Reactive coverage planning for robotic NDT of complex parts

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Abstract

Whenever parts of complex shape need to be tested using thermography, X-ray or other image-based inspection technologies, it is necessary to move the sensor system over the whole part to fully scan the surface. This is typically done using a robot that either moves the part or the sensor. In order to define the motions of the robot, a path needs to be calculated so that the part's surface is fully covered by the inspection while avoiding collisions. Additionally, variations of the part in terms of shape or material properties may require an adjustment of a previously planned path while the inspection is being done. We propose a path planning method that uses a tree-based approach with local optimization to plan and update the path during the inspection process. A pre-defined vector field of preferred scanning directions is used to ensure that the local optimization does not deviate too much from the global scanning strategy. While the robot is moving continuously, the currently covered surface area is calculated and the path is updated. By locally optimizing the area covered through the next robot position(s) and by including the global scanning strategy defined by the vector field, a decision is made which path to follow from the current position.
Results of the path planning method are presented for experiments with thermography of forged steel parts and X-ray inspection of composite parts. Tests indicate that a locally planned path leads to inspection times that are reasonably close the theoretical lower limit.

1. Introduction

Image-based inspection (e.g. thermography, X-ray or visual inspection) of parts of complex shape requires that a sensor system is moved around the part to fully cover its surface. This is typically achieved by using a complex handling system, e.g. a robot. The focus of the following investigations will be on 2D image based technologies, i.e. at each time instance the sensor provides a patch of data as compared to technologies that provide only point-like measurements. For industrial inspection, especially for inline testing, the inspection process has to meet certain criteria in terms of cycle time. This requires that the sensor is moving continuously rather than in a stop-and-go motion, where the robot briefly stops at each position. Planning of such a continuous motion is often based on a 3D CAD model of the part, however, as an additional challenge we often find that the CAD model does not match to the actual part with sufficient accuracy or that it is lacking important information. Consequently, the motion needs to be locally adapted during the scanning process depending on the actual properties of the part.
The following investigations aim at robotic inspection technologies, where

- the sensor provides a two-dimensional patch of data.

- the robot is moving continuously to scan the whole surface.
- local adaptation of the motion is required due to deviations in shape.

The main novelty of the work is that it provides a method of adapting the path in such a way that it complies with important boundary conditions (avoiding collisions, full coverage) and allows a fast local adaptation without losing track of the global scanning strategy. In section 2 the state of the art with respect to (reactive) path and coverage planning will be presented and the new methodology will be described in detail. Section 3 presents two applications that were used for doing experiments and provides the results. Section 4 concludes the paper.

2. Reactive path and coverage planning

2.1 Related work

Coverage path planning is the task of determining a path that passes over all points of an area or volume of interest while avoiding obstacles, ideally in the shortest possible time. This task is integral to many robotic applications, such as vacuum cleaning robots, painter robots, demining robots, lawn mowers, automated harvesters and inspection of complex underwater structures (1). 2D methods, e.g. cellular decomposition (2), topography based methods (3) or grid based methods (4) are used for tasks that are done in essentially flat environments. These have been extended to 3D coverage by using a planar coverage algorithm in successive horizontal planes, e.g. (5).

For full 3D coverage random sampling-based methods have been applied especially to deal with collisions or with occluded areas that are only visible from a reduced set of viewpoints. To handle this family of problems, global path planning strategies, utilizing sampling-based planning (6,7), have been applied to find feasible, collision-free paths through confined areas and obtain full coverage of the surface. The approach is based on the art gallery problem ("view planning problem"). Building upon a similar idea (8) introduced an off-line, sampling-based coverage algorithm to achieve complete sensor coverage of complex, 3-dimensional structures. The target application is autonomous ship hull inspection. By applying a random sampling method, the computational burden is reduced to efficiently deal with the high dimensionality of the problem. The approach by (8) first generates a set of view configurations that completely cover the target surface (by solving an instance of the art gallery problem) and then finds a path that connects them (by solving an instance of the traveling salesman problem). This might pose a problem for robots with differential constraints, given that a path connecting two given view configurations might be infeasible. To tackle this problem, (9) presented a random sampling-based algorithm that incrementally explores the robot's configuration space while constructing an inspection path until all points on the target surface are guaranteed to be covered. This algorithm generates view configurations and at the same time validates the feasibility of the path connecting them.

