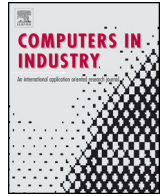




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# Fast dimensional inspection of deformable parts from partial views

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### ABSTRACT

One of the conventional ways to inspect deformable parts is to compare a data model against its nominal CAD model. This process assumes that the data model includes most of the visible surface including regions around fixation points where the part will be attached to others. This paper proposes a method to inspect deformable part by acquiring only regions that need to be inspected and then by applying to the CAD model a non-linear deformation using FEM modeling to minimize the differences with the partial views. The process first starts with a rigid alignment followed by an iterative process where the part's deformation is iteratively matched to the partial views. In this scheme, fixation points are not digitized and the non-linear part deformation calculations are estimated by interpolation. Test results performed on real parts compares favorably to deformation calculations using complete data model from the point-of-view of speed and accuracy.

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## 1. Introduction

Today's manufacturing industries have achieved significant development at automating their production processes, so much so that a great volume of parts can be produced in short time and at low cost. Nevertheless, there are still some processes that cannot be carried out in automated production line because of their long execution time or its requirement for human intervention. An example of this is the dimensional validation of deformable parts. In a normal inspection process, a sampled deformable part is extracted from the production line and fixated by a human operator onto a rigid stand or jig that mimics the conditions at final assembly. Once the deformable part is fixated onto the jig, the inspection can be performed using similar techniques to the one used for inspecting rigid parts. The most commonly used scheme to inspect rigid parts is to compare surface measurements produced by a 3D sensor to its nominal CAD model [1], where a rigid transformation is computed to align both models [2]. Following this registration process a tolerance analysis is performed from which a decision is made to classify the part to be in tolerance or not.

Other authors have already considered the possibility of inspecting deformable parts without fixation [3,4]. Similar to the rigid case, they first acquire a complete model of the part's surface without fixation and then compute a rigid and non-rigid transformation to align the complete data model against its CAD

model as if the part was installed onto a virtual jig. In order to do so they first have to detect the position of the fixation points and then virtually deform the data model with Finite Element Methods (FEM) where the boundary conditions are specified by displacements applied at the fixation points. Even though the method simulate the real process of part fixturing, it none the less require to acquire an entire model of the part's surface which is time consuming and hard to do because of occlusions and access limitations of the sensor. In addition, since most of the data measured by the sensor are surface data, applying FEM modeling to this model is inaccurate as the only reasonable deformation model one can deduce from the data is a thin-shell model. In some cases like sheet metal this approximation fits well but in most cases this assumption does not hold.

In order to solve some of those limitations, this paper presents a new method for inspecting deformable parts that do not require fixturing and where only partial views of the part's surface is needed. The assumption here is that partial data model does not contain all the fixation points and mainly focus onto regions where inspection is needed. We will demonstrate that the knowledge of the locations of all fixation points is not necessary and can be replaced by using characteristic points that are part of the partial data model. In addition, we will demonstrate that if a complete CAD model of the part is available it is better to apply the virtual displacement using FEM onto this model instead of the data model as it is more likely to represent the real deformation. FEM deformation calculations are renowned to be slow and not well adapted to real-time inspection, but we will demonstrate that by using pre-calculated deformation of the CAD model one can

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dramatically accelerated the processing speed by using an interpolation technique based on Radial Basis Functions (RBFs).

The rest of the article is organized as following. Section 2 presents a review of the related literature. Section 3 reviews the theoretical foundations of the proposed method. Section 4 describes the proposed method. Section 5 presents the test results on several parts and its corresponding analysis. Finally, we conclude and indicate some possibilities for future developments.

## 2. Literature review

Even though the manufacturing industry produces a great volume of flexible parts every year whose definitive shape can only be verified when they are assembled, there are surprisingly not many works in the literature that address dimensional validation issues directly. The present section presents a short review of deformable part inspection one can find in today's scientific literature.

Taking into account, that it is necessary to avoid human intervention in order to automate inspection, the first condition for such a system is to measure the surface geometry without fixation. Then, once a geometric model using data from the inspected part is produced, a comparison of this model against its nominal CAD model is carried out. In order to perform a correct alignment between the two models, it is required to first apply a rigid transformation followed by a deformation. As described previously, one approach consists of applying a deformation directly onto the geometric data model at fixation points with virtual displacements, simulating the fixturing process. This approach was explored initially by Weckenmann and Weickmann [3], and more recently by Gentilini and Shimada [4]. As discussed previously the pitfall of those methods are the need for a complete part surface data model which in most cases, is hard to do automatically and most importantly is not physically valid. Applying a FEM deformation to a surface model is only valid for sheet-metal at best as surface model are really a partial model of a part. In order to improve the precision, they propose an initial calibration process to determine the material properties experimentally but one could wonder if this calibration process is simply compensating for the fact that we only have a surface model of the part.

