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Adaptive Shape Servoing of Elastic Rods using Parameterized Regression Features and Auto-Tuning Motion Controls

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***Abstract*— We present a new vision-based method to control the shape of elastic rods with robot manipulators. Our new method computes parameterized regression features from online sensor measurements that enable to automatically quantify the object's configuration and establish an explicit shape servo-loop. To automatically deform the rod into a desired shape, our adaptive controller iteratively estimates the differential transformation between the robot's motion and the relative shape changes. This valuable capability allows to effectively manipulate objects with unknown mechanical models. An auto-tuning algorithm is introduced to adjust the robot's shaping motion in real-time based on optimal performance criteria. To validate the proposed theory, we present a detailed numerical and experimental study with vision-guided robotic manipulators.**

I. INTRODUCTION

The manipulation of deformable objects is currently an open (and hot) research problem in robotics that has attracted many researchers due to its great applicability in many areas, e.g. manipulating fabrics [1], shaping of food materials [2], etc. Note that physical interactions between a robot and a deformable object will inevitably alter the object's shape. The feedback control of these additional object degrees-of-freedom (DOF) is referred to in the literature as shape servoing [3].

For shape servoing tasks, an excellent feature extraction algorithm can describe the soft object to the greatest extent with the least number of feature coordinates. The most widely used image features are feature points, centroid points, distance/angle/curvature features, and other artificially marked points [4]. However, as the above are local features, and hard to describe the overall geometric information of soft objects. Thus, the development of global features present an advantage in this problem. In [5], the author used Fourier coefficients as feature vectors, and used a dual arm robot which relied on visual servoing to change the shape of the soft cables.

To execute shape servoing tasks, a controller requires a model (e.g. a Jacobian matrix) that describes the relationship between robot motions and feedback deformations. Existed methods used parameter linearization and least-squares methods to compute the deformation Jacobian matrix. However, both methods depend on the selection of the regression matrix and need a prior-known structure. The Broyden method was used to online estimate the Jacobian matrix in [6] without a known structure. Kalman Filter (KF) has an excellent performance in estimating unknown variables using a series of measurements observed over time in the presence of noise and uncertainty.

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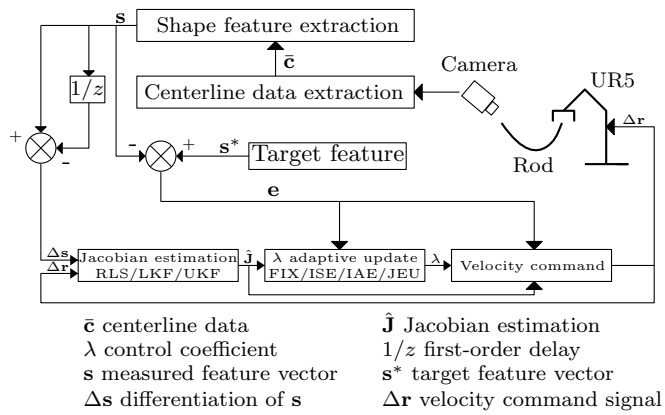


Fig. 1: The block diagram showing the overall workflow of the system.

Although model-free shape control is known for its simple structure and robustness to uncertainties, these controllers generally use a constant feedback gain (which limits the types of dynamic responses they can achieve). When the performance requirements change (e.g. deforming materials with different stiffness), a fixed gain may produce oscillations, cause the system to lose stability or even damage the manipulated object. Therefore, it is important to design a dynamic parameter tuning algorithm for shape servoing tasks, such that it can adapt to various performance requirements.

Fig. 1 shows the block diagram of the manipulation task.

A. Feedback Shape Parameters

The *naïve approach* to shape servoing is to synthesise a regulator that attempts to drive the full coordinates of $\bar{\mathbf{c}}$ (contour or centerline of the object) into a desired 2D contour. The main problem with this approach is that the raw vector $\bar{\mathbf{c}}$ is not an efficient signal for real-time control as its dimension very large. Therefore, it is necessary to design an algorithm that computes a reduced dimension feature vector, which can be used for feedback control. In this paper, we fit the feedback signal to a continuous curve $\boldsymbol{f}(\rho)$ that describes the 2D contour. The idea behind the proposed method proposed is to compute the coefficients of a linearly parametrized regression model of the 2D contour, and use it as a quasi-measurement of the object's shape.

