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Fixtureless Inspection of Deformable Parts Using Partial Captures

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A general scheme to validate the shape of a deformable part consists in performing a non-rigid alignment between measurements on the part's surface with its CAD model. In many algorithms, this process requires the acquisition of a complete model of the inspected part, including regions near its fixation points. This paper proposes a system to perform inspection without the need to digitize the entire part's surface or regions near fixation points. This algorithm uses instead of standard fixation points, surface feature points to compute the non-rigid transformation. Various tests on real parts show that a reduction of up to 58% of the RMS deviation in less than 3 iterations can be obtained using a single view of the part's surface.

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1. Introduction

Even though the manufacturing industry produces a great number of deformable parts whose definitive shape can only be verified after assembly, there are to date no systems capable of carrying out this verification process automatically. Current inspection systems capable of automatically verifying the surface shapes of both deformable and rigid parts are based on a comparison between surface data measured by various 3D sensing technology and their nominal CAD model.[1-3] Due to the flexible nature of deformable parts, it is necessary to first secure a part on a fixation assembly (called a Jig) before acquisition, making it difficult to automate the inspection process. Some works have been proposed to inspected parts by applying virtual deformations on a sensor based part's model generated by a full scan of the part's surface.[4,5] Other approaches apply deformation to the part's CAD model instead.[6] With both approaches, the calculation of the displacements applied during the deformation process is carried out using specific fixation points on the part. In those approaches, the acquisition of the fixation points requires sensors especially designed for such applications,[7] making the system complex and specific to a part.

This paper describes a procedure where the inspection of deformable parts can be carried-out with a limited set of local views. For this procedure, it is neither necessary to acquire the whole part's surface, nor regions around fixation points. In order to perform a local part inspection a scheme based on comparing a set of partial-view data models built from measurements and its CAD model, is presented. Since the partial-view data model is local, a simple iterative non-rigid alignment algorithm can be used to locally fit this view with its CAD model. The partial views are iteratively registered to the CAD model and the required deformations added to a global model. For each iteration the added partial views are matched with a new version of the deformed CAD model of the previous iterations. The process stops when the distance between all the partial views and the deformed CAD model reaches a minimum of the Root Mean Square (RMS) error.

The proposed method allows inspection systems to carry out partial inspection of deformable parts. This is particularly important when it is necessary to verify local features on the part's surface.

The rest of the paper is organized as following. The next section presents a review of inspection techniques of deformable parts found in the literature. Section 3 describes the proposed inspection procedure using partial-view models. Section 4 shows and analyzes the experimental results obtained. Finally, Section 5 concludes and describes future work.

2. Local Inspection of Deformable Parts

Surprisingly there has been little research found in the literature which deals with the issues associated with the inspection of deformable parts. Some of them are discussed briefly in this section.

In order to carry out the validation of deformable sheet metal Weckenmann et al.[4] consider a process where virtual deformation to the part's data model is applied using a Finite Element Modeling (FEM) framework which tries to simulate an actual assembly process. The deformed model obtained from the simulation is aligned and compared directly against its nominal model. This approach requires having a complete model of the part especially near regions around fixation points. This is necessary in order to set the boundary conditions of FEM simulation used to model the deformation. Gentilini and Shimada[8] propose a similar method to perform validation of deformable parts. They also consider an initial calibration process where material properties used in FEM modeling is determined experimentally.

Other research has considered the application of a reverse deformation on the part's CAD model instead of applying the deformation on the inspected model using a complete scan of the part.[9,10] Jaramillo et al.[6] propose the use of the radial basis functions to reduce the computational load during the calculation of deformations, and to speed-up the non-rigid alignment. Radvar-Esfahlan and Tahan[11] use the properties of surface geodesic distances to determine correspondences and make the comparison between the inspected part and its CAD model. In this framework, a reconstruction of the whole part's model is not required. However the acquisition of data around the fixation points is necessary in order to define the boundary conditions used in FEM simulation.

Following a geometrical approach instead of using FEM, Abenhaim et al.[12] propose an algorithm by which the non-rigid transformation is applied iteratively to the part's CAD model to minimize the distance with the part's scanned data.