A second approach consists of applying the deformation to the CAD model instead. The main advantage of this approach is that if the CAD model is accurate it has all the geometric information necessary to perform the correct simulation of the deformation. Some authors who have followed this approach have also used FEM to simulate the deformation as in [5,6]. Other geometric based methods have also been proposed in [7], which considered geometrical deformations instead of FEM with geometric constraints imposed by the real part. In most of these works, the iterative deformation process still require that the digitized part surface model should be as complete as possible which again makes the data acquisition process complex.

Unlike these methods, for which it is necessary to acquire a complete part surface model to work, we will describe a new method that can deform the part's CAD model from partial views by matching critical points found in those views with the CAD model. With this new method, data acquisition can be simplified focusing mainly on views that need to be inspected. In addition, the proposed deformation model can be optimized by using an interpolation technique using RBFs in order to accelerate significantly the calculation of the deformation, opening the door to real-time inspection.

## 3. The proposed inspection method

Recently a new generation of geometric acquisition systems that integrate the processes of registration and multi-views fusion

have been commercialized by various manufacturers. In all cases, these systems produce a polygon mesh from the measured surface data [8–10] that can be used for inspection. However, most of those systems still require human intervention to overcome acquisition problems such as dealing with occlusions, and having to fixate the part on a jig before the acquisition. The ideal inspection system would be one where the part is deposited onto a table and where an automated digitizer locates the part's orientation and then digitize in details only the sections that need to be inspected. In this following, we will describe a new method to perform surface inspection of deformable parts using only these partial views.

First, the full resolution polygonal mesh of the nominal CAD model is reduced in size using a training method. In this process, the deformations are simulated by using FEM for various conditions on a full resolution mesh where a set of minimum critical control points is identified. Using those critical points one can then represent deformation on a reduced mesh size and then compute back the full resolution mesh using RBF interpolation. This process is described in detail in [6] and has been shown to improve processing speed by order of magnitude over the traditional FEM methods with a controllable loss of precision.

Fig. 1 shows an overview of the proposed inspection system including the mesh reduction pre-processing stage. In the following, we will describe how partial view can be used instead of fixation points to register the CAD model with those views.

### 3.1. Acquisition

The data acquisition is carried out by using a 3D sensor and by generating a series of disjoint partial mesh models. The only obvious constraint is that the views captured by the sensor must contain at least a portion of the surface to be verified. In this approach there is no need for data registration and fusion of multiple meshes.

### 3.2. Detection of characteristic points

In this stage, some characteristic points of the acquired surface are identified and the correspondence between these points and the CAD model is automatically established. Fixation points, holes, corners, maximum curvature points, etc., have been used successfully as characteristic points.

### 3.3. Rigid alignment

This alignment consists of applying a rigid transformation between the partial data model points  $\mathbf{M}_{\text{partial}}$  and the part CAD model points  $\mathbf{M}_{\text{CAD}}$ . This transformation applied to the partial model is expressed as following:

$$\mathbf{M}'^{\text{partial}} = \mathbf{R}\mathbf{M}_{\text{partial}} + \mathbf{t}, \quad (1)$$

where  $\mathbf{R}$  is a rotation matrix and  $\mathbf{t}$  is a translation vector. The values of  $\mathbf{R}$  and  $\mathbf{t}$  are determined by the following minimization:

$$\left( \sum_{i=1}^N \|\mathbf{p}_i - \mathbf{R}\mathbf{q}_i + \mathbf{t}\|^2 \right), \quad (2)$$

where  $\mathbf{q}_i$  and  $\mathbf{p}_i$  ( $i = 1, \dots, N$ ) are points that correspond to  $\mathbf{M}_{\text{partial}}$  and  $\mathbf{M}_{\text{CAD}}$ , respectively. In addition to the transformation based on the landmarks, algorithms for fine alignment such as the Iterative Closest Point [11] are also used to solve automatically the correspondence problem.