Work addressing the optimality of the generated coverage paths, in terms of path length and time to completion typically requires full a priori knowledge about the environment. Hence optimal coverage methods are classified as off-line methods. These include line-sweep based methods for cellular decomposition algorithms in planar spaces (10) and genetic algorithms to achieve optimal coverage (11). Here the free space is divided into sub-regions using the trapezoidal cellular decomposition method (12). The specific

challenges of coverage planning for inspection robots for applications in thermography and visual inspection are described in (13).
Reactive path planning has not often been investigated for the purposes of inspection robots, a recent example is (1). Work related to reactive planning often aims at dealing with dynamic environments, where an - often mobile – robot has to find a path to reach a pre-specified destination, which is a central task for autonomous robots. A real-time path planning strategy for articulated robot arms in changing environments is presented in (14). It integrates the probability roadmap method (15) with 3D sensor data and adapts it for changing environments. With respect to the real-time capabilities that need to be considered, there is a relation to visual servoing methods (16,17). Visual servoing is used to adapt a robots motion based on sensor input, e.g. during the final approach when a precise grasping operation is needed.

2.2 Reactive coverage planning using tree structures

2.2.1 Particular challenges for reactive planning

Static (off-line) coverage planning uses a 3D CAD model to determine a scanning path that fulfils the following criteria:

- full coverage: all areas on the part need to be covered, provided that it is physically possible to do the inspection with the sensor. It should be noted that the sensor's field of view may be reduced, because elements of the surface might not be in the right distance or angle to the sensor. Consequently, coverage planning has to include a physical model of the sensor to determine which parts of the surface can be inspected from a given position.
- avoiding collisions: during the inspection process there shall be no collisions between the robot, the sensor, the part or the robotic workcell. This is typically ensured through a 3D simulation of the robotic workcell and can be considered industrial standard.
- optimizing inspection time: inspection time is highly relevant for inline inspection, consequently, the path should be optimized in terms of scanning time, while complying with the restrictions mentioned above.

Often an optimal scanning path is found through an iterative approach of automatic planning with some manual adjustments and experimenting.

Reactive path planning faces additional challenges: optimality can no longer be ensured when multiple local adjustments are made, collisions need to be assessed in real-time and full coverage has to be ensured without the need to "go back" to earlier positions.
With respect to optimality the main issue is that local adjustments may accumulate and lead to a global change that substantially increases the scanning time. E.g. a cylindrical object is typically scanned in a spiral-like motion and even if local adjustments are made, the overall scanning motion should still remain spiral-like.
Collision avoidance is particularly critical in reactive planning, because there is no possibility to preview the motion and have it assessed by a human operator. Additionally, the collision detection needs to be done in real-time and the situation is made worse by the fact that sensors are often moved very close to the part, e.g. when inspecting concave areas.
Finally, the dynamics of the robot's motion need to be taken into account to ensure full coverage. The robot typically does not follow the path by connecting the points through

straight lines. Instead it uses splines that sometimes “cut the corners”. Clearly, such small deviations could be addressed by having an overlap between the single image patches, but minimizing the scanning time requires that this overlap is as small as possible.

2.2.2 Proposed solution for reactive coverage planning

The overall approach of reactive path planning is to plan a few steps ahead from the current position and then to select the next step based on a set of criteria. The options for planning the path are represented by means of a tree-like structure as shown in figure 1.

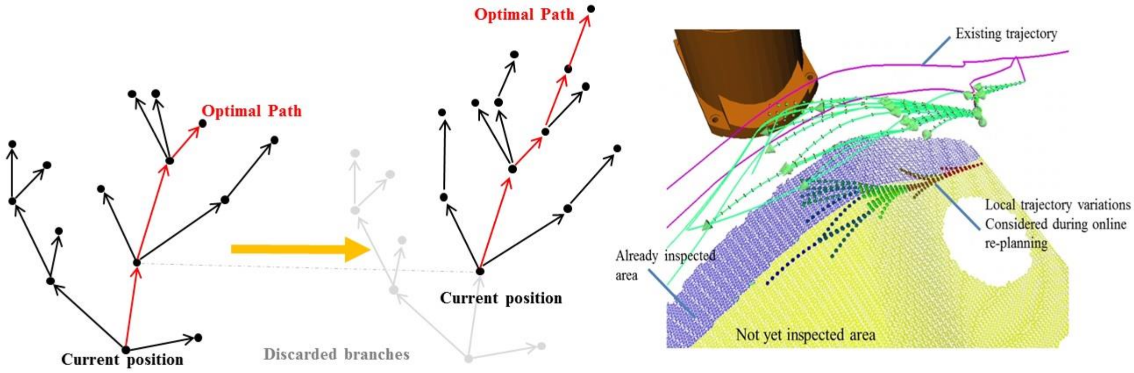

Figure 1. Tree of possible Inspection Paths (left), 3D Visualization (right). Options for the inspection path are generated in the form of a tree and a selection which branch to follow is made based on optimization criteria.

