Paper Seminar Report of:

Image-Guided Control of a Robot for Medical Ultrasound

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Group 8: Ultrasound-Based Visual Servoing

Seminar presented by Michael Scarlett

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Project Goal

The goal of this project is to develop visual servoing for intraoperative robotic ultrasound. The doctor would select a predefined volume from a reference image such as CT or MRI which was obtained before the procedure. Subsequently the robot would image the patient with an ultrasound probe at the predefined volume of interest. This technique would allow the doctor to obtain accurate anatomy of the patient in real-time, even when deformations and organ movement cause the reference image to differ from reality. An ImFusion plugin will be developed which obtains a 3D volume from individual ultrasound probe images, then calculates the 3D transformation between this volume and the volume of interest to move a KUKA iiwa lightweight robot.

Paper Selection

The paper chosen for this seminar presentation is "Image-Guided Control of a Robot for Medical Ultrasound" published in *IEEE Transactions on Robotics and Automation* in 2002. This paper describes the visual servo controller of a robot-assisted system for medical diagnostic ultrasound. Visual servoing is an automatic method for robot control that uses the error between the features of the input image and desired features of a reference image to move the robot closer to the volume of interest with the desired features. The system described by Abolmaesumi et al. uses a robot to position an ultrasound transducer, and a computer displays a GUI with real-time ultrasound images. The authors discuss image processing algorithms for feature selection and validate their results by performing carotid artery tracking in ultrasound images.

The ultrasound-based image-guided control system in this paper has a system setup that is similar to the one for my project. This paper also involves calculating the transformation between images to update the location of an ultrasound probe. Reading this paper allows me to understand visual servoing from a control systems perspective and become acquainted with how data will flow through the system. It also provides insight into how I would evaluate the performance of image processing algorithms for visual servoing when comparing different methods.

Motivation

Medical ultrasound exams often require ultrasound technicians to hold the ultrasound probe in awkward positions for prolonged periods of time. As a result a number of studies indicate that sonographers suffer from an unusually high incidence of musculoskeletal disorders. Robotic ultrasound offers ergonomic benefits by allowing the operator to remotely position the ultrasound probe. It allows the possibility of telemedicine through the Internet.

System Setup

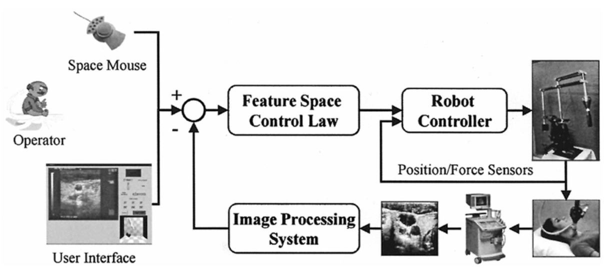

Figure 1: Block diagram of system

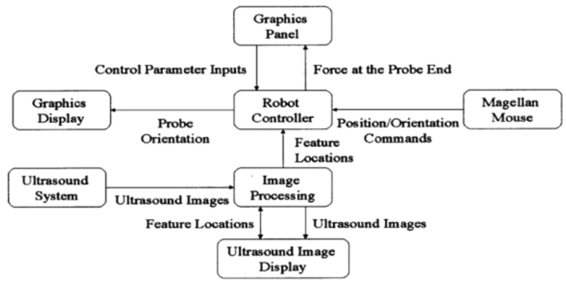

Figure 2: Data flow of system

A robot with six degrees of freedom is used to position the ultrasound probe on a patient. In addition to the ultrasound probe, the robot also has a force sensor and position sensor. The operator controls the robot from a computer with a GUI by selecting features from a screen showing the current ultrasound image using a mouse. Visual servoing is then performed to move the ultrasound probe to the location with the corresponding image features.

Feature Tracking

To perform carotid artery feature detection and tracking, the authors discuss the methods of 1.) cross correlation, 2.) sequential similarity detection, 3.) Star algorithm, 4.) Star-Kalman algorithm, and 5.) discrete snake model. Each are validated using an ultrasound phantom by moving the ultrasound probe back-and-forth with constant velocity along the x-axis of the probe coordinate frame.

The cross correlation algorithm obtains a sub-block of an image at time t_i then shifts the image in its neighborhood to look for a best correlated match within a fixed sub-block of the same size in a prior frame. The sequential similarity detection algorithm acquires a sub-block of the image at time t_i then shifts the image in its neighborhood looking for a minimum absolute subtraction (pixel by pixel) with a fixed sub-block of the same size in a prior frame. The Star algorithm uses an edge detection filter to track the carotid artery boundary in real-time, and the authors use a Kalman filter to account for its instability. The Star-Kalman algorithm estimates the radii of boundary points using a Kalman filter to calculate the likelihood of candidate edge points being on the actual boundary of the carotid artery. The Discrete Snake model selects candidate edge points of the original image, then finds a closed contour along these points that minimizes an energy function.

Visual Servoing

The authors also test the ultrasound visual servoing system by performing visual servoing along only the x-axis then performing image servoing using all axes. The Star-Kalman algorithm is used for feature extraction in both experiments.

