Application of a Search Algorithm Using Stochastic Behaviors to Autonomous Control of a Ventricular Assist Device

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***Abstract*— A ventricular assist device (VAD) is a device with mechanical pumps implanted adjacent to the patient's native heart to support the blood flow. Mechanical circulatory support using VADs has been an essential therapeutic tool for patients with severe heart failure waiting for a heart transplant in clinical site. Adaptive control of VADs that automatically adjust the pump output with changes in a patient state is one of the important approaches for enhanced therapeutic efficacy, prevention of complications and quality of life improvement. However adaptively controlling a VAD in the realistic situation would be difficult because it is necessary to model the whole including the VAD and the cardiovascular dynamics. To solve this problem, we propose an application of attractor selection algorithm using stochastic behavior to a VAD control system. In this study, we sought to investigate whether this proposed method can be used to adaptively control of a VAD in the simple case of a continuous flow VAD. The flow rate control algorithm was constructed on the basis of a stochastically searching algorithm as one example of application. The validity of the constructed control algorithm was examined in a mock circuit. As a result, in response to a low-flow state with the different causes, the flow rate of the pump reached a target value with self adaptive behavior without designing the detailed control rule based on the experience or the model of the control target.**

I. Introduction

A Ventricular Assist Device (VAD) is a device with mechanical pumps implanted adjacent to the patient's native heart to provide circulatory support (a left ventricular assist device, for example, pumps blood from the left ventricle to the aorta to assist blood flowing). Advanced hardware technology has enhanced the reliability of VAD long-term use, such as clinical application of implantable continuous flow VADs [1]. Accordingly, mechanical circulatory support using VADs has been an essential therapeutic tool for patients with severe heart failure waiting for a heart transplant [2]. On the other hand, considering about new treatment to recover cardiac function including destination therapy (DT) [3] or combination with myocardial regeneration therapy [4], there are many issues to solve, such as further device miniaturization, durability and antithrombogenicity improvements, circulation-control abnormality regardless of the improved treatment effects and stable blood flow, and various complications. To solve these issues, advanced software functionality such as VAD drive control may be equally important as hardware improvements. Many researchers have conducted studies on bypass flow control using cardiovascular mathematical models as well as continuous flow VAD optimization such as development of a function to change rotation speed via synchronization with the patient's heart rate [5-8]. Variations in rotation speed are expected to produce clinical effects including cardiac function recovery and complication prevention. Some devices have been already equipped with control functions to prevent outflow sucking and maintain bypass blood flow. At clinical sites, however, devices are usually used in a fixed rate or rotation number. Major reasons that the VAD automatic control functions are not used in practice are because of the difficulties in long-term stable measurement of biological information and modeling of complex circulatory systems controlled by the autonomic nerve or humoral factors. An algorithmic error consequent to an unexpected complex circulation behavior may cause dangerous device operation. These problems are likely to be solved when VADs are equipped with flexibly adaptive control like human body.

A recent physiological study has demonstrated that searching behaviors based on noise (or fluctuations) including muscle molecular level movement and heart rate variability play an important role in human adaptability [9-13]. Moreover, some researchers attempted to apply this mechanism to artificial object control such as robots or communication systems [14-17]. The objective of the present study was to realize ventricular assist devices which flexibly can response to unexpected changes. The mechanism of human adaptive behaviors was used to enable VADs to deal with the situations in which accurate modeling was considered difficult. Furthermore, this study was conducted to propose the application of a searching algorithm to VAD control using stochastic behaviors and to verify the beneficial effects on VAD control by this method according to the results of flow control. As the first step to investigate the benefits of this proposed method, continuous flow pumps, simple systems, were used to perform mock circulation tests.

II. Materials and Methods

A. Control Algorithm

Kashiwagi et al. proposed formula (1) called “attractor selection model” as a mathematical model to explain human sensing behaviors using noise [9].

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$$\dot{x} = -\nabla U(x) \cdot A + \eta \qquad (1)$$

In this formula, x, $U(x)$, A and η represent the system state, potential function (system dynamics), bias (an evaluation function indicating the goodness of fit for the system state) and noise (random variation), respectively. This model detects attractors via random walks; the inappropriate system state reduces Value A, and η becomes dominant.

To verify the benefits of this proposed method, attractor selection models were initially used to control and maintain blood flow on continuous flow pumps, comparatively simple systems. Continuous flow VADs mainly consist of a centrifugal pump or an axial flow pump. These pumps can adjust blood flow through changes in rotation speed on the internal impellers. Equation (2) is a general difference equation of formula (1).

$$x(t+1) = x(t) - A(t)\frac{dU(x(t))}{dx(t)} + \eta(t) \qquad (2)$$

To calculate the flow control on continuous flow pumps, the formula symbols were defined as follows: $x(t)$ = a control signal for rotation speed, $U(x)$ = a temporary target function (an approximate potential function with a turning point at $x(t)$ indicating the achievement of objective flow), A = an evaluation function to produce a $U(x)$-turning-point drawing effect, and η = noise. $U(x)$ was set with the Gaussian distribution function, and a parameter for the center of a turning point was defined as c as shown in a formula (3).