Starting from the current position, several branches emerge that represent paths going in different directions. The distance between the nodes is a parameter that needs to be set depending on several factors. The main criterion is how often (spatially) the path needs to be re-evaluated and adjusted, but also computational power has to be considered, because the tree probably will not reach sufficient depth when the robot is moving fast, and new positions might not be available by the time they are needed. The decision which branch to follow is taken based on two criteria

- locally, the path should not deviate too much from the global scanning strategy,
- the yet uncovered area that is covered by the path should be maximized.

It should be noted that these are local criteria, similar to a greedy search algorithm (18), and the presence of a global strategy is thus important to ensure reasonable global performance.

Once a decision about the path has been made, other branches will be discarded, new sensor data will be acquired along the path and the previously planned local path will again be adapted based on the incoming sensor data from the new current position.

2.2.3 Maintaining the global strategy

In order to ensure that the new path does not deviate too much from the global scanning strategy, or from a previously planned optimal path, a local representation of this path has to be found. This is done by embedding a vector field in the 3D model of the part. For each triangle in the 3D mesh of the part’s surface a vector is embedded that is tangential to the trajectory of the global scanning strategy. New branches that are introduced in the tree will be evaluated based on how closely they fit to this direction. This is done by using the inner product between the direction proposed by the global strategy and the direction of the new branch. Large deviations are penalized and the branches parallel to the globally planned path are preferred.

2.2.4 Ensuring full coverage

To allow efficient computation the part's surface is represented by a triangular mesh. The decision whether a surface area has been inspected is made based on the whole single triangle. This proved to be sufficient, provided that the meshing is sufficiently fine in areas of high curvature. Whether or not a triangle can be inspected from a given position is determined based on a physical model of the sensor data acquisition process. Typically a triangle needs to be within certain tolerances related to the working distance of the sensor and it should not be tilted too much relative to the sensor axis. But there may also be temporal constraints, such as that the triangle has to be in field of view for a certain period of time (e.g. in the case of active thermography). All of this is taken into account for each position along the robot's path.

In addition to this, it has to be considered how the robot is actually moving from one point along its trajectory to the next one. As mentioned, this motion is not along a straight line, but along a smoother curve, taking into account the robot's dynamical properties. This curve is represented by a spline as shown in figure 2. Details about how this is included in the path planning are given in (19).

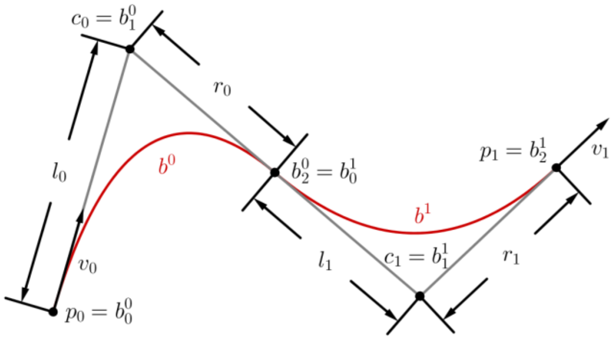

Figure 2. Actual Trajectory of the Robot. The robot does not exactly reach all positions along the path, but dynamics require a smoother path.

This leads to the second optimization criterion. Along this exact path, the robot should cover as much area as possible. The new coverage of yet uncovered areas is determined by calculating the sum over the areas of all newly covered triangles in the 3D mesh of the part along the particular branch of the path.

2.2.5 Avoiding collisions

Whereas the previous criteria are used to optimize the path, collision avoidance provides strict boundary conditions that must not be violated. For static path planning a 3D simulation model is used that includes the robot, its kinematic structure, the workcell, the sensor and the part that is being inspected. Depending on the accuracy of the model, the safety margin has to be larger or smaller, but for inspection tasks typically a very small margin is required and consequently an accurate 3D model is needed. Advances in computing power made it possible to run such simulations faster than real time, so that it is possible to assess collisions for several paths on the fly. Collision avoidance acts as a filtering stage that takes place before constructing the tree. Positions that lead to collisions are not forwarded to the tree construction stage and thus all paths that run through the optimization stage are free of collisions.

3. Experiments and evaluation

In the following section two applications are described, where reactive path planning is needed and experimental results are presented.

3.1 Description of the test applications

The first application deals with X-ray inspection of composite parts with an internal honeycomb structure. The composite parts are shell-like components used in the aerospace industry. The inspection is done by using two robots, where one robot is moving the X-ray source and the other one the detector. Both robots move in parallel on different sides of the part. In order to optimize image quality it is important that the axis of the inspection system is aligned to the axis of the hexagonal honeycomb structure. In the ideal situation the honeycomb structure looks like a dense grid of hexagons (see figure 3). However, the orientation of the honeycomb structure is not represented in the CAD model and thus only becomes visible after the first X-ray images are taken. Based on this information the robots motion needs to be adjusted so that both, the axis of the sensor and the axis of the honeycomb core are aligned. The test part in the experiment is a moderately curved carbon fibre part with a honeycomb core and a size of about $0.2m^2$.