### 3.4. Fixation points estimation

The missing fixation points of the data model are estimated using a RBF interpolation technique described in [12]. Using this

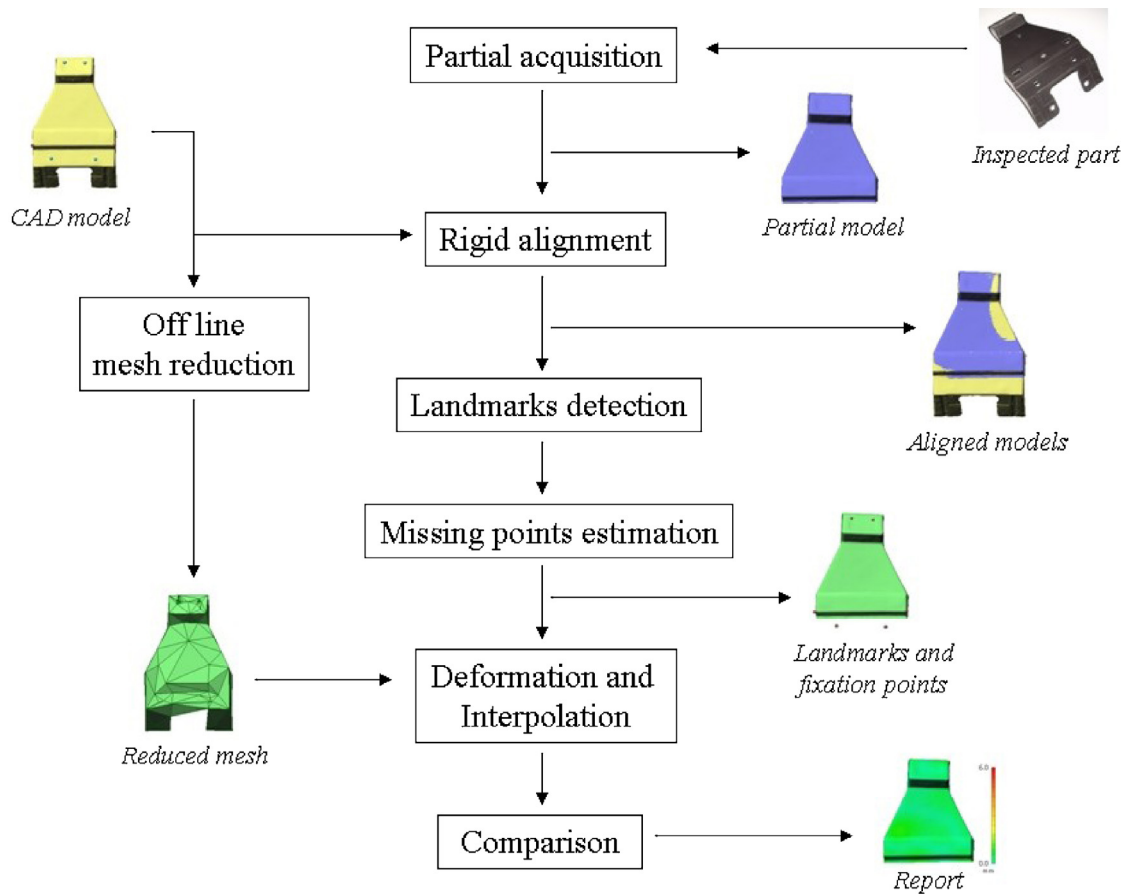


Fig. 1. Inspection method overview.

interpolation, the characteristic points, both fixation points, and additional characteristic points are taken as the centers of the RBFs, as shown in Fig. 2.

Given a set of centers or control points  $\{\mathbf{q}_j, j = 1, \dots, n\}$  taken from a set of points  $\{\mathbf{p}_i, i = 1, \dots, m\}$ ,  $m \geq n$ ; and  $d(a,b)$  which is a distance function between points  $a$  and  $b$ . The transformation

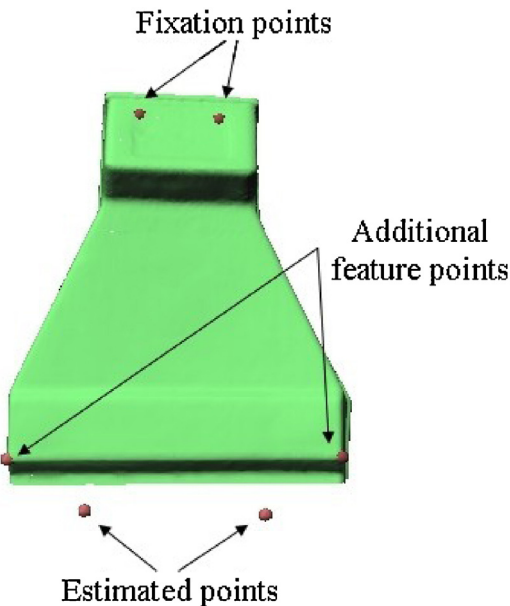


Fig. 2. Partial data model and landmarks.

