Mesh estimation for abrupt deformations of texture-less objects

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***Abstract*— Estimating object deformations is relevant in various industrial applications, including material testing and shape control. However, abrupt or sudden changes in the shape of objects present a significant challenge for existing methods that assume smooth or slow deformations. In this study, we propose a novel approach using our FMM-based contour mapping framework for estimating the deformation mesh of planar texture-less objects that undergo sudden shape changes. By analysing the geometry of the contour, we obtain contour point matches between consecutive deformation states that are used as input to update the deformation mesh. Our experiments and comparisons demonstrate the effectiveness of our method in overcoming abrupt deformations and estimating the deformation mesh.**

I. INTRODUCTION

Estimating the deformation state of objects [1] is important in various industrial processes [2], [3] as it has various practical applications such as identifying the object's behaviour (useful in material testing), computing a deformation model for shape control [4] (beneficial in robotics and automation) or performing more specific tasks (such as cloth smoothing [5]). Deformation meshes provide a discrete approximation of the continuous deformation behaviour of objects and thus characterise the object's deformation state. Current methods in the literature typically rely on matching visual features between iterations to update the object's mesh nodes (e.g., [4], [6], [7]). However, in cases where the visual texture of the object is not distinctive, such as objects without texture or with repetitive patterns, an adequate estimation of the object's deformation state becomes a challenge. Therefore, obtaining an adequate estimation of the object's deformation state when sudden shape changes take place and without relying on its visual texture presents a challenge. Building on our earlier research [8], we propose a new method in this paper that tackles this problem.

Our previous work, described in [8], introduced a method for contour mapping that maximises the similarity between geometric characteristics of matched contours using our proposed multi-scale Laplacian descriptors and the Fast Marching Method (FMM). This method is particularly interesting for robust estimation of deformations as it can handle non-isometric mappings (diffeomorphisms) between contours. In such cases, a homogeneous contour mapping method can be used to estimate the object's deformation between consecutive states without causing significant errors or drift. However, when object states change abruptly due to fast deformations or low sampling rates, assuming isometric deformations may result in inaccurate estimations of the actual deformation process. Focusing on this problem, in this paper we apply the mapping method from [8] to estimate the deformation mesh of the object, even when consecutively measured states present abrupt changes. Section II-A provides a summary of the elastic mapping method presented in [8]. Section II-B details the proposed framework, which is the main contribution of this paper. The experimental results are presented in Section III, followed by a final discussion in Section IV.

II. MESH ESTIMATION METHOD

A. *FMM-based contour mapping*

For completeness, in this section we summarise the elastic mapping method presented in [8]. The method takes as input two contours that are uniformly sampled and parameterised with parameters $\theta, \bar{\theta}$. We begin by computing the multi-scale Laplacian descriptors for both contours (as detailed in Section III.A. of [8]). These descriptors are computed at each point along the contour in the local reference frame, ensuring descriptor invariance to rigid transformations applied to the contours. Furthermore, the multi-scale nature of the descriptors enables comparison of local and larger size geometric features. After computing both descriptors, they are compared by generating a similarity surface denoted by $F(\theta,\bar{\theta}) \in \mathbb{R}^2$, where $F(\theta,\bar{\theta})$ represents how similar (in geometric terms) the respective neighbouring regions of points θ and $\bar{\theta}$ are.

The Fast Marching Method (FMM) [9] is applied to $F(\theta,\bar{\theta})$ to compute path $\mathrm{P} \in \mathbb{R}^2$. This path, defined on surface $F(\theta,\bar{\theta})$ as $\mathrm{P} = (\theta, \Pi(\theta))$, generates the coordinate pairs (or contour map) $\Pi(\theta) = \bar{\theta}$ that accumulate the lowest comparison cost when *travelling* along surface $F(\theta,\bar{\theta})$. Path P is usually referred to as the shortest path; the integral of the comparison cost $1/F(\theta,\bar{\theta})$ along P (i.e., $\int 1/F(\theta,\Pi(\theta))\mathrm{d}\theta$) represents the shortest *shape distance* between two compared contours according to our descriptors. Contour point matches can be directly obtained from the shortest path coordinates by setting a point's parameter θ as input to the path coordinates $(\theta, \Pi(\theta) = \bar{\theta})$.

