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Blood Flow Measurement Algorithms to Detect Bleeding Source Noninvasively

Keiichiro Ito, Tomofumi Asayama, Shigeki Sugano, *Fellow IEEE*, and Hiroyasu Iwata, *Member, IEEE*

***Abstract*—The purpose of this paper is to propose ultrasound visual servoing algorithms for controlling a robotic system equipped with an ultrasound probe for large pulsation and a displacement towards the out-of-plane of a US image.**

In this study, we aim to develop a robotic system for detecting bleeding source based on the blood flow measured by using a non-invasive modality like an ultrasound (US) imaging device. Some problems related to the measurement error still need to be addressed. As the first step in solving these problems, we focused on the large pulse amplitude and displacement of the artery towards the out-of-plane of a US image, and developed US visual servoing algorithms to control the probe. We conducted preliminary blood flow measurement experiments using an phantom containing artery model and a manipulator equipped with a US probe (BASIS-1). The results present the first experimental validation of the proposed algorithms.

I. Introduction

It is very important to detect the position and the speed of the bleeding for saving patients who have internal bleeding in the abdominal area [1]. Therefore, many researches have focused on the problem of detecting the position of a bleeding source using some modalities [2]-[4]. However, these methods specialize only on identifying the position of the bleeding source, and need a contrast agent because they depend on the doctor's vision. A medical doctor is not able to use the method with the contrast agent on a patient with a contrast agent allergy or a high severity of symptoms.

Therefore, we aim to develop a robotic system to detect a bleeding source based on the blood flow measured by using a non-invasive modality like an ultrasound (US) imaging device. We have developed a manipulator equipped with a US probe (FASTele-1, BASIS-1), and have also reported on the effectiveness of the manipulator [5], [6]. However, we could not have measured accurately the blood flow, because the manipulator was manually controlled.

Many measurement systems related to US imaging processing and visual servoing for internal objects have recently been developed. R. Chan et al. developed a method to measure the deforming speed for detecting the structure and vascular deformation [7]. Also, H. K. Chiang et al. presented an automatic flow velocity and Doppler angle measurement method that exploits the symmetric focusing property of annular array transducers to enable the measurement of the flow in any three-dimension direction [8]. However, the cross-section area of a blood vessel varies with the pulsation and angle of the US probe. US probe angle control of a cross-sectional image when the cross-section area is adequately measured is required. Also, a US image of the center of a blood vessel has to be maintained when the speed is measured using the US Doppler. In particular, a method for measuring the cross-sectional area of an artery and the blood speed for large pulsation and the displacement of the artery is a key technology needing establishment for the abdominal area, although this method has yet to be introduced.

Therefore, as a first step for ensuring there is an accurate blood flow measurement, we propose blood flow measurement algorithms in order to control the US probe for large pulsation and a displacement towards the out-of-plane of a US image.

Keiichiro Ito, Hiroyasu Iwata, and Shigeki Sugano are with the Department of Creative Science and Engineering, School of Modern Mechanical Engineering, Waseda University, 17 Kikui-cho, Shinjuku-ku, Tokyo, 162-0044, Japan. Phone: +81-3-3203-4457, Fax: +81-3-3203-4457, Email:{itokei-1985,jubi, sugano}@sugano.mech.waseda.ac.jp. Hiroyasu Iwata is also with the Waseda Institute for Advanced Study (WIAS).

II. A Frame of Method to Detect Bleeding Source

A. Bleeding Mechanism and Detection Method

In the blood vessel within a segmented range, there are two patterns; one is with the branching blood vessel and the other one is not with that. We modeled blood vessel that the bleeding source exists in the segment, as shown in Fig.1. The relation among the amount of each blood flow is (1). There is a blood flow change in the upside and the downside when branched flow (Q_3) and bleeding source (Q_4) exist in the segment. Therefore, the bleeding source would be detected if blood flow of upside and downside in one segment can be measured and there is a blood flow change.