In some research, in order to efficiently carry out the global inspection of industrial parts with complex shapes, it is necessary to plan the placement of the 3D sensor relative to the part in advance.[13] This planning is based on prior knowledge of the part's surface, that is, by using its design model and verifying specific characteristics.[14] Many of those characteristics are local features such as: holes or details on the surface. Some authors have considered planning part data acquisition in order to inspect local characteristics,[15] but most research found in the literature requires the capture of a complete model of the part's surface.[16,17] Other approaches consider the inspection of local characteristics by using data measured in specific regions.[18] In this work, the problem focuses on the automatic alignment of the surface regions in relation to the design model in order to carry out the comparison between the two models.

Unlike the research found in the literature, which require a full acquisition of the inspected surface, this paper proposes an approach whereby the inspection of local characteristics of the surface of deformable parts can be performed using a partial data model. It is assumed that the acquisition is planned so that the partial model contains the region of the surface to be checked.

3. The Inspection System

As discussed previously, a complete model of the part to be inspected is not always feasible using measurements from 3D sensors, especially near regions around the part's fixation points. In addition, a complex acquisition process is needed in order to register and integrate the views.[19] Because of occlusion and the sensor's accessibility problems, full model reconstruction of complex parts is hard to achieve and automate.[20] The present section describes a procedure by which the deformable part's shape inspection can be carried out without the need to perform a full surface reconstruction.

The inspection process is based on a comparison between the acquired 3D data and its CAD model. Since the parts under inspection are flexible, it is necessary to apply a non-rigid transformation in such a way that the corresponding fixation points of the two models match before comparison. However, since the data model may not contain all the fixation points, the proposed method is designed as an iterative process of successive non-rigid alignments where the deformation of the CAD model is carried out until the best approximation to the partial data model is reached. In this way, the verification of some local features is possible by using a model of partial-view data even with a single view. Fig. 1 shows a block diagram of the proposed system. The following section describes briefly every step of the proposed algorithm and explains its most innovative aspects in detail.

3.1 Data Acquisition

Using 3D sensor measurements, a partial view of the part's surface is performed. Instead of planning the views in order to acquire the full model, the measurements need to be performed in regions in which the inspection needs to be performed.

3.2 Detection of Landmarks

It is assumed that the region that is acquired contains sufficient feature points by which the alignment of the model can be carried out. In case the geometry of the region does not contain details, for instance holes or corners, additional fiducial markers can be added on the part's surface.

3.3 Iterative Algorithm for Non-Rigid Alignment

Since the assumption is that the acquired 3D data is only a partial-view model, the part's CAD model is used to deal with the complete deformation. In this iterative process, a deformed version of the CAD model is generated at each iteration in order to minimize the difference

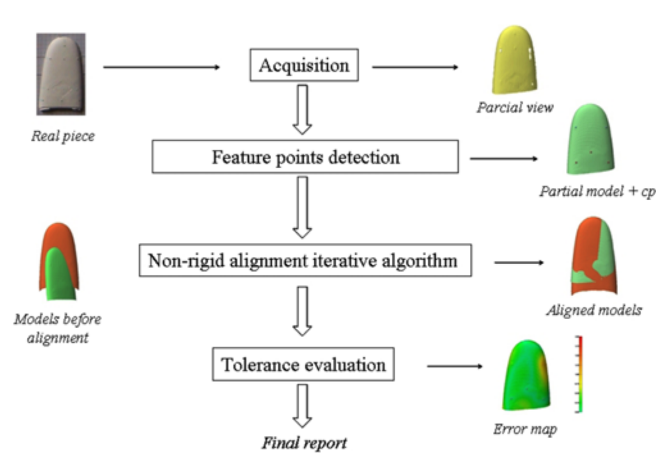


Fig. 1 Overview of the system to inspect deformable parts using a partial data model

between the partial views and the CAD models. Each partial-view is aligned with the CAD model using a non-rigid alignment procedure described at Algorithm 1.

It is assumed that the part's model has enough landmarks such as bumps and holes to allow the alignment operations. The input data for the algorithm are: the part's CAD model (M_{CAD}) for which the landmarks are known including the fixation points p_f, the partial view data model ($M_{partial}$), and its landmarks p_c. Although, the CAD model of the inspected part is given in IGES format, in order to calculate deformations it is converted to a polygonal representation. In tests carried out, partial view models can also be polygonal models built from data acquisition.

