Visual Servoing for Robot-assisted Diagnostic Ultrasound

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Abstract

A robot system for positioning an ultrasound probe has been developed [1]. Ultrasound visual servoing can be used to help ultrasound technicians position the ultrasound probe. The feasibility of visual servoing for motion in the plane of the ultrasound probe in one dimension has been addressed here. Tracking of the carotid artery for a long period of time has been demonstrated in real-time. Two different image processing methods have been evaluated, namely, the Star algorithm and a modified discrete snake algorithm.

1 Introduction

Medical ultrasound exams often require that ultrasound technicians hold the transducers in awkward positions for prolonged periods of time, sometimes exerting large forces. Not surprisingly, a number of studies indicate that they suffer from an unusually high incidence of musculoskeletal disorders (e.g. [2]).

Motivated initially by the need to alleviate these problems and present a more ergonomic interface to the ultrasound technicians, a teleoperation system for medical ultrasound diagnosis has been developed [1, 3]. Figure 1 shows the experimental setup of the system. The system consists of a master hand controller, a slave manipulator carrying the ultrasound probe, and a computer control system that allows the operator to remotely position the ultrasound transducer relative to the patient's body. The problem considered first as a test-bed for robot-assisted ultrasound is that of carotid artery examination. This examination is carried out to detect occlusive disease in the left and right common carotid arteries - a major cause of strokes.

Figure 2 shows the control block-diagram of the system. The motion of the robot arm and the hand controller of the proposed ultrasound system are based on measured positions and forces, acquired ultrasound images, and/or taught position and force trajectories. Several modes of control are discussed in [1], including the control of the transducer using ultrasound image tracking, for which the image Jacobian is derived. This could help the technicians guiding the motion of the ultrasound probe during the examination. Although there have been many approaches proposed for medical image feature tracking and registration (e.g., [4]), they are mostly for image modalities with a good image quality, e.g. MRI and CT, and can not easily be applied to ultrasound images. To cope with the problems incurred by speckles in ultrasound images, various algorithms have been developed previously for still images (see, e.g. [5, 6]). Of particular interest to the problem of visual servoing and shared control is the

Figure 1: Experimental setup for robot-assisted ultrasound [1]. The 6-DOF parallelogram linkage robot moves the ultrasound probe on the patient's neck for the carotid artery examination.

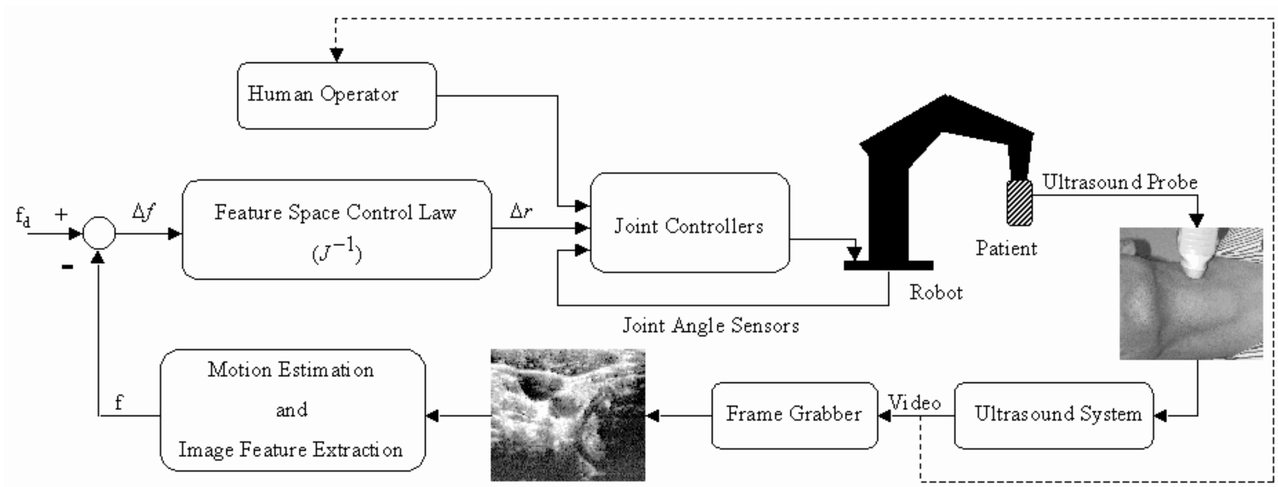

Figure 2: A block diagram of the control algorithm. The robot is under the shared control of the visual servoing algorithm, force sensor, and the operator. The probe is positioned on the patient's neck.