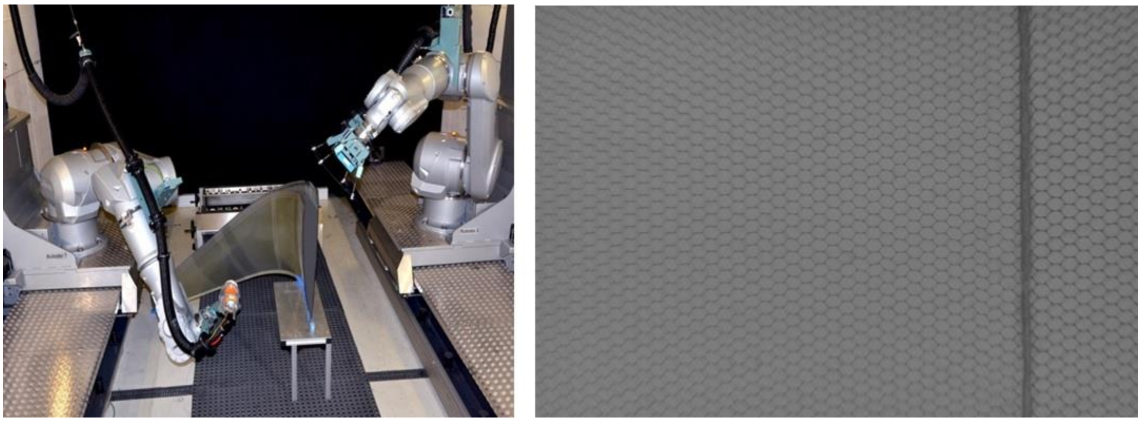

Figure 3. X-ray Inspection Robots (left), Honeycomb Structure (right).

The second application deals with the detection of cracks in forged parts using active thermography. A 100W infrared laser is used to locally heat the part and the dissipation of heat is analysed using images coming from a thermographic camera. A crack is typically visible through a higher local temperature gradient. A robot is used to move the part in such a way that the laser spot passes over the whole surface of the part. Adaptation is needed mainly along the edges of the part, because uncertainties of the part's shape and position would create problems along the edges and corners of the part. The example investigated in this application is the inspection of a smaller cam shaft, with a length of about 250mm and diameters between 20mm and 40mm.

3.2 Results

Assuming that the path ensures full coverage and is free of collisions, the main assessment criterion is the time needed for the inspection. The question here is how much does the locally (reactively) planned path depend on the tree size. For comparison also a theoretical lower bound is computed. This bound is determined by the size of the field of view of the sensor, the maximum scanning speed, and the total area of the surface. The results for both of the applications are summarized in the table below.

Table 1. Path durations for different parameters

	lower	Reactive planning; tree size [edges]				
Application	**bound**	**3**	**10**	**30**	**95**	**300**
X-ray inspection	3.6s	8.2s	7.8s	7.6s	6.8s	6.5s
Thermography	257s	2406s	1754s	1063s	779s	663s

X-ray inspection:
The simulation was carried out with a virtual X-ray sensor whose sensor has a size of 972 x 768 pixels. This resolution results in a field of view of approximately 60mm x 50mm on the surface of the test part. Since the test part has an area of 217393mm^2, the minimum theoretical scanning time at 20Hz acquisition rate is 3.6s. The fastest computed path needs about 6.5s. In an additional experiment the coverage planning algorithm was connected to a Blender simulation of the x-ray inspection sensor. The simulation provided rendered x-ray images of the sample part that were used to simulate varying orientation of the honeycomb structure. Due to the path adjustments that were made the inspection time of the part increased to 9.7s.

Thermography:
Due to the small region that is heated up by the laser, a region of 80 x 80 pixels of the camera image can be evaluated. At flat regions on the surface of the sample the corresponding area covers a square of about 5 x 5mm^2. At a minimum inspection time of a surface point of 80ms and a surface area of 80381mm^2 the lower bound for the inspection time is 257.2s. Since the crank shaft features areas with high curvature, the fastest computed path differs by a factor of 2.6 from the lower bound.

3. Conclusions

Reactive path planning is a method to allow robotic inspection systems to deal with unforeseen deviations between the model and reality. In order to allow the robot to locally adapt to such deviations, local adjustments of the robot's path are made that balance a set of optimization criteria. These adjustments need to consider that full coverage is maintained, that collisions are avoided and that the inspection time is still close to that of a globally planned path. The experimental evaluation on two different robotic inspection tasks indicates that even though the optimization is done based only on local criteria, a reasonable global behaviour is obtained.

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