The first step in the execution of the algorithm is to perform a rigid alignment between the $M_{parcial}$ and the M_{CAD}. This alignment is carried out by applying a rigid transformation $\mathbf{T}$ on the $\mathbf{M}_{parcial}$, this is

$$T(M_{partial}) = RM_{partial} + t, \tag{1}$$

where R is a rotation matrix and t is a translation vector.[21] The values of R and t are determined by the following minimization:

$$\min_{R,t}\left(\sum_{i=1}^{N}\|P_i - Rq_i + t\|^2\right), \tag{2}$$

where q_i and p_i, ($i = 1, \dots, N$) are the points that correspond to $M_{parcial}$ and M_{CAD}, respectively. In addition to the transformation based on the landmarks, algorithms for fine adjustment can also be used such as the famous Iterative Closest Point (ICP).[22]

The next step consists of duplicating the CAD model and dividing the generated copy into m_i parts according to the fixation points missing in the $M_{parcial}$. This task can be done by applying a segmentation algorithm to the surface models.[23,24] Since the objective is to complete the partial model in the regions around the fixation points, it is necessary that m_i contains the landmarks that correspond to the points of the $M_{partial}$. For each m_i region, a set of different landmarks needs to be considered in such a way that when computing their relationship to $M_{partial}$ each m_i is a different transformation. Similarly to step 2, in step 3 the alignment of the m_i is carried out using landmarks. The set of $M_{partial}$ and m_i is called a completed model and it is noted M_C. An example of the selection of an added region is shown on a plastic motorcycle part in Fig. 2. In the alignment between the M_{CAD} and the $M_{partial}$, a region is identified by selecting the first of them to show a fixation point that is missing in the second one as well as the corresponding landmarks (Fig. 2(a)). This region is the cut off from the M_{CAD} and is aligned with the $M_{partial}$ using the local landmarks (Fig. 2(b)).

Because the M_C contains all the fixation points, the calculation of the displacements of those points from the M_{CAD} model to the M_C can be carried out. Then, these displacements are used as boundary conditions for an FEM simulation to calculate the deformed CAD model M'_{CAD}. Due to the structure of the parts, thick shell finite elements are used to calculate deformations.[25] The material parameters used in the simulations were adjusted empirically from previous experiments. The rigid transformation applied to the $M_{partial}$ and the FEM deformation applied to M_{CAD} compose the process of non-rigid alignment which is applied between both models at each iteration.

Once the non-rigid alignment has been performed between the partial-view model and the CAD model, an evaluation of the current approximation is carried out in relation to the previous results. The evaluation is achieved by computing the deviations between the minimum distance from $M_{partial}$ to M_{CAD} and by computing the RMS value. The RMS value for a given set of deviations $\{d_i, i = 1, \dots, N\}$ is given by:

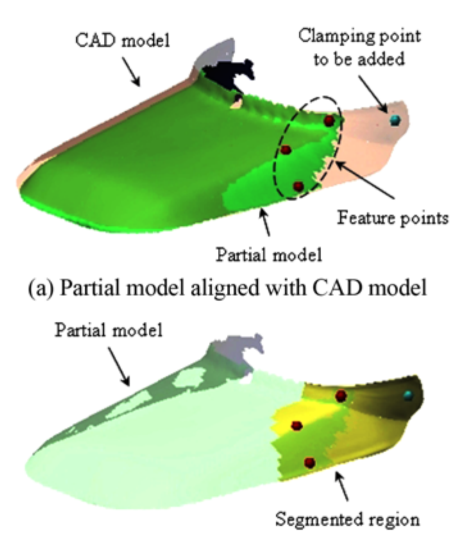
$$RMS = \sqrt{\frac{1}{N}\sum_i d_i^2}. \tag{3}$$

In the present work, the deviation of the i-th point of the partial-view data model is calculated as the minimum Euclidian distance to the CAD model. If the current RMS deviation is lower than the previous one, the process is repeated. If not repeated the final deformed model is the previous M'_{CAD} and the iterative process ends. In order for the process to continue at each iteration, the RMS error must reduce continuously until it reaches a minimum value. That is, the RMS value cannot increase or remain constant and therefore must converge to the first local minimum value found. In addition, since the number of iterations to reach such minimum value is unknown, a stopping condition

Algorithm 1: Non-rigid alignment algorithm

Input data:
- M_{CAD}: CAD model with landmarks
- p_f: fixation points of CAD
- $M_{parcial}$: Partial view data
- p_c: Landmark points in the partial view
- Step 1. Rigid alignment of $M_{partial} \rightarrow M_{CAD}$
- Step 2. Cutting off regions m_i, from M_{CAD}
- Step 3. Alignment of $m_i \rightarrow M_{partial}$ using p_c
- Step 4. Calculation of displacements of p_f
- Step 5. Deformation $M_{CAD} \rightarrow M'_{CAD}$
- Step 6. Computation of RMS from $M_{partial}$ to M'_{CAD}
- Step 7. IF current RMS < previous RMS, THEN Step 1
  ELSE $M'_{CAD} = M_{CAD}$

Output: M'_{CAD}: CAD model deformed and aligned with partial view



(a) Partial model aligned with CAD model
(b) Region selected from CAD model
Fig. 2 Addition of missing clamping points to partial data model

is set in which there is a limit on the maximum number of iterations.