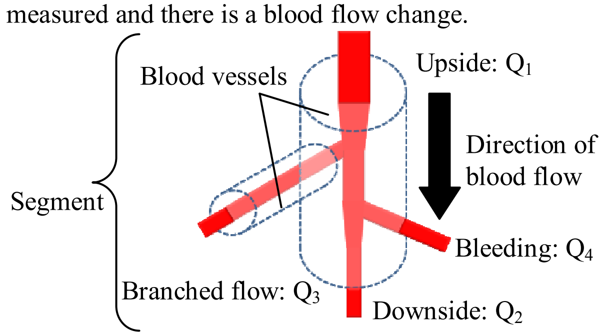


Fig.1 Model of blood vessel with bleeding source in a segment

$$Q_1 - Q_2 = Q_3 + Q_4 \tag{1}$$

In order to select a factor affecting the blood flow change from three "One depending on the branched blood vessel ", "One depending on the bleeding source", and "One depending on the branched blood vessel and the bleeding source", we propose a method to detect bleeding, as shown in Fig.2.

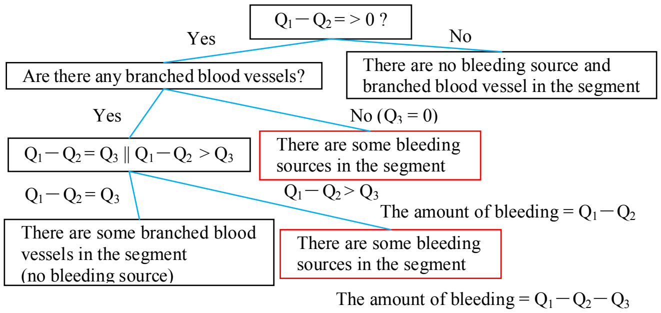


Fig.2 Proposed method to detect bleeding source

B. Blood flow measurement

R. W. Gill reported on a method to calculate the blood flow [9]. The parameters for calculating the blood flow are the cross-section area (S(t) cm^2) and the blood speed (V(t) cm/s) changed by the pulse amplitude. Based on the blood flow distribution, V(t) is not the maximum speed but the average speed in the cross-section of the blood vessel. In addition, the blood flow is usually defined as the stroke volume in the medical field. Based on the report, we calculate the average blood flow Q ml/stroke, (2)

$$Q=\frac{1}{T}\int_0^T S(t)\cdot V(t)dt \qquad (2)$$

III. Blood Flow Measurement System

A. System Overview

Fig.3 shows the blood flow measurement robotic system. The system is composed of a US imaging device, BASIS-1 and a PC for robot control and image processing. An output image from the US imaging device is processed and sent to the PC in order to control the probe. The US imaging device (MicroMaxx (SonoSite Inc., Micro-convex probe (1-5 MHz)) outputs the image signal, then captured by video grabber Epiphan's DVI2USB Solo into a PC (Core2Duo 2.0GHz).

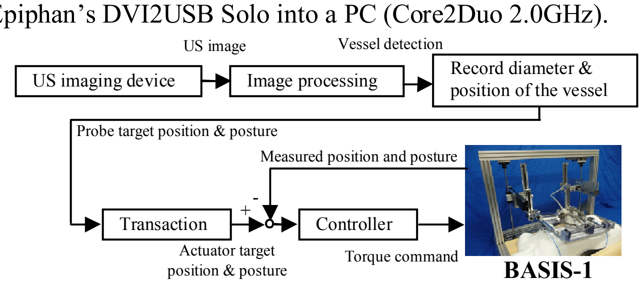


Fig.3 Block diagram of the proposed system

B. Measurement Algorithm for Cross-Sectional Area

Fig.4 shows the flow for extracting an optimal cross-section and measuring the cross-section area, S(t). Since the blood pressure in an artery is uniform in the radial direction compared to that in a vein, an optimal cross-section image of an artery can be approximated as a circle. In addition, a ratio of the major and minor axes of a circle approaches one. Also, the ratio might be maintained virtually constant before as well as after the pulsation of an artery. This means that an optimal arterial cross-section can be extracted, if the US probe can be controlled so that the ratio of the major and minor axes approaches one. The medical doctor determines the region of interest (ROI) including the measured blood in the US image, and then the image is binarized to get a clear-cut outline of the contour. In the optimal cross-section image, the cross-section area of one heartbeat from the point of the peak value is measured (S(t) cm^2). In addition, the system also measures the amplitude, pitch, center of the amplitude, and the cyclical change of the artery diameter based on the change of the position of the arterial center and detected contour.