given by the RBFs applied to a  $p_i$ ; such that RBFs are expressed as linear combinations of the shape:

$$U(p_i) = \sum_j C_j \Phi(d(\mathbf{p}_i, \mathbf{q}_j)), \quad (3)$$

where  $C_j$  is the weight vector associated to each center  $\mathbf{q}_j$ , and  $\Phi$  are the basis functions. The present method use the multi-quadric functions defined as:

$$\Phi(d) = (d^2 + b^2)^{1/2}, \quad (4)$$

where  $d$  is the distance function and  $\beta$  is a free parameter. These RBFs can be computed very efficiently as described in [13]. As originally proposed by Eck [14], the  $\beta$  parameter is calculated for each  $\mathbf{q}_j$  center as the minimum distance to the other  $\mathbf{q}_k$  centers,

$$\beta_j = \min_{j \neq k} d_j(\mathbf{q}_k). \quad (5)$$

Considering the linear term  $p_i$  that allows recovering the original model when no displacement is applied to the control point, the interpolation functions are described by:

$$F(p_i) = \sum_j C_j \Phi(d(\mathbf{p}_i, \mathbf{q}_j)) + \mathbf{p}_i. \quad (6)$$

When the transformation is applied to estimate the position of the missing fixation points in the partial model,  $\{\mathbf{p}_i\}$  represents the set made of characteristics points of the CAD model. The  $\{\mathbf{q}_j\}$  set represents the characteristic points on the partial data model which are used as the centers of the RBFs.

### 3.5. Calculating the deformations

The calculation of the deformation required to evaluate the non-linear alignment between the CAD model and the partial

views is carried out using FEM on the approximated CAD model [15,16]. Since in previous stages, the rigid alignment has been solved and the positions of the fixation points missing on the partial model have been estimated, it is then possible to determine the displacement field that need to be applied to the fixation points on the CAD model in order to deform the CAD model towards the partial views. The FEM model used for this calculation is using thick-shell elements. In this case Mindlin–Reissner formulation is used for the simulations [17]. Once the deformation has been calculated using the reduced mesh, the RBF interpolation is once again used to compute the node locations for the full resolution mesh.

### 3.6. Comparison and validation

Once the non-rigid alignment process has been completed, the partial data model is compared to the CAD data model and its validity is determined according to a tolerance range established by the part's designer. Such comparison is performed by calculating the Root Mean Square Deviation (RMSD) of the points in the partial-views data model with respect to the part's CAD model. The RMSD value for a given set of deviations  $\{d_i, i = 1, \dots, N\}$  is given by:

$$\text{RMSD} = \sqrt{\frac{1}{N} \sum_i d_i^2}. \quad (7)$$

The deviation of the  $i$ th point of the partial-views data model is calculated as the minimum Euclidian distance to the CAD model.

## 4. Experimental results

This section presents the results of the tests performed on three industrial parts. The three parts are made of plastic and are cover-like parts that can easily be approximated as thick-shells. Two of them are motorbike parts and the third one is an industrial packaging part. The surface data was digitized using a Minolta Vivid 9i range sensor with a RMS precision of 0.1 mm. The tests were carried out using an Intel Celeron of 2.20 GHz processor with 2 GB of RAM under Microsoft Windows 7. The three parts deformation is modeled using thick-shell elements implemented in the SAP 2000 finite elements software package [18]. The RBF interpolation algorithm was implemented in MATLAB<sup>®</sup> [19].

The material parameters used for the deformation calculation are as following: Young modulus = 25,000 kgf/cm<sup>2</sup>; Poisson ratio = 0.35. The geometric dimensions of the part's bounding box and average thickness are shown in Table 1.

