Image-based Contact Stabilisation Inside the Beating Heart

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INTRODUCTION

While catheters have enabled a variety of beating-heart intracardiac procedures, the range of procedures has been limited by the inability to provide detailed visualization of the tissue at the catheter tip and by a lack of dexterity for tissue manipulation. Recent work has demonstrated that incorporating a tip-mounted camera (cardioscopy) can provide excellent imaging during tissue contact [1]. Furthermore, robotic control can provide additional dexterity. A fundamental challenge to implementing a robotic solution, however, is to provide the capability to stabilize the robot tip on a tissue structure inside the beating heart while ensuring that the applied forces are not excessive. While current solutions employ a combination of ultrasound imaging and force sensors [2], this paper proposes an image-based contact stabilization algorithm.

Cardioscopic images are acquired by pressing an optical window containing a chip-based camera and LED against the intracardiac tissue such that the blood is displaced. Exploiting the fact that images during contact with tissue are distinctly different from noncontact images of blood, it is possible to estimate the contact state and design a controller to drive robot position so that contact is maintained over a desired fraction of the cardiac cycle. This contact ratio acts as a proxy for mean contact force over the cardiac cycle. This low-bandwidth "force" control is relatively safe since it slowly adjusts robot tip position in response to the higher frequency heart motion. This paper describes the image-based controller together with initial validation results.

IMAGE-BASED CONTACT STABILIZATION

Our contact state estimator uses the Bag of Features (BoF) algorithm [3], a supervised machine learning algorithm usually used for high-level content retrieval in images. This approach uses a set of image descriptors as an input. In this study, we used the FAST feature detector [4] and LUCID descriptor [5], for a good balance between performance and computational burden. After training on a set of manually labeled examples, the algorithm is used for predicting the contact state c of a given input image,

$$c(t) = \begin{cases} 1, \text{contact} \\ 0, \text{no contact} \end{cases} \quad (1)$$

Thanks to low computational burden in the feature detection and prediction steps, the estimation executes at video rate.

Using the contact state estimator, we wish to derive a controller that will stabilize the robot tip at a position which produces tissue contact for a specified fraction, r^d, of the cardiac cycle. Since the motion of certain heart structures is predominantly uniaxial, the contact ratio, r, can be expressed as a function of robot tip position, $x(t)$, and heart position, $x_h(t)$, along the direction of motion. This is illustrated in Fig. 1for a valve annulus.

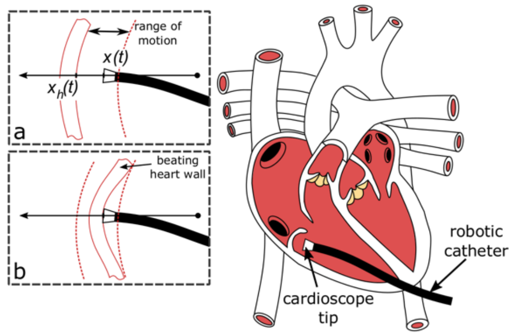

Fig. 1 Example of a transapically-inserted catheter approaching the pulmonary valve annulus to perform intracardiac surgery. (a, b) show the contact between the catheter at position $x(t)$ and the heart for two extremes of the wall movement $x_h(t)$.

Assuming that the measured heart rate, $1/T_c$, is slowly varying, the contact ratio can be computed from

$$r(t) = \frac{1}{T_c}\int_{t-T_c}^{t} c\left(x(u), x_h(u)\right)du \quad (2)$$

Stabilizing the contact can then be achieved by regulating the value of r to a desired value r^d using proportional derivative control:

$$\dot{x} = K_p(r^d - r) - K_d\dot{r} \quad (3)$$

Using this controller, robot tip position adjusts to regulate r to the desired value r^d. Under the assumptions that heart rate remains stable or slowly varying and that the contact ratio does not saturate, $r(t)<1$, controller stability can be demonstrated using the candidate Lyapunov function:

$$V(r) = \frac{1}{2}(r^d - r)^2 \quad (4)$$

This 1 DOF controller can be used during teleoperation as part of a hybrid position-"force" control scheme. In this scenario, the operator controls tip orientation as well as tip position in the plane of contact while the contact stabilizer controls position normal to the plane of contact.

EXPERIMENTAL VALIDATION

To validate the approach, the contact state estimator was first trained and evaluated. Subsequently, the controller was tested in bench experiments. Each experiment is described below. The behavior of the contact estimation algorithm was validated on cardioscopic images taken from six *in vivo* experimental surgeries, performed using five different cardioscopes (Fig. 2). A total of 1540 images were selected to build a balanced dataset, which was divided into three subsets: 70% for training; 15% for tuning algorithm parameters; and 15% for validation. The trained contact state estimator exhibited a specificity of 95.4% and a sensitivity of 95.4%. The average computational time (core i7 CPU) was 2.63msec per image.