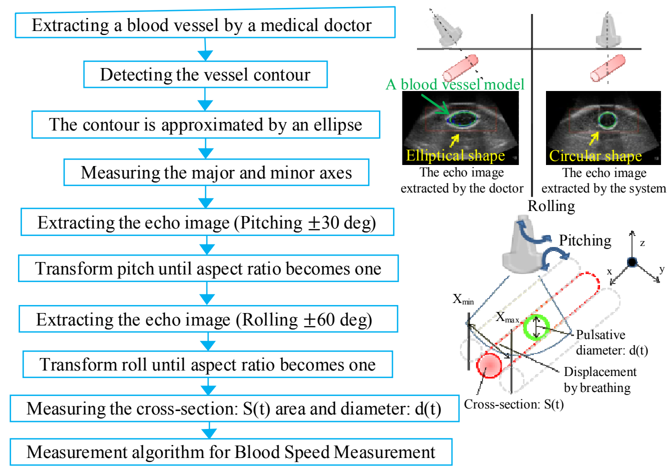


Fig.4 Flow chart of measurement algorithm for cross-sectional area

C. Measurement Algorithm for Flow Speed

Fig.5 shows the flow for extracting the optimal longitudinal -section and measuring the blood speed, V(t). We propose two types of position controls for the US probe to extract the optimal longitudinal-section servoing displacement of an artery towards the out-of-plane of a US image; Cyclic servoing to the displacement (Servo 1), Compensating the timing and position of starting Servo 1 (Servo 2).

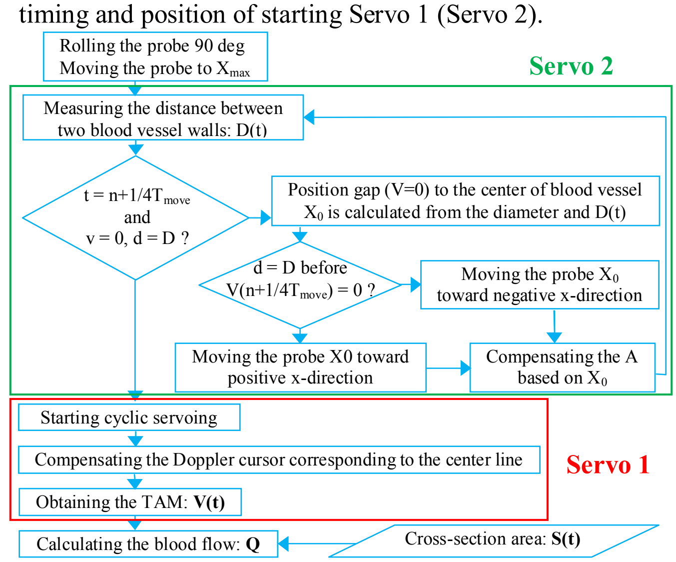


Fig.5 Flow chart of measurement algorithm for blood speed

In Servo 1, the expression of a simple harmonic motion is used based on the amplitude (A), center of the amplitude (a) and cyclical change of the arterial diameter, d(t) measured in the optimal cross-section image. T_{move} is the pitch of the displacement and acquired by a respirometry, t is the elapsed time from the point of center of the oscillation, and X(t) and V(t) are entered into the PC. However, the difference of phase and center of oscillation might occur when the US image switches from a cross-section to a longitudinal-section view. The purpose of Servo 2 is to determine the timing and position of starting Servo 1 to compensate for the position and phase of the US probe based on distance of blood vessel walls (D(t)), as shown in Fig.6. The distance between two blood vessel walls equals the arterial diameter. This means that the US probe can be controlled corresponding to the optimal longitudinal-section if Servo1 can be started when the distance between two blood vessel walls equals the arterial diameter.