Results

COMPARISON OF DIFFERENT FEATURE TRACKING ALGORITHMS; S_{60} AND S_{200} REPRESENT STANDARD DEVIATIONS OF THE ERROR IN DESIRED FEATURE VELOCITIES OF 60 PIXELS/S AND 200 PIXELS/S, RESPECTIVELY AND R REPRESENTS THE PEAK TO PEAK DISPLACEMENT OF THE ACTUAL FEATURE ALONG THE U-AXIS IN PIXELS

Method	S_{60}/R	S_{200}/R	kflops/frame
Correlation	8.7%	15.5%	100
SSD	6.3%	13.5%	50
Star	10.7%	18.9%	30-150
Star-Kalman	6.5%	13.6%	20
Snakes	8.0%	N/A	50-300

Both the SSD and the Star-Kalman algorithm can track moving features in an ultrasound image with a small error. The Star-Kalman algorithm requires less kflops/frame than SSD and requires the least of all five algorithms. The Snake algorithm is the least reliable and diverges at a velocity greater than 100 pixels/s so its results were not included for S_{200}/R.

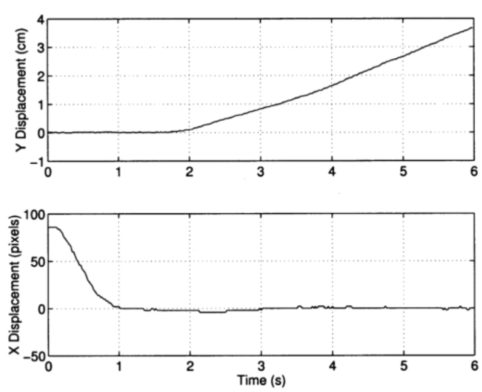

Figure 3: Experimental results of image servoing in single axis

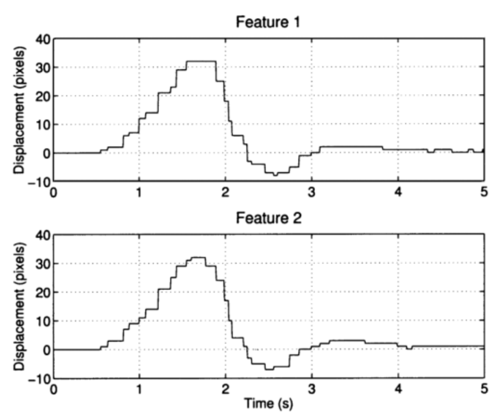

Figure 4: Experimental results of image servoing in three axes

When the robotic ultrasound system performs visual servoing along a single axis and visual servoing in three axes, it maintains the feature position in the center of the image automatically. In both of these cases there is no significant error in displacement.

Practical applications

The authors note that the location of the ultrasound transducer can be determined via forward kinematics, which makes it possible to reconstruct 3D ultrasound images. The authors present a 3D ultrasound imaging method based on the Star-Kalman algorithm. They also describe a system for teleultrasound through the Internet.

Evaluation and Criticism

The paper provides a useful introduction to the concept of visual servoing and its implementation in a robotic ultrasound system. It allows me to understand the data flow in the system and the interfaces between different high-level components in a way that I could relate it to my project. Due to the way in which information is presented, it is possible to understand how visual servoing works based on this paper alone without consulting outside references.

The paper does an excellent job of illustrating their system setup with diagrams so that it is clear what each part of the system does. Their experimental design and results also contains many figures that complements their textual explanations. I find that papers which contain many diagrams are much easier to read than equivalent papers that present the same information in only a textual format because mentally recalling a single diagram is easier than recalling a section of prose. The figures and diagrams allow the authors to provide a clear and concise explanation.

The authors give insight into the applications of visual servoing for ultrasound, including 3D ultrasound and teleultrasound. This is useful because it explains why this information is relevant and what the potential for future research in this area was at the time it was written.

My only concern about the paper is that the discussion of image processing algorithms only focuses on those for carotid artery tracking, in contrast to the rest of the paper which is more general. The authors discuss the Star-Kalman algorithm that they created for carotid artery tracking in great detail, but I think that the cross correlation and SSD methods warrant more discussion. The authors only use carotid artery tracking to evaluate the accuracy of their algorithms. This makes their results less generalizable for locating other anatomical structures, and at the very least the authors should have described other types of anatomy that may be suited for their algorithm. I would remedy this by changing the abstract to specify that image processing algorithms are evaluated specifically for carotid artery detection, or by incorporating results from previous papers on the accuracy of various algorithms.

For my project I would hope to incorporate the design techniques in this article for controlling the KUKA robot. In particular, my project could incorporate the same techniques for data flow that are mentioned in the paper to modularize the components of the software. The design of my project would be more analogous to the teleultrasound system depicted by the authors due to the usage of ROS for communication between ImFusion and KUKA Sunrise.

I would also hope to use techniques similar to the ones used by the authors to determine which image processing algorithms are most effective. The authors provide an objective way to compare different image processing algorithms by providing a side-to-side probe movement that is used to evaluate all algorithms. They also quantify results using an ultrasound phantom rather than a human so that their data is reproducible. I would hope to evaluate the effectiveness of visual servoing by testing motion in a single dimension then evaluating its effectiveness in all dimensions.

Bibliography

- Abolmaesumi P, Salcudean S, Sirouspour MR, DiMaio SP. Image-guided control of a robot for medical ultrasound. *IEEE Trans Robot Autom*. 2002;18(1):11-23. doi:10.1109/70.988970.