B. *Mesh estimation for abrupt deformations*

Figure 1 presents the proposed vision-based method for estimating the deformation mesh of predominantly planar

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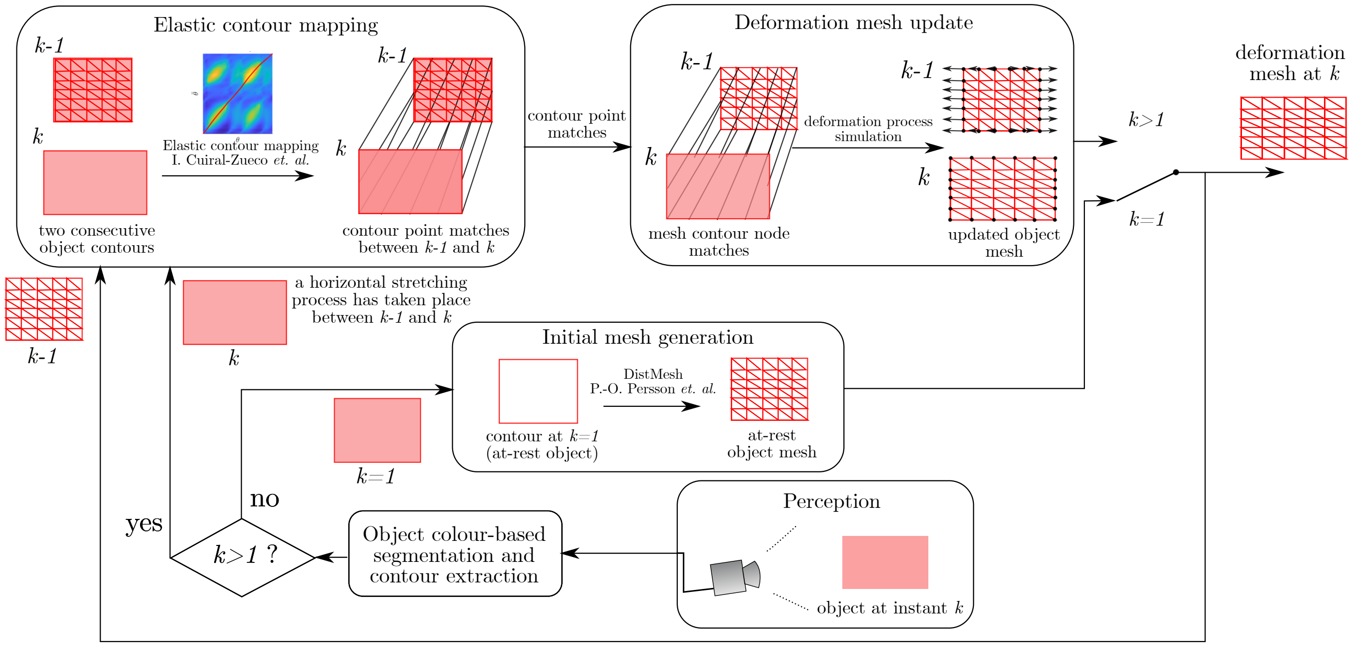

Fig. 1: Flowchart of the proposed method. Assuming that the object begins in an at-rest state, the initial mesh is generated at the beginning of the process ($k = 1$) using DistMesh [10]. In each iteration, the mesh is updated using the object's contour from incoming frames. Contour mapping based on the Fast Marching Method (FMM) compares consecutively retrieved contours, obtaining contour point matches, which are used as input for the mesh simulation process. This allows for updating the positions of nodes that are not part of the contour and provide a deformation mesh for each iteration k.

