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Automated CAD-based sensor planning and system implementation for assembly supervision

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Abstract

Industrial manual assembly, especially within the area of large-scale assembly, often lacks process monitoring since the feedback about performed assembly tasks is only generated by the worker. Optical sensor systems thereby offer the potential to monitor assembly states automatically and derive the required information without intervening the work in progress. With the growing trend of customization, not only the assembly process itself, but also the monitoring system must be adapt- able at short notice. However, most machine vision systems, as they are today, are commonly task-specific solutions and are therefore hard to be transferred to another inspection task or other work objects. To lower the barriers on applying machine vision into varying environments, this paper introduces an automated CAD-based sensor planning and implementation pipeline. An analysis and derivation of common constraints in assembly design is laid out, followed by a method of generating and optimizing inspection features and sensor poses. A strategy to implement the image processing pipeline based on the derived features is presented and applied on an assembly use case.

Keywords: Assembly; Flexible automation; Industry 4.0; Vision systems; Sensor planning

1. Introduction

In many industries, manufacturers are faced with the challenge of offering their products in a growing number of variants while at the same time reducing production times. This results in an increasing complexity and variety of processes and enhances the demand for flexible production and assembly systems. The industrial assembly often counters the required flexibility with manual processes which generally lack the transparency needed for a responsive process control. Especially large-scale assemblies, as they occur in the aircraft industry, pose considerable challenges for the process control, due to parallel and complex part flows and a large number of actors within a large assembly environment. Information feedback about the assembly progress is at most done by the worker and therefore prone to error. A sensory assembly supervision would offer the possibility to automatically record assembly states and derive the required information, necessary for process control without intervening the actual work in progress. [1]

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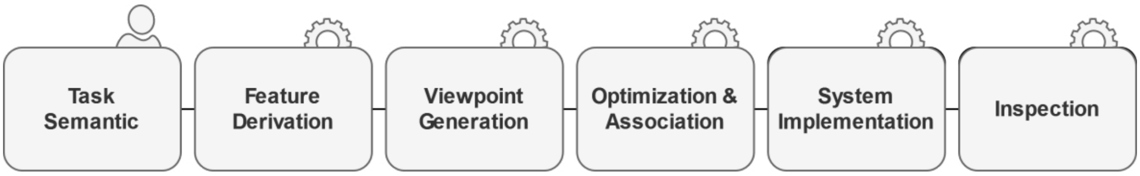

Fig. 1. Pipeline for task-specific planning and implementation of machine vision systems.

The industrial application of machine vision systems for inspection or quality assurance has developed over the last decades from the first specialized applications for the inspection of single, simple objects to concatenated, process-integrated, automated solutions. However, the planning and commissioning of such systems requires a considerable, task-specific effort, which complicates the transfer into variant-rich, manual production environments. The correlating steps of hardware selection, definition of camera poses (position and orientation in relation to the object), implementation of image processing algorithms and testing and validating represent an iterative, time consuming and expert-based process chain [5].

An automation of this sensor planning and commissioning process would have the potential to shift steps from online to offline phases (less downtime in the production), reduce the necessary expert knowledge and shorten the overall and the reconfiguration time. Figure 1 shows an automated pipeline for the task-specific and simulation-based configuration of machine vision systems. A reoccurring problem during automated sensor planning approaches is the dependency of the later steps on the semantic of the respective inspection task - the inspection purpose and the associated object features. While many research has been published in the field of automated, task-specific system implementation, especially with the recent advances of industrial, synthetic training data [9], the sensor planning approaches often lack to include an understanding of the actual task semantic.

Therefore, as a contribution to this pipeline, this paper presents how the task-semantic for assembly supervision tasks can be derived from CAD-data and shows that the following process chain can be executed based on this information only.

2. Related work on visual sensor planning

Visual sensor planning is an ongoing topic of research, especially in the field of surface inspection. It is aiming at modelling the relationship between object and sensor to either derive its *optimal* or *acceptable* solution for the given task [6]. Already in 1995 Tarabanis [11] published a survey on sensor planning which classifies different approaches into two categories *synthesis* and *generate-and-test*.

Synthesis approaches aim to derive an optimal relationship between object, sensor and illumination by modelling constraints like visibility, concealment, perspective, field-of-view and resolution as analytic functions. With the use of task-specific quality measures (e.g. maximum robustness, minimum number of sensors) the "best" viewpoint (position and orientation of the sensor) for the given inspection task can be calculated automatically [3]. Even though the output of these analytic, continuous approaches might diverge towards a global optimum, the search space in which the final viewpoint has to be calculated is of high dimension. Depending on the complexity of the object and inspection task this optimization might not even be possible to be solved. In difference to these continuous approaches, *generate-and-test* attempts are based on the idea of viewpoint candidates and are performed by dividing the solution space and evaluating single configurations. First attempts in discrete viewpoint generation were made by Sakane [8] 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 objects, the methods of viewpoint candidate generation moved into focus of research.