The partial-view data model of parts 1 and 2 was generated from the deformation using the corresponding FEM simulation

**Table 1**  
Part dimensions.

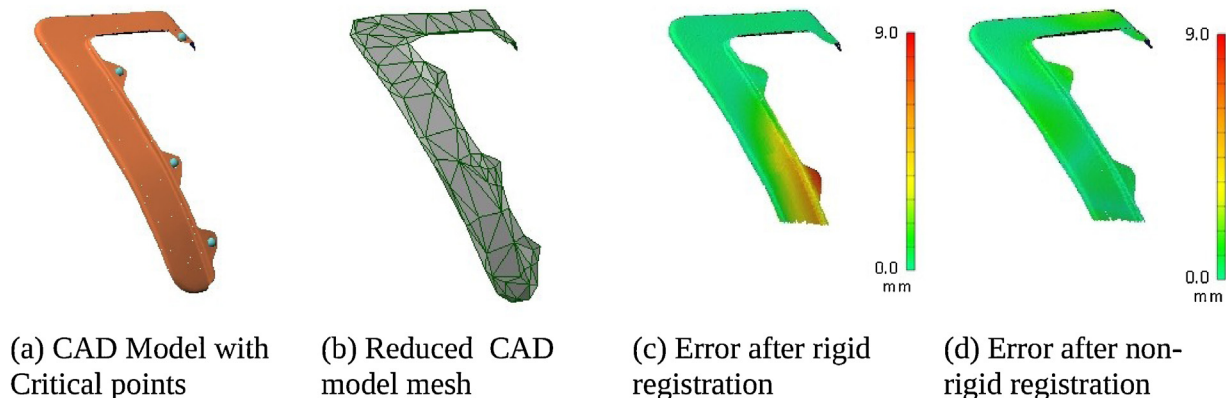
Parts	x (mm)	y (mm)	z (mm)	h (mm)
1	148.97	245.64	36.13	3.0
2	160.46	252.61	54.91	4.0
3	49.73	85.62	12.92	2.0

that approximates the real deformation of the parts. In this case, the approximation proposed in this study is compared directly (using the partial model) to the deformation calculation for which the whole model is acquired including its fixation points. The partial data model of part 3 was generated directly by using the surface data of the real part without fixation; in this latter case, a single view of the part was taken for data acquisition by using the range scanner.

Figs. 3a, 4a, and 5a show the CAD models of parts 1, 2, and 3 respectively. Figs. 3b, 4b, and 5b show the reduced mesh models obtained from the training stage. Figs. 3c, 4c, and 5c show the deviations that result from comparing the partial-view data models and the CAD models after a rigid transformation is applied between the models. Figs. 3d, 4d, and 5d show the deviations between the partial-view data model and the deformed CAD model after deformation is applied.

Table 2 shows the most relevant numeric results of the tests: the total number of nodes in the initial CAD mesh; the number of nodes in the mesh obtained in the training stage; the number of fixation points; the number of fixation points contained in the partial model; the number of additional reference points used to perform the estimation of missing fixation points missing in the partial model; the maximum distance of between the CAD model and the data points; the time to calculate the deformation using the high-resolution mesh model and its reduced version; the RMSD value for the rigid alignment; the RMSD after the deformation is applied. The deviation values are calculated as the minimum distance between the data partial model and the reference CAD model.

One can see in Figs. 3–5 and in Table 2 that the proposed method achieves a better alignment between the partial-views of the deformed CAD model than the rigid transformation alone. In the worst case a RMSD of 0.13 mm was obtained for a part of 2 mm thick on average (Part 3) compared to 0.32 mm obtained for the rigid transformation. This may be due to the fact that the actual part deformation is actually very small. For the other two parts (1 and 2), a reduction of more than one order of magnitude is observed. In all cases, the times to calculate the deformations using the reduced models have been reduced by one order of