texture-less objects that present abrupt (sudden) deformations. The method processes RGB images captured by a camera to perform a colour-based object segmentation (in the CieLAB colour space) and to extract the object's contour (using α-shape contour extraction). At the beginning of the process ($k = 1$), the initial mesh is generated from the contour information using DistMesh [10] under the assumption that the object is at rest. In each iteration, the mesh is updated using object contours extracted from incoming frames. The Fast Marching Method (FMM)-based contour mapping compares consecutively retrieved contours to obtain contour point matches, which are used as input for the mesh simulation process. This enables updating positions of nodes that are not part of the contour. A variety of mesh-based deformation simulators may be employed, however, it is recommended to choose the one that best conforms to the object's behaviour. In this particular paper, a conventional mass-spring-damper-based simulation was used in order to update the mesh using position-based dynamics.

III. EXPERIMENTS

This section describes two comparative experiments conducted using an Intel Realsense D435 camera, which provides the RGB frames used in the framework. A light source is aligned with the camera's optical axis to illuminate the texture-less object, allowing for better perception. To evaluate the method's ability to handle sudden deformations, we captured new camera frames at a rate of 0.5 Hz. The objects were manually deformed in a rapid manner, resulting in abrupt changes between consecutive frames.

Each image sequence was analysed using two methods to show the relevance of our framework. The first method is the one presented in this paper, while the second method involves a mesh update based on an homogeneous contour mapping similar to those used on previous papers such as [11]–[14]. Homogeneous contour mapping involves sampling both contours with the same number of equidistant points, resulting in a map where contour length variations are assumed to occur uniformly throughout the contour. In contrast, the elastic contour mapping used in our proposed method allows for the identification of cases where specific parts of the contour stretch or contract while others remain unchanged.

Both experiments carried out in this study can be seen in Figure 2 and in the **attached video** [1]. The figure shows, for each experiment, three key frames for both the elastic and the homogeneous contour mapping methods: the initial mesh ($k = 1$), the frame where the abrupt deformation is first detected, and the final state of the mesh after the deformation. The object mesh is displayed in red, while the point matches between consecutive iterations are illustrated as grey lines. For comparison purposes, an additional frame is presented after the sequence where the mesh before the abrupt deformation is overlapped in yellow. Next to the frames, the evolution of the mesh's deformation distribution is presented for both methods. The deformation values are computed as the relative change in length of the mesh's edges with respect to their length at $k = 1$.

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[1] `https://youtube.com/playlist?list=PLdAqOP-RbNIyhJPk0hx2AuC-aoraUGErv`