We illustrate this principle with four representative examples: polynomial, Bézier, NURBS, and Fourier in the paper. Here, for space considerations, we only briefly introduce Bézier. Bézier curve approximates the curve with a polynomial expression using control points. $n+1$ control points can determine a n-degree Bézier curve which is described as follows:

$$\boldsymbol{f}(\rho) = \sum_{j=0}^{n} B_{j,n}(\rho)\,\mathbf{p}_j,$$
$$B_{j,n}(\rho) = \frac{n!}{j!\,(n-j)!}(1-\rho)^{n-j}\rho^j, \tag{1}$$

where $\mathbf{p}_j = [a_j, b_j]^\intercal$ are control points as well as the shape parameters of the 2D contour. Bézier curve has a first-order derivability. It guarantees that the fitting will advance smoothly with the control points without fluctuations, thus, it can represent complex shapes.

B. Approximation of the Local Deformation Model

Since we consider regular (i.e. mechanically well-behaved) elastic objects, it is reasonable to assume that small robot motions $\Delta\mathbf{r}_k = \mathbf{r}_k - \mathbf{r}_{k-1} \in \mathbb{R}^q$ will produce small changes $\Delta\bar{\mathbf{c}}$ in the observed 2D contour. We locally model this situation (around the current operating point) with the following expression:

$$\Delta\mathbf{s}_k = \mathbf{J}_k \cdot \Delta\mathbf{r}_k \tag{2}$$

where $\Delta\mathbf{s}_k = \mathbf{s}_k - \mathbf{s}_{k-1} \in \mathbb{R}^p$ denotes the features' changes, and the matrix $\mathbf{J}_k$ represents a Jacobian-like matrix that transforms robot motions into shape changes, and which cannot be analytically computed as the deformation properties of the object are *unknown*. Instead of identifying the full mechanical model, in this paper we design an algorithm that computes local approximations of $\mathbf{J}_k$ in real-time. For estimating the Jacobian-like matrix, we use two KFs, LKF and UKF, which show excellent real-time performance and are robust to external disturbances.

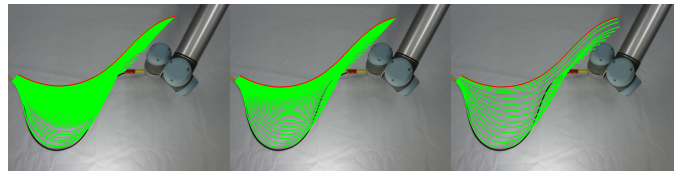
C. Shape Servoing Controller

Let us assume that at the time instant k, the transformation matrix $\hat{\mathbf{J}}_k$ has been exactly estimated by the online estimator, so that the shape-motion difference model satisfies, $\mathbf{s}_k = \mathbf{s}_{k-1} + \hat{\mathbf{J}}_k \cdot \Delta\mathbf{r}_k$. Define the deformation error as $\mathbf{e}_k = \mathbf{s}^* - \mathbf{s}_k$, and consider the following performance index, $Q = \mathbf{e}_k^\intercal\mathbf{e}_k + \lambda\Delta\mathbf{r}_k^\intercal\Delta\mathbf{r}_k$. We can compute the velocity command $\Delta\mathbf{r}_k$ as:

$$\Delta\mathbf{r}_k = \left(\lambda\mathbf{E}_q + \hat{\mathbf{J}}_k^\intercal\hat{\mathbf{J}}_k\right)^{-1}\hat{\mathbf{J}}_k^\intercal\mathbf{e}_{k-1} \tag{3}$$

D. Online Parameter Tuning

In general, the weight λ is constant, which makes the controller not adaptable to different control performance requirements. Meanwhile, elastic rods of different materials have different physical properties for manipulation. Some can be manipulated at high speed, while some are only suitable for chronic uniform deformation. Introducing parameter optimization criterion, the controller can be adaptively extended to various application scenarios.



(a) RLS (b) LKF (c) UKF

Fig. 2: Initial (black solid line), transition (green solid line) and target (red solid line) configurations in the experiment with a single robot among RLS, LKF and UKF.

II. Experiment

In this section, we conduct experiments using a UR5 robot. An experimental video can be downloaded from https://github.com/q546163199/experiment_video/raw/master/paper1/video.mp4.

Fig. 2 shows the strong adaptability and robustness of the proposed methods.

III. Conclusion

This paper presents a new visual servoing framework for automatically manipulating elastic rods to a desired configuration. It includes shape feature design, Jacobian matrix estimation, and online parameter optimization. First, new shape features based on a regressive identification process are presented to characterize the object's contour. Second, we compare the performance of two KFs (LKF, UKF) in estimating the nonlinear time-varying Jacobian matrix. Then, the velocity command and its implementation are derived. To optimize control parameters, we utilize various performance criteria and an adaptive update law combined with a gradient descent rule. Finally, numerical and experimental results validate the effectiveness and feasibility of the proposed control method.

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