**Fig. 3.** Non-rigid registration with CAD model of Part 1.

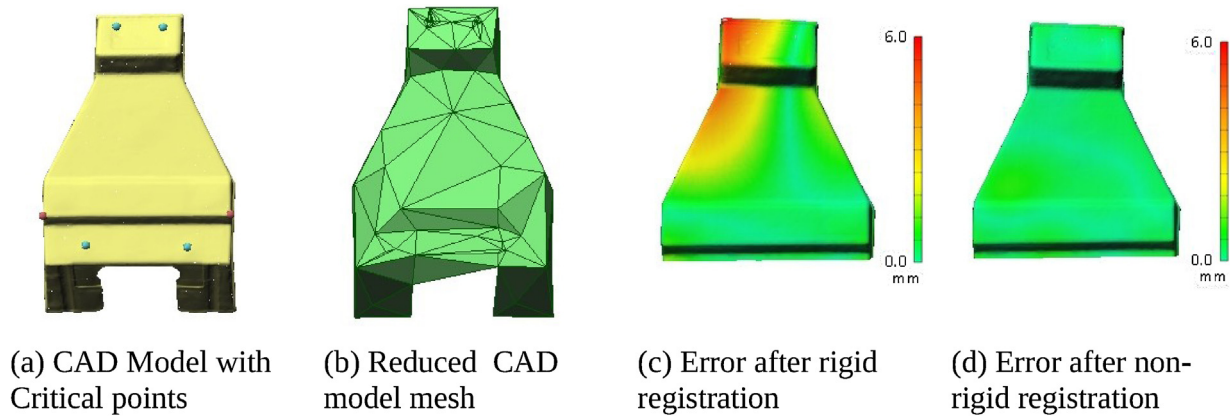


Fig. 4. Non-rigid registration with CAD model of Part 2.

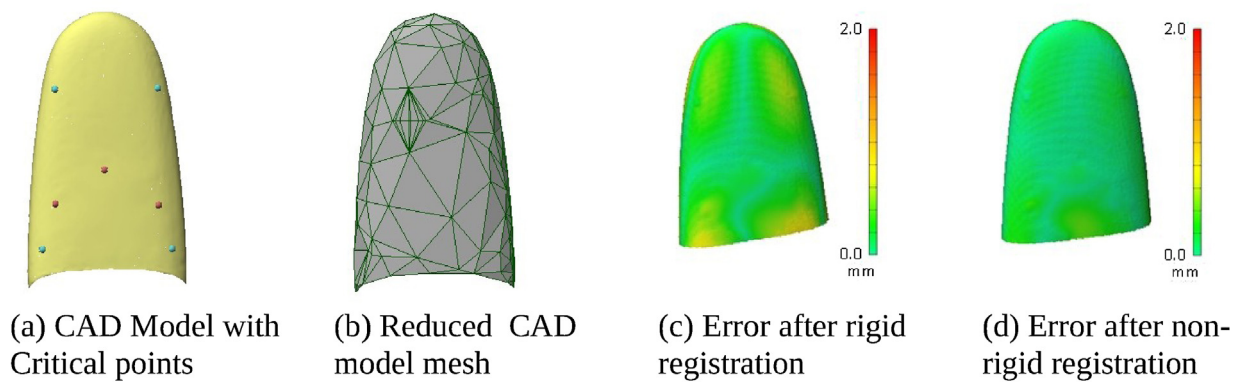


Fig. 5. Non-rigid registration with CAD model of Part 3.

Table 2  
Numeric results.

Parameter	Part 1	Part 2	Part 3
Size of CAD model mesh (# of nodes)	51,645	97,794	30,090
Size of reduced CAD model (# of nodes)	94	94	94
Number of CAD fixation points	4	4	4
Number of detected fixation points of partial-view model	3	2	2
Number of additional landmarks	0	2	3
Maximum comparison distance (mm)	9.00	6.00	2.00
Computation time using full CAD (s)	43	55	6
Computation time using reduced mesh (s)	<1	<1	<1
RMSD with rigid alignment only (mm)	1.87	1.95	0.32
RMSD including deformation (mm)	0.59	0.27	0.13

magnitude compared to the same computation using the full resolution model.

### 5. Conclusion

The paper proposes a new method by which a local inspection can be performed on deformable parts without having to fix the part onto a jig or to construct a full surface model from multiple views. Instead we demonstrate that one can do deformable part registration using only partial views, basically regions that need to be inspected. Since the partial data model may not contain all the fixation points, the method use an interpolation technique based on RBFs in order to calculate the approximate positions of the

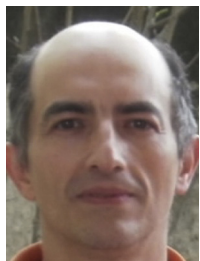
missing fixturing points. We also demonstrated that the mesh reduction technique can speed-up the FEM calculation at almost real-time rate opening the door to the design of on-line automated inspection systems.

The tests performed on the three parts show that it is possible to obtain a reduction of more than one order of magnitude in time to calculate the deformation using the interpolation with the RBF scheme. A similar reduction in error is also observed between the rigid registration and the deformable one. Future studies need to be performed in order to determine how well the method works form more complex parts where shell-elements are not sufficient.

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