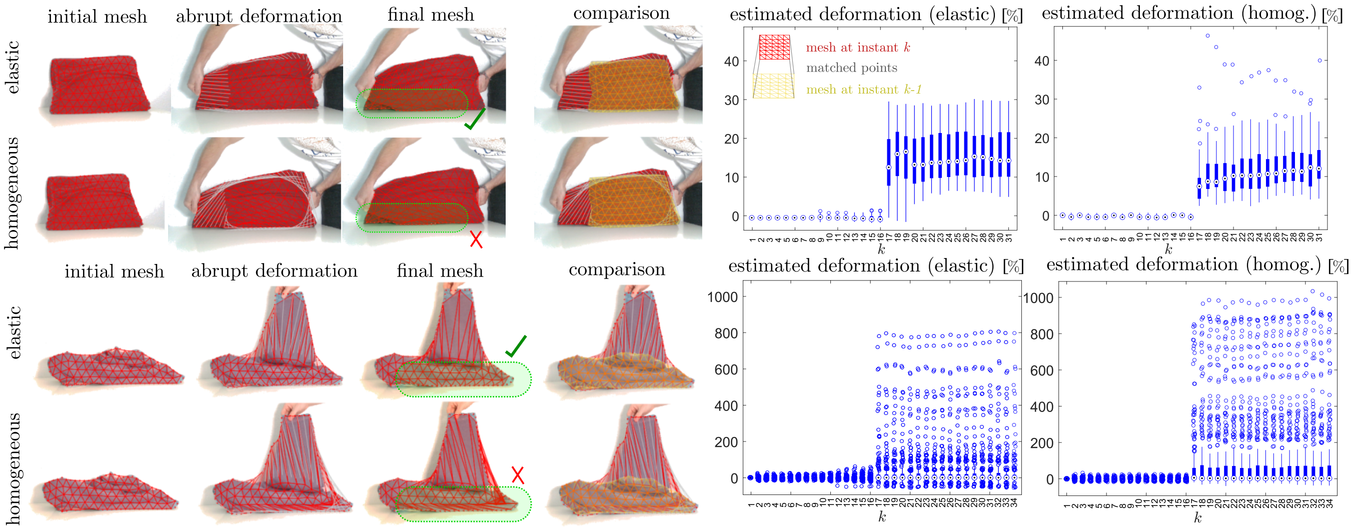

Fig. 2: Two examples using the proposed method (see details in Section III). In the first experiment (red cushion), the elastic contour mapping accurately identified the non-isometric deformation, as shown by the horizontal gray lines that represent the point matching on the abrupt deformation frame. In contrast, the homogeneous contour mapping assumed a uniform contour deformation, resulting in slanted gray lines and an inaccurate mesh deformation estimation. The green box in the figure indicates a mesh collapse that occurred in the case of homogeneous mapping. This collapse could have been caused by the uneven distribution of the estimated deformation, as evidenced by the more pronounced warping of certain areas of the mesh. In the second experiment (blue sweater), the elastic mapping correctly identifies that most of the contour remains unchanged while the homogeneous mapping estimates a contour point shifting process throughout the bottom of the object.

A. *Experiment: red cushion*

In this experiment (Fig.2, first experiment), a red cushion was suddenly stretched horizontally, resulting in the bottom and top segments of the cushion's contour being stretched while the sides' length remained relatively unchanged. The elastic contour mapping method accurately identified this non-isometric deformation, as demonstrated by the predominantly horizontal gray lines representing the point matching in the abrupt deformation frame of the elastic contour mapping sequence. Conversely, the homogeneous contour mapping method assumed that the deformation was evenly distributed across the contour, resulting in slanted gray lines and a mesh deformation that did not accurately represent the actual process. The analysis of the deformation distributions revealed that the elastic contour mapping method yielded a more uniform distribution of the stretching process. This result was expected since the object was uniformly stretched horizontally. In contrast, the homogeneous contour mapping method produced a more uneven distribution with outliers that reached up to approximately 40%. This may be due to some areas of the mesh collapsing, as highlighted by the green box in the final mesh frame.

B. *Experiment: blue cloth*

This experiment represents an extreme case where a folded sweater's sleeve is suddenly lifted (Fig.2, second experiment). Although the initial mesh does not represent the actual object configuration, it serves as an illustrative case of the method's performance in cases where the deformation is highly localised in a specific part of the object. The elastic mapping correctly identifies that most of the contour remains unchanged, while the homogeneous mapping estimates a contour point shifting process throughout the bottom of the object. This is well observed in the final mesh frame, where a set of edges on the bottom of the object has been significantly deformed. In the case of the final mesh of elastic contour mapping, the mesh presents less overlap with the object, which is likely due to the need for higher mesh resolution that allows nodes and edges to fit better into significantly deformed object configurations. The deformation distribution plots reveal that the elastic mapping method produced mostly outliers, as expected for the highly localised deformation process, while the homogeneous mapping method showed a more scattered distribution, which contradicts the actual deformation process.

IV. DISCUSSION

We proposed a method for estimating the deformation mesh of texture-less objects using visual sensors. The approach builds upon our previously proposed FMM-based contour mapping framework and addresses the more complex task of estimating the object's deformation mesh when sudden deformations occur. Two experiments demonstrate the effectiveness of the method. A limitation is that deformations may occur without affecting the object's contour and thus may not be perceptible by a camera considering the object lacks visual texture. Future work could involve extending the problem to three dimensions and evaluating different deformation simulators. Another potential avenue is to extend the framework to prevent object breakage.

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