Stereo Tracking and 3D Reconstruction of Underwater Pipes

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While manipulating flexible oil pipes in deep underwater environments, it is desired to monitor the pipe geometry in order to avoid damaging the equipment due to excessive tension. In order to achieve this goal, we propose an algorithm for tracking and reconstructing the pipe medial axis (PMA) using stereo cameras. The underwater scenario involves monochrome and low-resolution images, and a moderate amount of noise from floating particles and fish, such as presented in Figure 1. The pipe is marked with an alternating pattern of contrasting colors, and is compelled to configure a plane curve. These characteristics are used by the algorithm to achieve precise and robust results.

Given the bright marks on the pipe, the tracking algorithm attempts to find a bi-dimensional curved region $\mathcal{R}$ representing the pipe, by maximizing the intensity of the pipe projection in the image I. $\mathcal{R}$ is defined by the function $\mathbf{R}(s,t,\mathbf{x}(t))$, where $\mathbf{x}(t)$ is the projection of the parametric curve describing the PMA. This problem is summarized in Eq. 1:

$$\mathbf{x}^* = \arg\max_{\hat{\mathbf{x}}} \iint I(\mathbf{R}(s,t;\hat{\mathbf{x}}(t)))\, ds\, dt. \tag{1}$$

Trying to directly solve Eq. 1 would incur in errors, such as the collapse of the curve or the degeneration of the extremities. Therefore, this paper proposes to divide the problem into two unidimensional tracking phases, which first locates the pipe extremities along the longitudinal axis (t dimension), and then adjusts the whole curve in the transversal direction (s dimension). In order to be able to do that, the input image is transformed from the spatial domain into the longitudinal and transversal parametrization based on the curve, defined as

$$T(s,u) = \sqrt{I(\mathbf{R}(s,t))}, \quad \text{where } u = \int_{t_{min}}^{t} \left\|\frac{d\mathbf{x}(\tau)}{d\tau}\right\| d\tau. \tag{2}$$

The simplification provided by this transform enhances the tracking execution time substantially, given the fewer operations executed and the reduced image size.

The first phase of the tracking, which searches for the pipe in the longitudinal dimension, considers that pipe extremities lay upon a bright region of the alternating pattern marked over the pipe. The tracking is done by maximizing the energy in a window around each pipe extremity, using a Gauss-Newton approach, such that

$$u^* = \arg\max_{\hat{u}} \int_{\hat{u}-\omega/2}^{\hat{u}+\omega/2} \int_0^1 T(s,u)^2\, ds\, du \tag{3}$$

Each extremity is handled separately and the window size is as large as the pipe thickness.

Equivalently, the transversal tracking aims at maximizing the energy inside the region $\mathcal{R}$ along the s dimension. This is done by adjusting the previously detected PMA by a smooth function $\phi(u;\mathbf{q})$, which is governed by the parameter vector $\mathbf{q}$ and modeled as a B-spline. The problem can be described as finding the parameter vector $\mathbf{q}^*$, such that

$$\mathbf{q}^* = \arg\max_{\hat{\mathbf{q}}} \int_0^1 \int_{u^*_{min}}^{u^*_{max}} w(s)\, T(s+\phi(u;\hat{\mathbf{q}}),u)^2\, du\, ds, \tag{4}$$

where $w(s)$ is a weighting function used to increase the robustness of the tracking around the border of the pipe. By transforming Eq. 4 into a least-squares problem, it can be solved using the Gauss-Newton method.

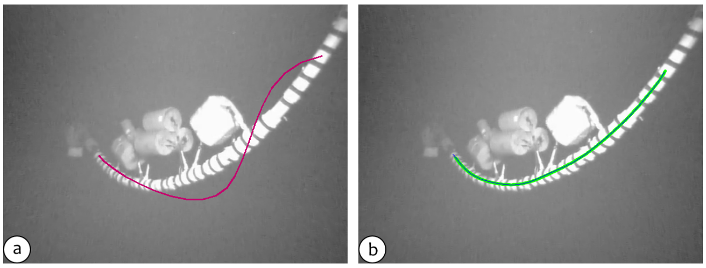

Figure 1: Underwater pipe tracking scenario. (a) shows in magenta the initialization, and (b) presents in green the tracked curve at the following frame.

Once the current position of the pipe projection in both images has been found, it is necessary to reconstruct the pipe in order to assess its geometry. The chosen approach is to reconstruct the PMA as a rational B-spline, which, according to Xiao and Li [2], requires to simultaneously fit a rational B-spline to each of the sample points. Therefore, the whole fitting can be modeled as a least-squares problem and solved minimizing the cost

$$\sum_i ||\mathbf{p}_i - \mathbf{x}(t_i;\{\mathbf{q}_k\})||^2 + \sum_j ||\mathbf{p}'_j - \mathbf{x}(t_j;\{\mathbf{q}'_k\})||^2, \tag{5}$$

where $\mathbf{p}_i$ and $\mathbf{p}'_j$ are sample points, and $\{\mathbf{q}_k\}$ and $\{\mathbf{q}'_k\}$ are the control points of the B-splines. By assuming that the pipe lies on a plane, it is possible to relate the curve projection in both images by an homography, which can only alter the x coordinates of the rectified curve points. These additional constraints are contributions of this paper. The solution, together with the centripetal parametrization [1], requires only $2\gamma+3$ values (where γ is the number of control points) to be optimized on the Levenberg-Marquardt algorithm.

The technique has been evaluated on videos from synthetic and real scenarios, by analyzing tracking and reconstruction errors. On synthetic videos, the mean tracking error was 0.011 pixels and the maximum 0.646 pixels, while 98.2% of the points had an error less than 0.1 pixel. The mean reconstruction error was 0.0066 m. On videos from a 1 : 8.89 scale experiment, the mean reconstruction error was less then 0.5 cm in 7 of 8 videos (which represents 1/6 of the pipe's diameter). While it is impossible to assess these errors on videos from the actual operation, there is strong evidence that the reconstruction is precise and accurate. Further details on the implementation of this algorithm is described in the paper.

[1] E.T.Y. Lee. Choosing nodes in parametric curve interpolation. *Computer-Aided Design*, 21(6):363 – 370, 1989. ISSN 0010-4485. doi: http://dx.doi.org/10.1016/0010-4485(89)90003-1. URL `http://www.sciencedirect.com/science/article/pii/0010448589900031`.

[2] Yi Jun Xiao and YF Li. Optimized stereo reconstruction of free-form space curves based on a nonuniform rational b-spline model. *JOSA A*, 22(9):1746–1762, 2005.