ability to track images in real-time over a long period of time. Different feature tracking methods were modified for this purpose and are presented here, namely, the Star algorithm and the discrete snake algorithm. The Star algorithm has already been used in ultrasound image processing for a different purpose, to detect boundaries of the ventricular cavity [7]. A temporal Kalman filter is used together with this algorithm to stabilize the result. The discrete snake method was originally proposed in [8], to extract boundaries from ultrasound images. Both methods are implemented in real-time to track the carotid artery in ultrasound images.

This paper discusses the feasibility of automatically guiding the ultrasound probe as a function of its image, termed "ultrasound image servoing". The proposed image processing algorithms to track the carotid artery in real-time are described in Section 2. Section 3 presents the visual servoing for one dimensional motion in the plane of ultrasound image. Experimental results confirm the accuracy and stability of the proposed ultrasound visual servoing method.

2 Feature Tracking in Ultrasound Images

Two feature tracking methods are presented here. These methods are the Star algorithm, and the discrete snake algorithm. Video-images from an ultrasound examination were obtained. The video images were digitized and processed using a 450 MHz Pentium III PC with a Matrox Meteor frame-grabber.

2.1 The Star Algorithm

The Star algorithm [7] was implemented to track the carotid artery in real-time. The algorithm uses an edge-detection filter to detect the carotid artery boundary along rays emanating from a point interior to the carotid artery. It determines (x_c,y_c) (center coordinates of the cavity) as the center of gravity of extracted boundary points.

Figure 3 depicts a boundary that results using the Star algorithm. In this case, the number of radii is 32. The algorithm needed 6 iterations to converge. The cubic B-spline algorithm was used to interpolate the estimated points.

Although the Star algorithm performs in real-time, its instability is high. This is improved by using a constant velocity kinematic model and a temporal Kalman filter [9]. In each frame, a measurement of the system (centroid coordinates of the carotid artery) is made and used as an input to the algorithm.

Motion of the carotid artery could be tracked at 30 frames/second. The average tracking time is 10 to 30 seconds. The maximum duration which the system can track the carotid artery depends on the quality of the ultrasound images.

2.2 The Discrete Snake Model

The snake model was originally proposed to find a continuous closed contour that minimizes an energy function. Even though this model has been studied

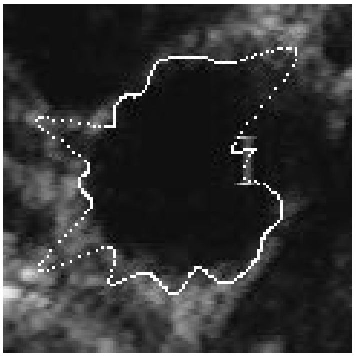

Figure 3: Estimated boundary of the carotid artery using the Star algorithm for one frame. 32 edge points were estimated and interpolated using the cubic B-spline algorithm.

extensively, it still suffers at least two fundamental problems. The first problem is that snake models can easily be trapped by noise. The second problem arises from the difficulty in determining the weighting factors that control the deformation behavior of a snake.

To solve these problems, the approach proposed in [8] was chosen. Rather than performing snake deformation on the original image, the discrete snake model carries out energy minimization on selected edge points of the original image. The main idea is that instead of searching the next position for a snaxel (control points of the snake) along its searching path *pixel by pixel*, the discrete model only considers the *peak points*, i.e, local maxima of the edge detection algorithm, as the searching space. It is discrete in the sense that the snaxel positions (i.e. local maxima) distribute discretely in contrast to continuously as in the conventional snake model. As a consequence, it is anticipated that the optimal snake can be derived by searching only a limited number of peaks. The immediate advantage of the discrete concept is that the searching space for the optimal solution is generally reduced, which is very important in real-time tracking.

Instead of using an early vision model described in [8], a method similar to the Star algorithm to find candidate edge points has been used. Also, a global minimum among energy of candidate edge points for each radius is found instead of searching for a minimum among adjacent points.