As an extension to the early approach of generating a sphere around the object, [4] introduced a method of using the object silhouette to create an envelope curve in the distance of the sensors depth of field around the object. The advantage of this method is the dependency of the viewpoint candidates on the objects geometry. Especially objects which are not symmetrical around the center of mass in all axes benefit from this dependency. Current approaches move from sampling the space around the object to the active use of the object surface. 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 [2]. 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. [6] 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 sensor planning approaches have been proven to work well for surface inspection tasks as the features (e.g. surface defects) depend on the objects shell. So the requirements on the planning task would either be a complete acquisition of the objects surface or the inspection of those areas with a high probability of those features described through the objects topology. However this is not easily transferable to other inspection purposes like assembly supervision tasks as the relevant features describing an assembly progress are not directly related to the objects topology but to the relationship between different objects. Therefore this paper is contributing to the task-specific, active sensor planning approaches by supplementing feature-area definition process for assembly supervision tasks from the relationship between the assemblies parts.

3. Task semantic and feature derivation

Besides several sub-tasks, the main process within assembly is the joining of single parts or units to a final product or sub-assembly which happens in several consecutive steps. The purpose of an assembly supervision system is then to check whether a certain assembly step is completed, which can either be achieved by directly monitoring the performed activity or by an inspection of the activities result - meaning the shape of the assembly.

3.1 Analysis of CAD-features

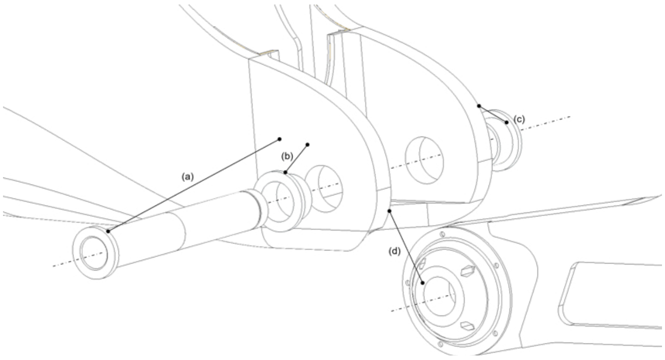

Fig. 3. Mating information defined in the products design phase.

We focus on an approach of monitoring the assembly's shape which is determined in the design. In case of an assembly, this is done through relationships or joints between components. The objective of the assembly inspection is to verify the correct shape of the assembly. Therefore, the assembly features - as defined in the CAD-design - can be considered as basic inspection features for the assembly supervision.

In literature many different definitions for assembly features exist. Most have in common, that assembly features define a relationship or motion between a minimum of two parts [12]. A reasonable systematization for our use case is layed out by Shah [10], who classifies them into low-level and high-level features. While low-level features represent basic geometrical entities like points, lines, curves and planes, high-level features connect those entities with offsets and limits to relationships. Making use of this classification, we can express every relationship with geometric primitives.

Possible ways to access the assembly features are internal or external approaches. Internal approaches access the data directly from the CAD system over its provided API. In this way it is possible to even access the high-level features, but it entails the disadvantage of the dependence on the system itself as every CAD system is based on a different data structure. In contrast to this, external approaches are file based and can use neutral, standardized data formats like DXF or STEP. These exchange formats can be accessed across different systems but contain less information than the original CAD-format [7].

As the inner data structure is similar among the common CAD programs, an internal solution can easily be extended to be applicable on other CAD programs in future work. Therefore, we designed an interface, directly accessing the API of Autodesk® Inventor 2022, which derives all assembly information regarding parts, positions, kinematics and their relationships and joints.

Figure 3 shows an example assembly from the aircraft industry, consisting of two main parts, connected with two sockets and a bolt. Using the interface, three plane contacts (a, b, c), one plane offset (d) and four cylindrical mates and their geometrical primitives were extracted.

3.2 Calculation of feature areas

To utilize the assembly features for the viewpoint candidate generation process, they need to be transferred to feature areas lying on the surface of the parts. Feature areas define regions for the sensor planning process, which have to

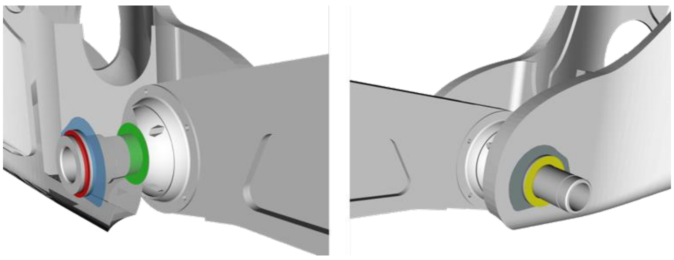

Fig. 2. Feature areas on the surface of the parts define areas which have to be (partly) visible for assembly step detection.

be (partly) visible from the sensor in order to perform the machine vision algorithms and to derive the information regarding the progress of the respective assembly step. Every feature area belongs to a minimum of two parts - depending on the respective constraint from the CAD model - and is associated to one assembly step.

