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## Isogeometric surface fitting from tomographic images

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**Abstract** — Manufactured lattice structures often deviate from their original *as-designed* CAD models, which can greatly affect their mechanical response. In this work, a method is proposed to adjust an existing CAD model so that it matches *as-manufactured* defects using image-based techniques within a B-spline framework. By regularizing a Virtual Image Correlation method with a membrane strain energy and a high regularity multipatch interconnection, our approach achieves accurate shape measurement with pixel accuracy.

**Keywords** — Active Contours, Virtual Image Correlation, Multipatch B-spline, Lattice structure

**Introduction** Additive Manufacturing (AM) processes open the door to the creation of increasingly complex structures. Lattices are cellular architected structures known for their ability to achieve high specific characteristics. When manufactured, lattice structures exhibit geometrical defects that can be revealed by X-ray computed tomography reconstructed volume images (3D CT). The Marching Cubes algorithm is then typically used to extract a triangular surface mesh from the 3D CT. This mesh can contain a very large number of nodes, depending on the size of the image. From it, a volume mesh can be built and used to compute the mechanical response of the structure, showing that the defects may strongly impact the mechanical properties [1]. However, such methods based on finite elements are notoriously expensive to compute. Besides, because the mesh is in a different format than the initial *as-designed* CAD model, characterizing the geometrical transformation is challenging.

This work focuses on constructing an explicit CAD description of a real *as-manufactured* lattice part. This process uses a theoretical *as-designed* CAD geometry and an implicit description of the real part as a 3D gray-level image. Lattices are complex geometric objects that require a multipatch B-spline representation [2]. The proposed method conforms to the Active Contours framework [3], where the gray-level metric is inspired by the Virtual Image Correlation method [4, 5]. The regularization is divided into two parts : inside a B-spline patch, a membrane elasticity constraint [6] is weakly prescribed, while another method is used to impose a high regularity multipatch continuity between patches.

**Methods** The multipatch B-spline surface geometry depends on the position of its control points. To deform this geometry, each control point undergoes a displacement  $\mathbf{U}$ . These displacements are the degrees of freedom of the problem. They are computed by minimizing a sum of cost functions, also called energies:

$$\min_{\mathbf{U}} (E_{image}(\mathbf{U}) + \alpha E_{intra}(\mathbf{U}) + \beta E_{inter}(\mathbf{U})) \quad (1)$$

- $E_{image}$  : This energy is used to attract the geometry to the good location in the image. Given the amount of data contained in a 3D CT, performing calculations on the entire image would be very costly. Therefore, the virtual image correlation is used as the image energy.
- $E_{intra}$  : This energy is used to regularize the problem within a B-spline patch. The intrinsic regularization of B-splines makes Virtual Image Correlation work well with relatively coarse meshes. However, as the spline mesh is refined, tangential deformations that preserve the geometry degrade the conditioning of the problem. An additional regularization is therefore needed. Here, bi-laplacian or gradient-based regularizations, which are commonly used in the literature, appear

to degrade the results by also penalizing out-of-plane displacements. As a remedy, the regularization term proposed in this work is based on the membrane strain energy. This energy increases when the surface is subjected to tangential strains, such as in-plane shear and stretching. This regularizes the in-plane deformation while leaving the out-of-plane modes unaffected.

- $E_{inter}$  : This final energy regularizes the inter-patch problem. It takes the form of a penalization term that ensures higher regularity ( $C^1$ ) at the interfaces between the patches.

**Results** The problem was solved using the Gauss-Newton algorithm on a  $267 \times 327 \times 327$  voxels binned 3D CT of a nylon lattice strut, measuring approximately 13 mm long and 4 mm in diameter. The multipatch B-spline geometry shown in Fig. 1b consists of 6 patches, each forming  $\frac{1}{6}$  of a tube containing  $2 \times 4$  B-spline elements. With degree 2 basis functions, the mesh contains 144 nodes, reduced to 108 after eliminating duplicate nodes at patch edges, resulting in a sparse problem with 324 degrees of freedom. This is a significant improvement over the Marching Cubes mesh of Fig. 1a. Virtual Image Correlation, spanning 10 voxels above and below the B-spline surface, explores the image with approximately 8 integration points per voxel. Fig. 1b demonstrates the ability of the method to detect complex defects. A distance field estimator to the actual surface in the *as-manufactured* 3D CT is presented in Fig. 1c. This estimator illustrates the ability of the method to correct defects from approximately six voxels to less than one voxel.

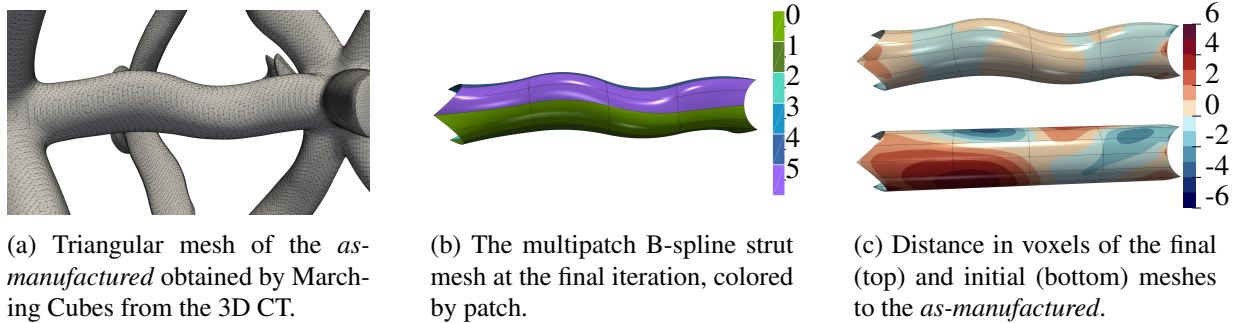


Figure 1: Example of applying the developed surface fitting method to the strut of a lattice structure.

**Discussion and Conclusion** In summary, the accuracy of the image resolution is achieved with the proposed method, highlighting the efficacy of the regularization techniques. The explicit representation of the *as-manufactured* geometry, along with the introduction of a morphing field, will facilitate quantitative assessment of geometric defects and enable the development of more cost-effective numerical simulations [7].

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