Vision-based Virtual Fixtures Generation for MIRS Dissection Tasks

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INTRODUCTION

Nowadays, cancer and precancerous lesion are major health problems. Assistive polyp dissection is a possible solution to accomplish high quality intervention while lowering down the surgeon fatigue. It could be performed in three stages: (i) polyp detection from images; (ii) safe margins definition around the polyp; (iii) path planning for assisted cutting. Vision-based procedures extract region of interest directly from the images, exploiting texture and color information as region descriptors. Modern developments in deep learning, e.g. the use of convolutional neural networks (CNNs) have made major advances in this field [1]. This paper proposes a vision-based pipeline for assistive polyp dissection. Our approach starts from stereo endoscopic images processing, including detection and segmentation of the region of interest, and leads to the definition of accurate points needed in path planning for assistive/autonomous cutting. In this work, we use the generated path as Virtual Fixture (VF), i.e. a constraint that restrict the motion of the robot manipulator along the path through haptic guidance forces rendered to the user. The goal of the work is to propose a functioning pipeline for assistive polyp dissection, exploiting basic computer vision concepts and impedance control to enforce the VF constraint. The work is a natural continuation of [2] towards a fully autonomous surgical interventions exploiting vision-based methods.

MATERIALS AND METHODS

As shown in Figure 1, our system is composed by the da Vinci Research Kit and an experimental setup replicating a surgical scene containing a polyp (blue object). We define an inertial word reference frame $(O - x_w y_w z_w)$, performing Zhang's stereo calibration [3] and identifying the transformation between $(O - x_w y_w z_w)$ the camera reference frame $(O - x_c y_c z_c)$. Then, acquiring images with the tool in different positions, we identify the transformation between $(O - x_w y_w z_w)$ and PSM (Patient Side Manipulator) frame $(O - x_t y_t z_t)$ by using the absolute orientation formulation, which allows defining 3D object points and robot tool positions in the same coordinate system [4].

A. Vision algorithm

Figure 2 represents an overview of our system, that takes endoscopic stereo images as input. A segmentation step is adopted restricting the acquired images to the object of interest. We apply a Watershed transformation on left gray-scale image, defining the polyp region, later used as seed point to apply the widespread *GrabCut* segmentation method [5], obtaining polyp's binary mask. We adopt a modifications of this algorithm, solving the minimization problem by a graph cuts minimization algorithm and defining the statistical models for the data energy function as a Gaussian Mixture Models based on color distribution. Simultaneously, Semi-Global Matching and Mutual Information (SGBM) is used for disparity computation from stereo images, with post-process enhancement via weighted least squares filter. The obtained disparity map is segmented using the previously computed polyp's binary mask. This allows calculating two different disparity map, one related to the object and other one to the background. Then, disparity information are reprojected in 3D space, producing object's point cloud and background point cloud. We identify the 3D centroid of the polyp in the space as a 3D vector. After that, the maximum distance from centroid is computed, allowing defining four extreme points of the object. A Sample Consensus method is selected to estimate a plane model from the background point cloud approximating the surface on which the robot's tool will perform the cutting path. This approximation is adopted due to the small curvature of the background.

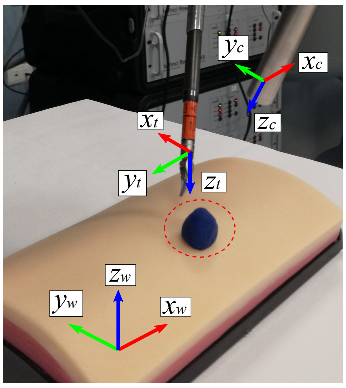

Fig. 1: Experimental setup, recreating patient's anatomy using phantom. The blue object represents a polyp.