$$U(x) = a \times \exp\frac{-(x-c)^2}{2b} + d \qquad (3)$$

Constant a: Amplitude, b:Width of a temporary potential, c: Center of the potential, d: Offset

Value A tends to be high on a true $U(x)$ turning point; therefore, even when accurate $U(x)$ was not obtained because of the difficulty in modeling, c (the center of the $U(x)$ turning point) was updated to the side that had become high in the previous A by increasing or decreasing according to the Value A. This process allowed inaccurate $U(x)$ to draw to a potential neighborhood true value, and adaptive behaviors were expected accordingly. Value A is an important element which influences systems' behaviors. In this trial, we predicted behaviors to gain arbitrary objective blood flow, and experimentally set Formula (4) to provide a high value in case that the current flow is close to the desired value or the current difference from the objective flow is smaller than the previous difference.

$$A(t) = \frac{\exp\left(e \cdot \left(\left|Flow\_r(\tau-1) - Flow(\tau-1)\right| - \left|Flow\_r(\tau) - Flow(\tau)\right|\right)\right)}{\exp\left|f \cdot (Flow\_r(\tau) - Flow(\tau))\right|} \qquad (4)$$

e, f: Constant, *Flow*: Mean flow rate, *Flow_r*: objective flow rate, τ: observation time of *Flow*

After η was defined as Gaussian noise, a bias was added to the median value according to the increase or decrease in the previous A, in order to improve the search efficiency.

B. *Mock Circulation Test*

To evaluate behaviors based on the implemented algorithm, control testing on a closed loop for mock circulation was performed using a prototype model of a developing axial flow pump [18]. The axial flow pump used had a structure to rotate the impeller in the brushless direct current motor, and this was the same as a general continuous flow VAD. In addition, the axial flow pump had a mechanism to support the rotor with the internal impeller through fluid dynamic bearing (Figure 1). This pump was connected to a soft reservoir via the inflow and outflow PVC tube (inner diameter: 1/2 in., length: 1 m, respectively), and the supply side on the pump was equipped with the function of circulatory resistance to generate the pump head (Figure 2). The motor of this pump was operated by a widely-used motor driver which was able to change rotation speed via external signals. The working fluid was 37 wt% glycerol-water solution at 27 degrees Celsius.

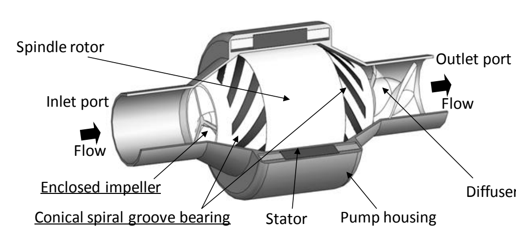
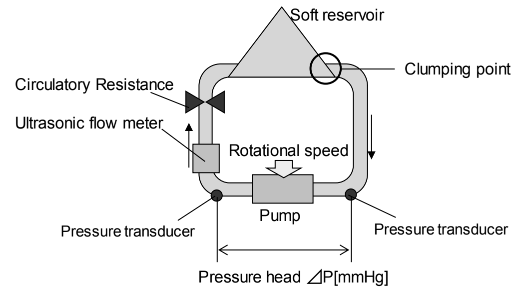
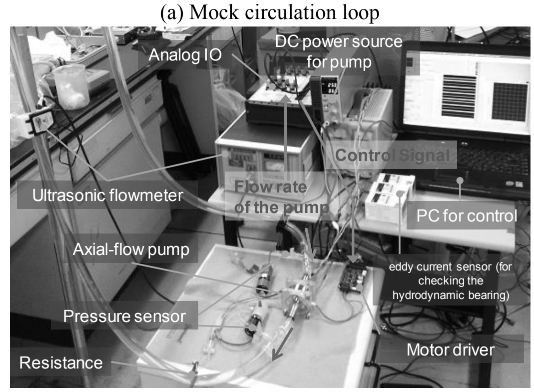


Figure 1. Structural drawing of a prototype axial flow pump under development used in the mock circulation test.



(a) Mock circulation loop



(b) Experimental setup and control system

Figure 2. Schematic diagrams of mock circulation test (measurement items, ⊿P [mmHg]: Pressure sensors, Flow rate [L/min]: Ultrasonic flowmeter, Control signal: x [V], Parameter of the control: $dU(x)$, A, c, n).

The rotation speed control was designed to provide a feedback when any flow signal calculated by the ultrasonic flow meter (T106, Transonic Systems Inc.) is input into the PC and subsequently to output an implementation signal calculated by the proposed algorithm. A pressure sensor (PA-500, Nidec Copal Electronics Corp.) was used to determine the pump inflow- and outflow-side pressure, pump flow measured by the ultrasonic flow meter, and rotation speed control signals and also to record the control parameters (⊿$U(x)$, A, c, and η). The sampling and parameter updating cycle were set to 100 Hz and 1 sec, respectively. As the target pump used had a levitated dynamic bearing structure, the algorithm was designed assuming that the actual rotation speed corresponding to rotation speed control signals were known. The rotation speed received from the control signals was set in the range of 7000-12000 rpm so that the bearing was able to maintain stable levitation.

