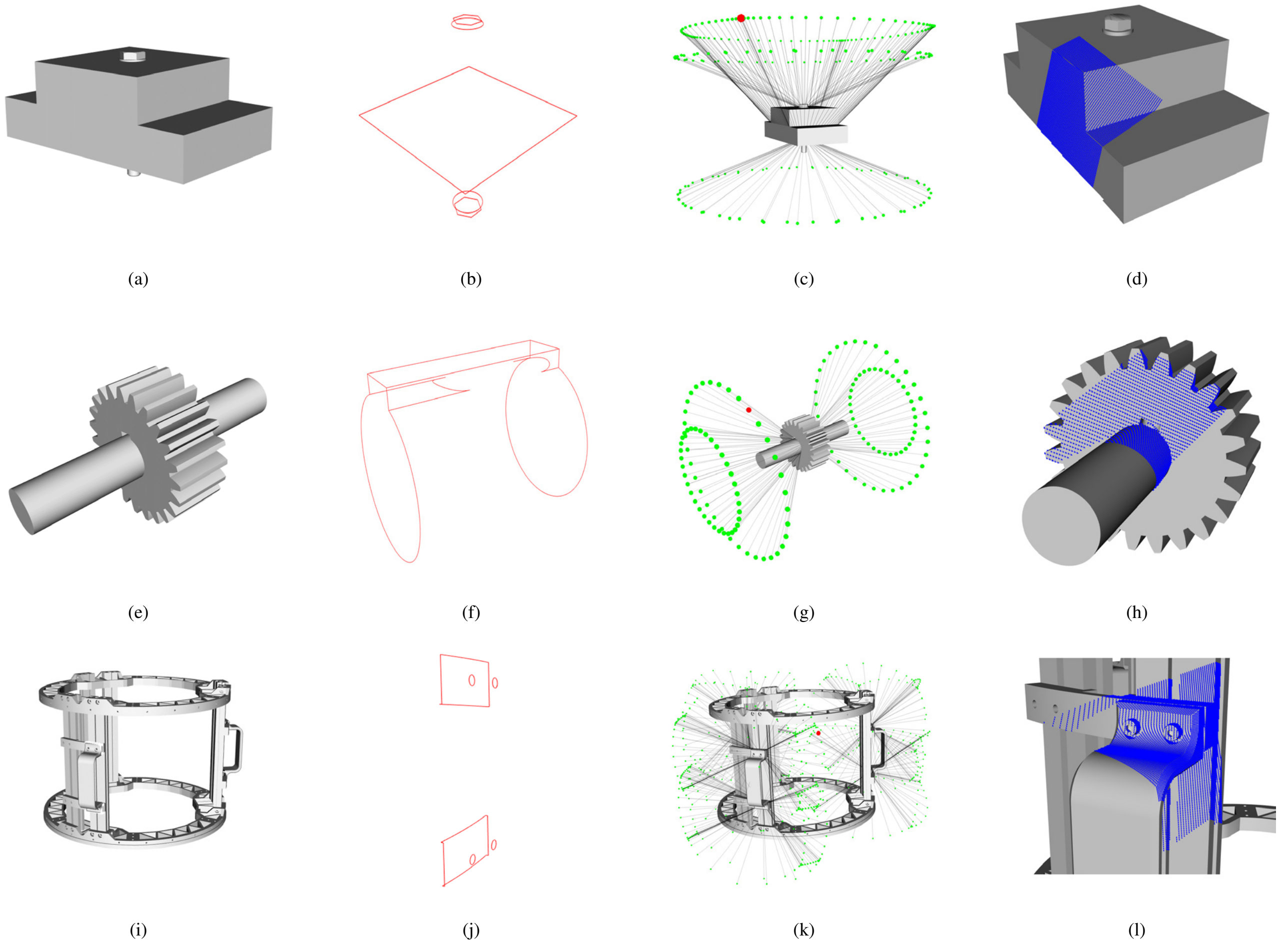

Fig. 4: Visualization of the exemplary application of the feature and viewpoint generation procedure. The 3D-models assembly joint (a)(e)(i), the respective geometrical features (b)(f)(j) as a basis for viewpoint candidate generation (c)(g)(k). The coverage area for selected viewpoints is presented in (d)(h)(l).

5.1. Application and discussion

Conclusively the presented pipeline has been applied on three different assemblies to create a set of viewpoint candidates. Used machine vision hardware is an uEye camera with a 5 MP Sensor, a resolution of 2456 x 2054 px and a pixel size of 3.45 µm . The lens has a focal length of 12 mm and a fixed aperture with a depth of field from 120 to 140 mm. These parameter are identical for all applications. No position restrictions were defined, meaning that the sensor can be placed freely around the objects.

The first assembly (see Fig. 4a-4c) consist of two cubes of different size placed on each other with a hole in their middles. A bolted joint with a screw, two washers and a nut connects them. The derived features for viewpoint generation are two rectangles describing the positioning task of the two cubes, two circles (contact between washers and cubes) and two different hexagons which arouse from the contact between screw, nut and washers. One orientation angle per point was calculated, which led to a number of 502 viewpoint candidates placed along the line of sight of the respective contour points.

Second application is based on an assembly of gear mounted on a shaft using a key (see Fig. 4e-4g). The peculiarity of this assembly is, that the contact contours of the key are inside the groove of the gear and therefore points are not visible from any possible viewing angle. These points are filtered during the viewpoint candidate generation. Using two orientation angles, a total amount of 144 possible viewpoints were calculated.

The last application is a more complex assembly where three different handles are attached and evenly distributed around the curved secondary object. The contact contours are circles and curved lines respectively connected with straight lines, which results from the curved surface the handles are attached to. A number of 792 viewpoint candidates was calculated.

In other viewpoint candidate generation approaches, the number of viewpoints equals (or is at least proportional) to the number of facets of the part. Table 2 compares the number of facets of each assembly with the amount of generated viewpoint candidates. It shows that our task-specific viewpoint generation procedure highly reduces the amount of candidates, which will benefit in a less complex and time-consuming optimization and sensor planning phase. Additionally it is ensured, that every single viewpoint candidate describes a sensor pose from which the

Table 2: Relation between facets and generated viewpoint of the different assemblies

assembly	number of facets	number of viewpoint candidates
bolted joint	8786	502
gear	6768	144
handle	9422	792

features which semantically describe an assembly joint are visible.

Having the basis of generated viewpoint candidates per feature, the next step would be the optimization, verification and selection of a set of final viewpoints with the use of the sensor simulation. However this is beyond the scope of this publication. For a qualitative verification of the generated candidates, one per example was selected (marked red in Fig. 4c,4g, 4k) and the coverage area of the viewing frustum is illustrated in Fig. 4d, 4h and 4l.

6. Conclusion and outlook

This work addresses the field of visual sensor planning for assembly inspection, especially the area of task-specific viewpoint candidate generation. As related work is most commonly focusing on total object coverage, the necessity for a task-specific analysis is pointed out which leads to a novel pipeline for feature derivation in assembly joints. Based on general geometrical features and constraints, the approach is able to generate contact curves from 3D-models and uses viewing functions to place the respective viewpoint candidates.

Yet this approach is not capable of an examination of every possible assembly joint, but it shows the possibilities of task-specific viewpoint planning. Consequently further research topics towards the presented configuration pipeline (see Fig. 1) are the viewpoint optimization related to assembly-specific constraints as pointed out in the task semantic as well as work in automated software implementation based on the analyzed features.

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