Fig. 3 shows an example of a sequence of rigid and non-rigid iterative alignments with their corresponding error maps for one of tested part.

3.4 Tolerance Evaluation

This is the final stage in which the inspection system decides whether the part is acceptable or not. Since in this case only a portion of the part is known, it is assumed that that information is sufficient to carry out the validation. In order to determine if the part is valid, a tolerance range for the evaluated characteristic is established in the inspection process. Such range can be defined considering a symmetrical interval around the nominal value whose limit is given by the established geometrical tolerance. Since it is a surface shape tolerance, the nominal value is the part's CAD model. In the tests performed, the geometrical tolerance was defined as the mean thickness of the part. However, this is a parameter that must be specified by the manufacturer. In general, in order to establish the adequacy of the surface of an inspected part, a comparison against its nominal model is carried out. However, in this case only a portion of the part is acquired and it is not necessary to compare all the model points on the partial model of the acquired surface. In this paper, we evaluate the RMS deviation (Eqn. 3) of the points in the partial-view data model with respect to the part's CAD model only. The partial-view model will be in tolerance if difference values are lower than the average thickness of the part.

4. Results

This section presents the test results carried out on a synthetic model and four real plastic parts. The registration was computed on an Intel Core Duo with 2.16 GHz, 2.0 GB in RAM, running Microsoft Windows XP. The data of the real parts were acquired with a Minolta Vivid 9i range sensor. During data acquisition, filtering processes for removing noise and smoothing the surfaces were applied. The parameters of the material used in the FEM calculation are: Young's modulus = 25.000 Kgf/cm^2, Poisson ratio = 0.35. Fig. 4 shows the experimental setup. The material parameters were adjusted empirically matching FEM simulations against real deformations with full data models, before carrying out the tests on the partial models.

Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9 show the part's CAD models, the data models, the deformed models, the landmarks, and the error of the alignment before and after applying the iterative algorithm of non-rigid alignment. Fig. 5(a), Fig. 5(b), and Fig. 5(c) show the synthetic part's CAD model, the partial-view data model, and the deformed model respectively. The fixation points of the model are shown in blue on the CAD model in Fig. 5(a); the landmark points used to perform the alignment between the CAD and the partial-view model are shown in red on both models in Fig. 5(a) and Fig. 5(b), respectively. The landmarks with which the regions are aligned are shown in yellow on the completed model in Fig. 5(c). In the case of the synthetic model, the assumption is that the partial-view model does not contain any of the four fixation points that the CAD has; then, in this case, four regions are added, that is, one for each fixation point.

Fig. 6(a), Fig. 7(a), Fig. 8(a) and Fig. 9(a) show the real part's CAD models with their landmarks, that is, the fixation points (in blue) and the points used to align the added regions (in red). Fig. 6(a) represents a small plastic cover, and Fig. 7(a), Fig. 8(a), and Fig. 9(a) are the surface models of three plastic motorcycle parts. The alignment of each added region is carried out by using the landmarks different from the fixation points except for Part #4, which uses the fixation point nearest to the added region for the alignment process.

Fig. 6(b), Fig. 7(b), Fig. 8(b), and Fig. 9(b) show the partial-view of the part's model. Those figures show, in blue, the fixation points that the partial-view model contains and, in red, the landmarks used in the partial-view model for the alignment of the added region. Except for the synthetic part and for Part #4, each partial model is generated using a single view obtained with the Minolta range scanner. The partial data model for Part #4 is a portion of the full model deformed applying the FEM with the boundary conditions from the real deformation. Fig. 6(c), Fig. 7(c), Fig. 8(c) and Fig. 9(c) show the completed models which are composed of the partial-view model and the CAD regions rigidly aligned using the feature points that are indicated in both the CAD and the corresponding partial-view model. These figures also show, in blue, the fixation points used for calculating the displacement of the fixation of the CAD during the algorithm of iterative non-rigid alignment.