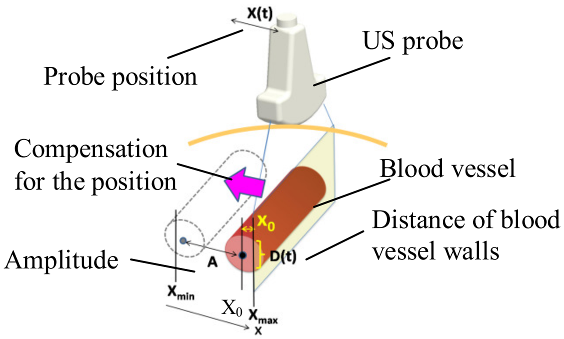
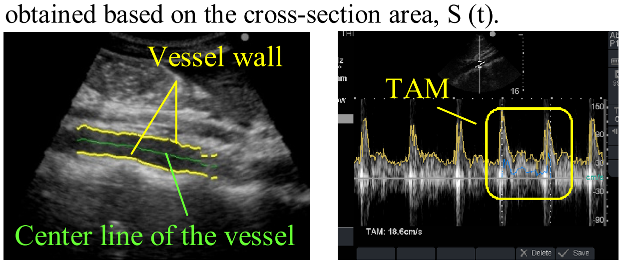


Fig.6 Determining the timing and position of starting Servo 1 (Servo 2)

We defined the point midway between the two blood vessel walls as the center of the vessel in the longitudinal-section image for blood speed measurement, as shown in Fig.7-a. A medical doctor manually compensates the Doppler cursor corresponding to the centerline of the vessel. V(t) is obtained by using the function measuring Time Average Mean, (TAM), as shown in Fig.7-b. After extracting the TAM of the cycle, Q is obtained based on the cross-section area, S (t).



(a) Defining the point of Doppler cursor

(b) Blood speed obtained US Doppler

Fig.7 Flow speed measurement by using US Doppler

IV. Experiments and Results

A. Experiment of Cross-Section Area Measurement

1) Purpose: The purpose of this experiment was to evaluate the proposed method for measuring cross-section area.

2) Methods: We used a model which is consists of a mock body cavity model made of an agar phantom, stimulant blood vessel models made of silicon and a pulsative blood flow pump (Harvard Inc., stroke volume 15-100 ml). In order to displace the vessel model, we recreate the displacement by a mechanical linkage that has a piston motion. Table I lists each parameter based on average of human body [10].

Table I Parameters of the experimental model

Beating rate 1/min	Stroke volume ml	Cross-section area of the vessel model cm^3	Depth of the vessel model mm	Displacement mm
60	35	4.91	20	±15

3) Results: Table II and III presents the cross-section area measurement error for the optimal cross-section image extracted by using the proposed method under four conditions. We confirmed that the cross- section area could be measured with an error 7.1 % under pulsation and displacement.

Table II Difference between true area and measured area by image processing under non-pulsation and non-displacement (N = 5)

	True value	Measured value by using image processing
Cross-section area cm^2	4.91	4.59 (Error rate: 6.5 %)

Table III Measured cross-section area by the system under four conditions (N = 5)

	Non-pulsation	Pulsation
Non-displacement	4.59 cm^2	4.89 cm^2 (Error rate: 6.6 %)
Displacement	4.57 cm^2 (Error rate: 0.5 %)	4.92 cm^2 (Error rate: 7.1 %)

B. Flow Volume Measurement Experiment

1) Purpose: The purpose of this experiment was to evaluate the blood speed measurement algorithm and the flow volume measured by the proposed method.

2) Methods: We used the model and Coriolis flow sensor (Keyence, Resolution 10 ml/min). We implemented the proposed algorithm to measure the flow speed after executing the algorithm to measure the cross-section area. Also, the calculated flow volume was compareed to the true value and the manual measurement value.

3) Results: As shown in Fig.8, the distance between blood vessel model walls measured has a maximum error of approximately 4.4 % when compared with the change in the blood vessel model diameter measured from the cross-section image. We confirmed that the measured flow speed has a maximum error within approximately 3 % compared to that without the displacement, as shown in Fig.9. We also confirmed that the flow volume measured by using the proposed method has an error of approximately 17.7 % compared to that from the flow sensor and reduced the standard deviation by 21 % compared to that from a manual measurement, as shown in Fig.10.