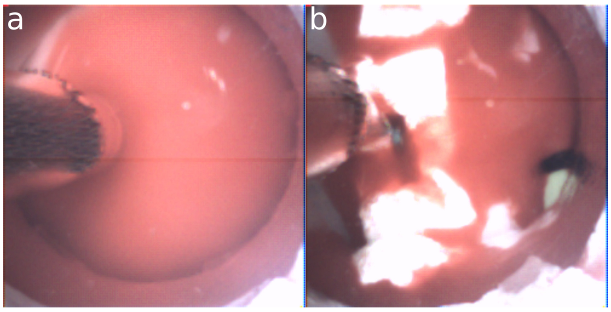

Fig. 2 Sample cardioscopic images. (a) No contact; (b) Contact.

To prepare for in vivo testing, the contact stabilization controller was evaluated in bench experiments as shown in Fig. 3. A concentric tube robot with a cardioscope camera at its tip was used together with a target oscillating at 75 "beats per minute." The *z*-direction of the robot was aligned under teleoperation to be approximately collinear with the direction of target motion and at a distance of several centimeters from the target. The contact controller was then turned on such that the robot approached the target and attempted to stabilize at the desired contact ratio. The controller gains were adjusted using a desired ratio of $r^d = 0.5$ to obtain an overdamped response. The final gain values were $K_p = 8,\ K_d = 3$.

Fig. 4 depicts the step response of the controller as it moves, initially from non-contact, to set points of $r^d = \{0.2, 0.4, 0.6, 0.8\}$. It is observed that robot displacement is smooth and the desired contact ratios achieved without overshoot. These tests will be repeated *in vivo* during the next few months.

DISCUSSION

The need for force sensing and haptics has long been debated in the robotics community. Despite general agreement on the benefits of force sensing, their cost, size and reliability have remained impediments to their general use. Furthermore, in medical applications, surgeons performing minimally invasive procedures have learned to substitute visual cues of tissue deformation for haptic feedback. Extending this visual approach to intracardiac surgery is difficult, however, owing to the opacity of blood, the poor resolution of ultrasound and the inability to directly image tissue with fluoroscopy.

The proposed technique combining cardioscopy and image-based contact stabilization provides a means for overcoming these challenges that does not rely on force sensing nor on high-bandwidth catheter motion. Furthermore, since it is designed specifically around the expectation of a changing contact state, it does not suffer the usual stability problems associated with robot controllers making and breaking contact.

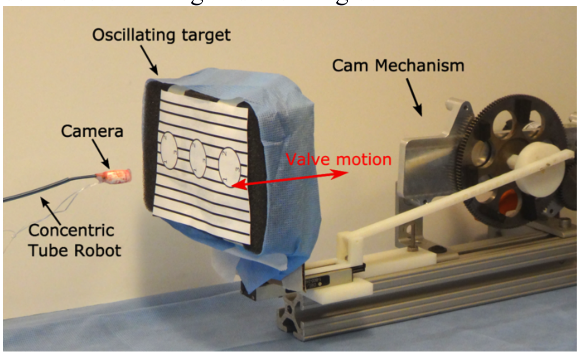

Fig. 3. Test set up for evaluation of contact controller. Cardioscope mounted on the tip of a concentric tube robot advances to press against oscillating paper target.

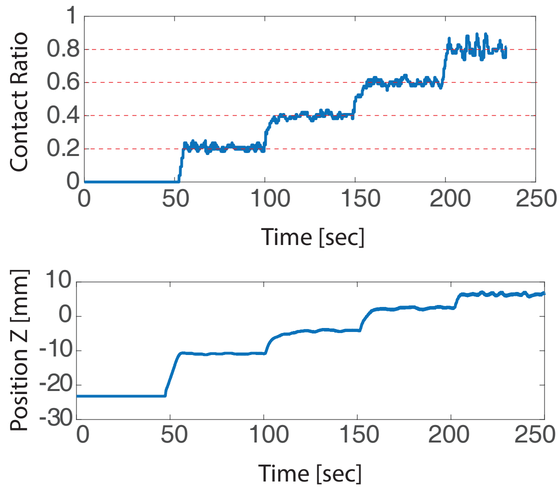

Fig. 4. Step response of contact ratio controller for a sequence of set points using the test set up of Fig. 3.

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