Fig. 5(d), Fig. 6(d), Fig. 7(d), Fig. 8(d) and Fig. 9(d) show the deviations map of the partial-view model with respect to the non-deformed CAD model. The alignment between the CAD and the partial-view models was carried out only by using the landmark points for both the synthetic model and Part #1. The algorithm for fine alignment was applied for Part #2 and the alignment using landmarks and the fine alignment was applied to Part #3 and Part #4.

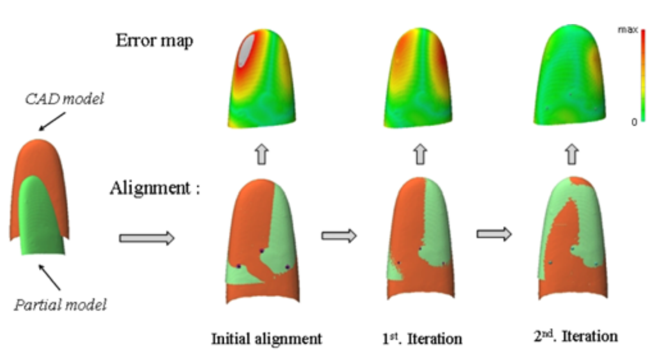
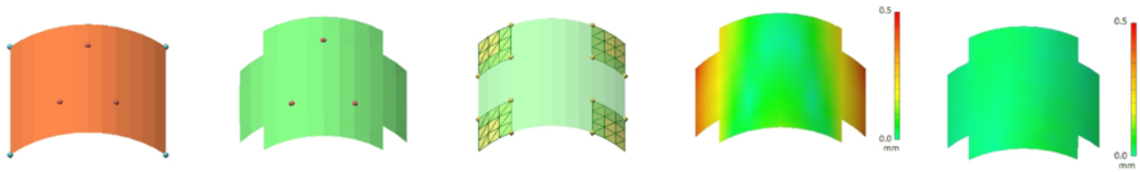


Fig. 3 Example of iterations of the non-rigid alignment algorithm

Fig. 4 Experimental setup

Finally, Fig. 5(e), Fig. 6(e), 7(e), Fig. 8(e) and Fig. 9(e) show the deviations between the partial data model and the deformed CAD model obtained after applying the iterative non-rigid alignment algorithm.

Table 1 summarizes the test results. The following information is given for each of the models: the number of fixation points of the part, the number of fixation points contained in the partial data model, the number of added regions to complete the model, the number of landmarks used for the rigid alignment, the number of iterations to reach the minimum, and the computation time to calculate final deformation. The deviation values are calculated by computing the minimum distance between the data model nodes and the reference model. Initially, the reference model is the CAD model; then the deformed model obtained for each iteration is used as a reference. The value of the final RMS



(a) CAD + p_c (b) Parcial + p_f (c) Completed + p_c (d) Initial Error (e) Final Error

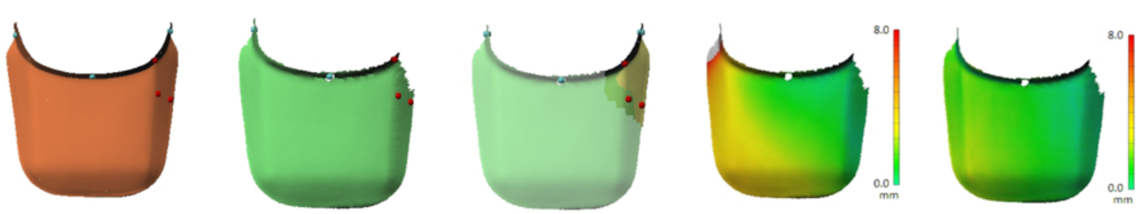
Fig. 5 Models and results for the Synthetic Part

(a) CAD + p_c (b) Parcial + p_c (c) Completed + pf (d) Initial Error (e) Final Error

Fig. 6 Models and results for Part #1

(a) CAD + p_c (b) Parcial + p_c (c) Completed + pf (d) Initial Error (e) Final Error

Fig. 7 Models and results for Part #2



(a) CAD + p_c (b) Parcial + p_c (c) Completed + pf (d) Initial Error (e) Final Error

Fig. 8 Models and results for Part #3

(a) CAD + p_c (b) Parcial + p_c (c) Completed + pf (d) Initial Error (e) Final Error

Fig. 9 Models and results for Part #4

deviation is the lowest value of the deviation obtained as a result of applying the algorithm of the iterative non-rigid alignment. In that case, the reference model represents the best approximation to the real part deformation according to the proposed algorithm.