Figure 4 shows the estimated boundary of the carotid artery using the discrete snake method. 32 control points have been chosen and the cubic B-spline algorithm has been used to interpolate the control points. The estimated boundary is more accurate than the Star algorithm. The method was implemented in real-time for a sequence of ultrasound images. The motion of the carotid artery could be tracked at 30 frames/second most often in the range of 10 to 15 seconds and for as long as 40 seconds of ultrasound video.

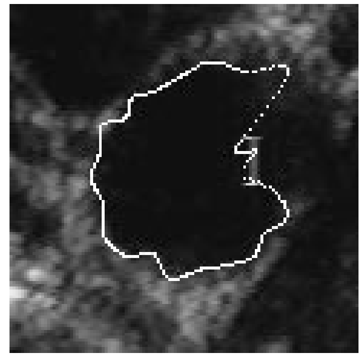

Figure 4: Estimated boundary of the carotid artery using the snake algorithm. 32 edge points were estimated and interpolated using the cubic B-spline algorithm.

3 Ultrasound Visual Servoing

Visual servo-control [10] could be used to control motion in the plane of the ultrasound beam. Its feasibility is determined by the ultrasound image Jacobian J_v, which relates differential changes in image features to differential changes in the end effector location [10]. The rank of the J_v is at most three and will be equal to three for two or more feature points non-collinear with the origin [1]. Thus, as expected, with non-trivial ultrasound images, it is possible to control the motion of the ultrasound transducer in its image plane.

The two proposed motion tracking algorithms have been used to evaluate the feasibility of ultrasound image servoing. A cylindrical phantom with a plastic pipe mounted in the middle was filled with water to simulate the ultrasound image of the carotid artery. The position of the ultrasound transducer, mounted at the end-effector of the robot, on the phantom surface is shown in Figure 5. While the motion along the z_p axis is controlled by the force sensor mounted at the robot end-effector, the visual servoing is performed in one dimension along the x_p axis to center the position of the pipe in the ultrasound image. Figure 6 shows the tracking performance by using the Star algorithm. Experiments show good stability of the visual servoing system. Similar results could be achieved by the

Snake algorithm.

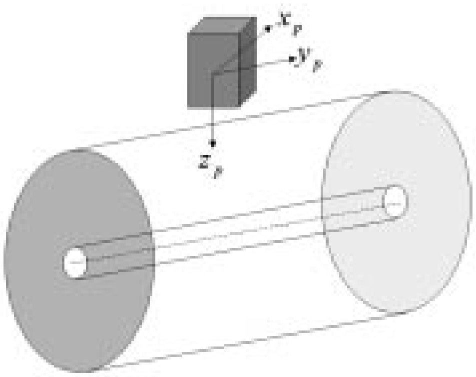

Figure 5: Position of the ultrasound probe on the cylindrical phantom; a plastic pipe in the middle simulates the ultrasound image of the carotid artery.

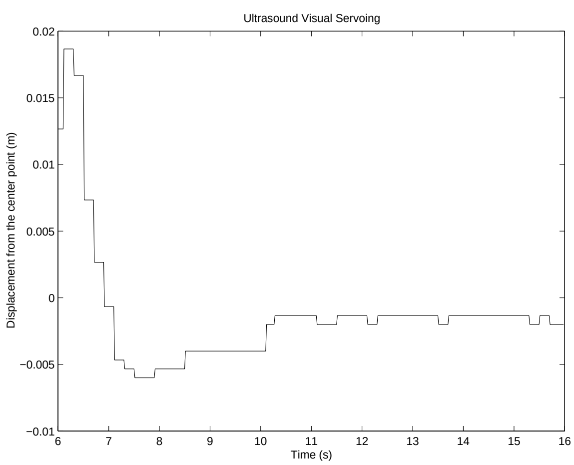

Figure 6: Visual servoing with the ultrasound robot in one dimension; the probe is moved away from its initial position by the operator and then it is left alone to converge to the centeral position by means of the visual servoing algorithm.

In the immediate future, the system will be used to explore the use of operator-computer shared control of the ultrasound probe and ultrasound image servoing in more degrees of freedom. It is hoped that other applications of the system, including the ability to acquire 3-D images and to perform precise registration will also be developed.

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