B. Path Planning and Virtual Fixture

The object 3D points are projected on the surface model and their coordinates transformed to be defined in PSM reference frame $(O - x_t y_t z_t)$. Particularly, the object ex-

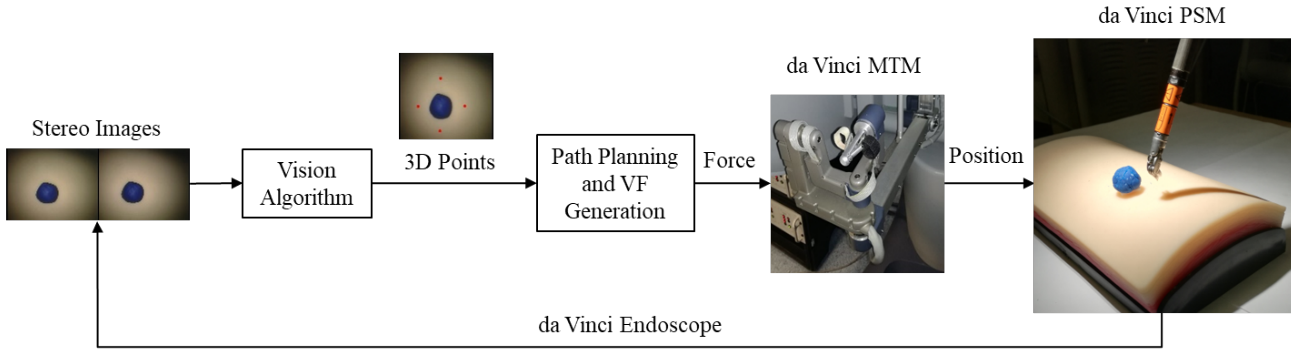

Fig. 2: Overview of the method.

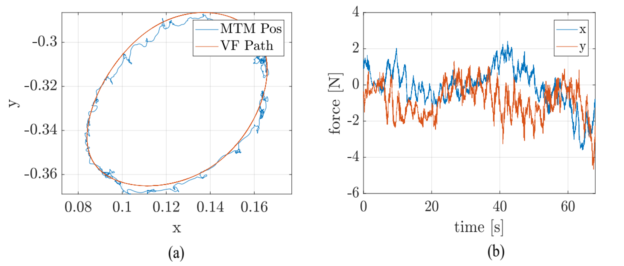

Fig. 3: (a) Virtual Fixture path (red line) and Master Tool Manipulator (MTM) position during the dissection task; (b) Estimated Haptic guidance forces displayed to the user through the MTM.

treme points coordinates are adjusted with a security margin, that allows performing the cutting in safe conditions avoiding collisions between the tool and the polyp. Once these 3D points are determined, they are used to build the VF geometry. Similarly to [2], we formulate the path for cutting through a parametric curve. In this work, we adopt a closed B-Spline curve defined by:

$$\Gamma(s) = \sum_{i=0}^{n} N_{i,k}(s)\, p_i \qquad (1)$$

where $\Gamma(s)$ denotes the curve, k its order, $s \in [0, 1]$ is the normalized curve parameter and $N_{i,k}$ are its basis function. The 3D points identified by our vision algorithm are used as controls points of the curve (p_i). Finally, a simple constraint enforcement method is adopted, i.e. a spring-damper like force is imposed onto the VF path that thus exhibits attractive behavior, i.e.: $f = K_p(x_d - x) - K_d\dot{x}$. To this end, Newton-Raphson method is used to find the nearest point on the curve x_d starting from the current robot TCP position. The attractive force f is displayed through impedance control of the Master Tool Manipulator (MTM) robot, realized thanks to the identification of the dVRK dynamic model [6].

RESULTS

The proposed vision-based assistive control is evaluated executing multiple dissection tasks. As previously explained, four polyp's extreme points are computed directly from the images, and their coordinates are adjusted by adding a secure margin of 1 cm. These points are used to define the B-Spline representing the dissection path. Graph in Figure 3 (a) contains a VF path and the MTM end-effector position in the xy plane of the MTM reference frame. As it is possible to notice, the user follows the determined path during the procedure thus improving its precision and accuracy. Figure 3 (b) shows the estimated haptic guidance forces to the user through the master side (MTM) during the tasks.

CONCLUSIONS AND DISCUSSION

In this paper, a vision-based assistive dissection procedure is presented, which finds application in polyp resection. The overall technique uses online generated VFs to constraint the robot to follow an optimal dissection path, created via specific points obtained directly from images of the surgical scene. The presented method aims at the full automation of polyp/tumor dissection. The obtained results suggest the feasibility of the proposed pipeline for polyp dissection. As future works, more advanced computer vision techniques will be considered, overcoming the inaccuracies in 3D reprojection, which could occur in more realistic surgical conditions. Also, an accurate study on medical procedures for polyp dissection will be considered for a correct definition of safe security margins for cutting.

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