V. Discussion

We confirmed that the proposed method can improve the standard deviation compared to that from a manual measurement, as shown in Fig.10. In emergency medical medicine, however, the measurement error should be within approximately 10 % [1], because the accuracy of the volume is required for deciding treatment and volume of blood transfusion. We considered two chief flow volume measurement error factors: Image processing, Pulsation and displacement.

As shown in Table II, the cross-section area measured by image processing has an error of approximately minus 6.5 % compared to the real area. The contour detection using a binarized image has to have the threshold level set to high to get a clear-cut outline of the contour. As this result, the contour was thicker compared to the true contour, and the measured cross-section area was smaller than the true area.

As shown in Table III and Fig.9, proposed algorithms have some errors. In cross-section area measurement, the error 7.1 % occurred compared to that without pulsation and displacement. The main error factor would be increase of the cross-section area with the pulsation, because the error (6.6 %) under pulsation and non-displacement was larger than the error (-0.5%) under non-pulsation and displacement. Therefore, the system might be required to measure the cross-section area under pulsation more accurately. As shown in Fig.8, the difference between the walls and the diameter means that the proposed servoing algorithm of US probe for the displacement has small positioning error. We considered the flow speed measurement error occurred by the small positioning error. In order to measure a flow volume more accurately, we confirmed that this system needs accurate contour detection method and automated method adjusting servo gain for tracking the center of the vessel.

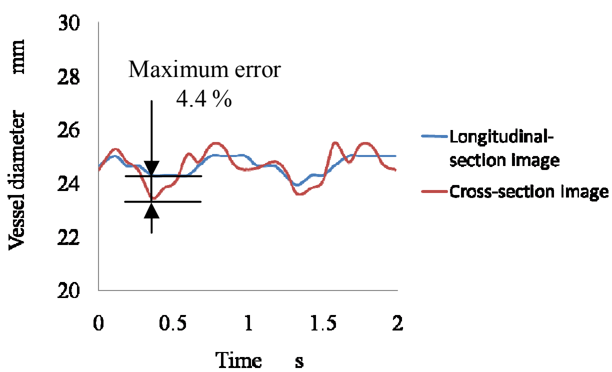


Fig.8 Difference between the two blood vessel model walls and the diameter (N = 5)

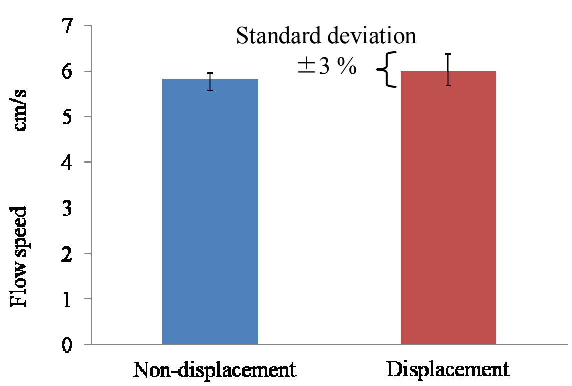


Fig.9 Flow speed measurement result under two condition (N = 5)

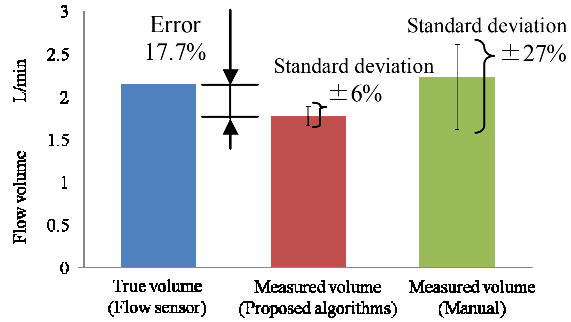


Fig.10 Flow volume measurement result by flow sensor, proposed system and manual (N = 5)

VI. Conclusion and Future Work

We proposed US visual servoing algorithms to measure the blood flow under large pulsation and displacement towards the out-of-plane of a US image. We confirmed that the proposed algorithms could measure flow volume and reduce the standard deviation than manual measurement. In clinical settings, however, the pulsation and displacement vary among different patients. Reducing the measurement error, which influence the blood flow measurement error, are an important technological necessity. As future work, the algorithms need to be extended. The contour of a blood vessel has to be accurately detected.

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