In order to create feature areas, a 3D-model of every part is needed and an isotropic remeshing is performed to equalize their facets size. Depending on the type of the assembly feature and the definition of their low-level features, different clipping principles were implemented and automatically performed on the mesh of the parts. Figure 2 shows the derived feature areas for our use assembly, noting that the size of the areas is parameterizable and is directly affecting the perspective number of viewpoint candidates for this feature.

4. Viewpoint Generation and Association

The facets of the derived feature areas are the input for the subsequent step of viewpoint planning. In order to calculate viewpoint candidates, following information must be available:

- Facets of the feature areas with their vertices and normal

Fig. 4. Matching results with the respective bounding boxes of the detected (red) and expected (blue) position of the template in the image frame.

- Intrinsic parameters of the available sensors (focal length, depth-of-field, etc.)
- Viewpoint restrictions: regions where no sensor can be mounted (eg. areas for the worker)

For the viewpoint candidate generation we attempt an approach based on the on the orientation of the feature areas facets. Since the feature areas were calculated based on different parts their resulting surface is rarely smooth. Therefore neighbor facets are combined and their common normal vectors are calculated. Conclusively viewpoint candidates are placed in depth-of-field around the object. A raytracing algorithm, using the sensor parameters, is performed to exclude viewpoints due to self-occlusion or occlusion from a secondary object. For a detailed overview of the technique of assembly specific viewpoint placement, we refer to [1]. In order to select viewpoints, quality criteria for a *good* viewpoint are proposed:

1. *Coverage*: The number of facets of the associated feature area is calculated for each viewpoint candidate. A facet is considered visible if the facets center is not concealed from another object or facet and if the angle between the viewpoint normal and the facet normal is less than 45 degrees.
2. *Cost*: To reduce the number of sensors in the system and guarantee that no one-to-one association between a single feature area and sensor is generated, the viewpoint candidates are analyzed according to common areas of overlapping. Depending on the number of intersections between viewpoints of different feature areas, a higher cost score is calculated.

We applied this method using two uEye cameras with a 5 MP sensor, a resolution of 2456 x 2054 px, a pixel size of 3.45 µm and two different lenses with a focal length of 12 mm and 35 mm. Assembly features (see Figure 3) (a), (b) and (d) were associated to one sensor, while feature (c) is covered from the other sensor.

5. System implementation

The last step in the process chain is the implementation of inspection algorithms. We make use of the fact, that the relative pose between object and sensor is known from the planning steps. The attempted 2D based approach consists of two phases - *template generation and filtering* and *projection and matching*.

5.1 Template generation and filtering

A template-based technique is using provided patterns or features and attempts to find them in an image. To generate the templates, we isolate the parts involved in the respective assembly step and extract the contour edges within the particular feature areas. These contour edges are then filtered based on their visibility from the viewpoint of the camera. Thus only the visible parts of the contour remain as a template for the assembly supervision of the respective step.

5.2 Projection and matching

This concludes the offline phase of the process chain and the actual assembly supervision starts. With the known sensor intrinsics and extrinsics from the planning phase, together with the templates associated with the different assembly steps, we can calculate the expected position of the template within the recorded image. Once a new image is recorded, the edges are extracted and the matching algorithm is performed. It provides a similarity score and the position of the template within the image. Both values are validated and a decision, whether the assembly step is completed is made, based on defined thresholds.

Figure 4 shows the results for the assembly of the socket and the bolt. This way we were able to detect the completion of all four assembly steps with the use of the two cameras and the derived semantic from the CAD-data.

5. Conclusion and outlook

The work presented in this paper addresses the topic of automated visual sensor planning and system implementation in the field of assembly supervision. As the configuration of a machine vision system is highly dependent on the inspection task and its object, the associated process chain is iterative, expert-based and requires a complete repetition in case of changes to the object or process. Therefore, a method is presented to automatically derive the required information regarding the inspection task and thus enabling an automated sensor planning and system implementation pipeline for assembly supervision tasks. With this pipeline we were able to automatically plan, implement and commission the machine vision system with the use of CAD-data only.

In order to increase the applicability, future work includes the analysis of further assembly features and the respective derivation of feature areas. In addition, an expansion of the presented approaches regarding the association between sensor, its viewpoint and the feature area in order to reduce the overall number of sensors in the system, is an important topic for future work.

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