The numerical results show an improvement in the non-rigid alignment between the data partial-view model acquired and its CAD model. Except for the synthetic model, the reference points of the CAD landmarks used for computing the rigid alignments at each iteration were determined in an approximated way on the partial data model. For that reason and because the model that is aligned is deformed compared to the reference model, a fine alignment is necessary in addition to the rigid alignment applied using only the reference points. Since in some cases, the shapes are smooth and do not present characteristic details as for the synthetic Part and Part #1, one needs to use fine alignment algorithms with some restrictions,[26] such as those imposed by the correspondence of the landmarks, otherwise the fine alignment algorithms will not converge.[27]

The results show that the iterative algorithm converges in a few iterations (<3) to a minimum value of the RMS deviation. In order to find the best approximation of the partial data model deformation, only two iterations were needed for the evaluated models.

On the other hand, the time required to complete the non-rigid alignment depends mainly on the FEM simulation to calculate the deformations. As this process is carried out at each iteration, the time required to compute the final deformation is proportional to the number of iterations that the non-rigid alignment algorithm requires to determine the minimum deviation. Computation times for the various test parts are shown in Table 1.

Unlike the case in which we have a complete data model, in this case the determination of the displacement applied on the CAD model to obtain a deformed model is carried out in an approximated way at each iteration. Even for the synthetic model in which the position of the characteristic points is accurately known, the final result presents a deviation greater than zero (RMS = 0.01 mm). Here, the error is introduced mainly because the completed region at each iteration is an approximation to the deformed region of the complete model. In the tests carried out with the real parts, additional errors were found due to the determination of the positions of the landmarks as well as the differences that the real part presents with respect to the approximated model used in the simulations. It is also possible to infer from this analysis that for each added region the resulting error increases.

5. Conclusion

This paper proposes an inspection system for deformable parts which allows local inspection of the part's surface without acquiring regions around the fixation points. The system can be especially useful when it is necessary to verify a specific region and not the whole surface of the part. This implies that the system requires acquiring points only from the region that needs to be inspected.

The inspection process is based on a new iterative non-rigid alignment algorithm. A transformation to the CAD model is applied at each iteration which is calculated by minimizing the error with the partial-view model. Regions around fixation points that are not contained in such model are replaced with equivalent regions from the CAD model.

The results show that the proposed non-rigid alignment algorithm improves the alignment of the models of deformable parts even in cases in which the data model does not have any of the fixation points. In addition, in the tests on real parts a local inspection was carried out using a single view. This means that the process of data acquisition can be simplified and can focus on the acquisition of specific regions of interest.

The main advantage of the proposed method is that in order to inspect only the specific regions of the surface of a deformable part, it is not necessary to perform a full acquisition of its surface. In addition, unlike other systems which require fixing points to perform the alignment process in the proposed system, the alignment of the models is performed stepwise using only visible points on the surface. This raises the possibility of simplifying the acquisition process and to focus the acquisition time to regions that need to be inspected.

From tests carried out, it was found that the greatest difficulty with the algorithm is the precise detection of landmarks which also impact the accuracy of the subsequent non-rigid alignment of the regions added to the partial model. Since this work focuses on providing a general solution to the inspection problem using partial-view models without fixation points, the automated detection of landmarks to compute the alignment of regions added to the partial-view model represents an important issue for future developments.

Finally, although the results obtained allow us to infer the benefits of the methodology, in order to give up a more complete evaluation of the advantages and limitations of the proposed approach, a more exhaustive experimentation is required. This should include tests considering different amplitude profile error, tolerance, and the effects of noise in measurements.

Table 1 Numerical test results for various parts

Parameter	Synthetic Part	Real Part 1	Real Part 2	Real Part 3	Real Part 4
Number of fixation points CAD	4	4	4	3	4
Number of fixation points partial model	0	2	2	2	3
Number of added regions	4	1	1	1	1
Number of landmarks	15	3	3	3	1
Number of iterations	2	2	1	2	1
Computation time (sec)	9	18	58	12	84
Maximum distance (mm)	0.50	2.00	3.00	8.00	9.00
Initial RMS (mm)	0.19	0.77	0.78	2.97	1.87
Final RMS (mm)	0.01	0.32	0.42	1.42	1.07

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