A random rotation number was set to run the pump operation testing. Subsequently, the target flow was set to 5 L/min to begin this control algorithm. Initially, the circulatory resistance was changed to examine the basic behavior, and we observed the variations in the flow, rotation speed, control signal, and other control parameters accordingly. Secondly, inflow sucking (extreme negative pressure on inflow side because of a flow obstruction) was generated on the pump assuming that the environment was unexpectedly changed to evaluate the behavior. The sucking was generated by the tube on the inflow side and the soft reservoir connection part from the outside (Figure 2. (a)), which were unclamped soon after a sucking condition was satisfied (Before this procedure, we conducted a stationary operation to confirm that the negative pressures caused by sucking were not automatically released at the event of full sucking). Similarly, the changes in the pump behaviors were observed.

III. Results

Figure 3 lists the results of the circulatory resistance changes. In this test, our proposed method was used to control the blood flow of an axial flow pump to maintain an arbitrary target flow. The objective flow of 5 L/min was achieved when this control was added to pump operation by the steady rotation speed of 4.5 L/min. Subsequently, when the circulatory resistance was reduced, the following changes were obtained: 1. the pump flow increased, 2. η became

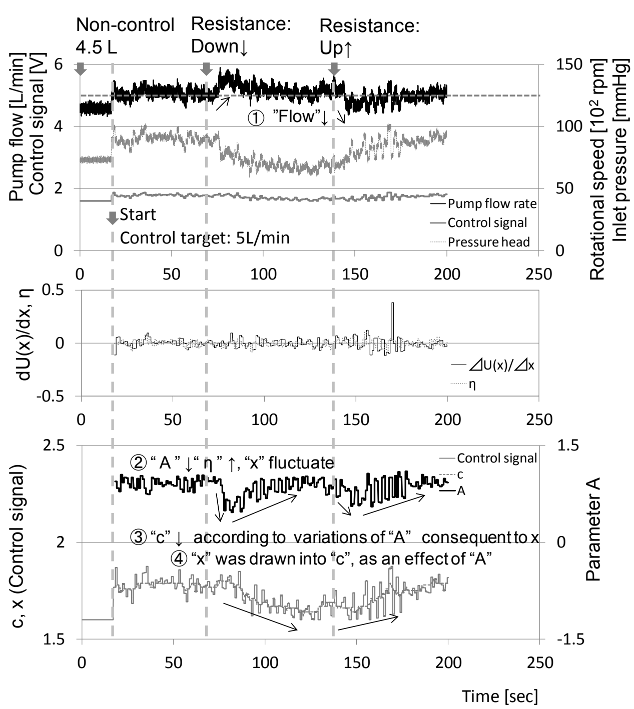


Figure 3. The behavior of the pump to changes of the circulatory resistance

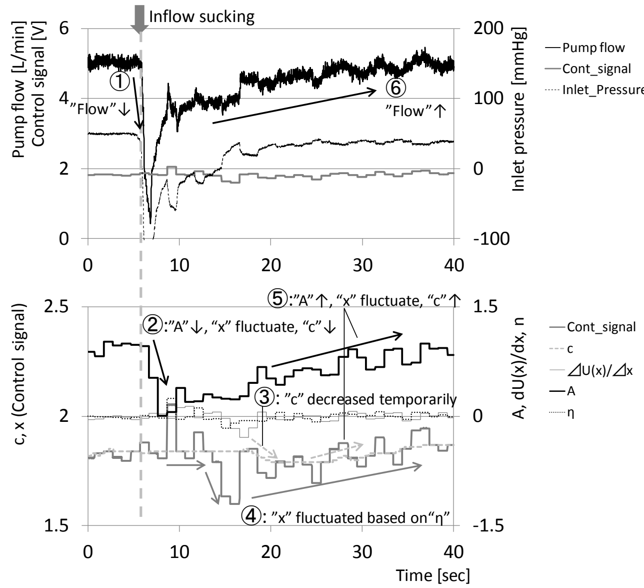


Figure 4. One example of the adaptive behavior on inflow obstruction (unexpected disturbance).

dominant because of a decrease in A and this changed x, 3. c was updated along with the change of A consequent to x, and finally 4. x was drawn into c, the center of $U(x)$, as an effect of A. Accordingly, the flow achieved the desired value again. We observed that the flow achieved to the target value when the circulatory resistance increased further after it had reached the initial value.

Furthermore, one case of behaviors in inflow sucking was listed in Figure 4. According to the result, 1. the flow decreased because of inflow sucking, 2. a decrease in A allowed η to be dominant and this changed A consequent to the variation in x, 3. c temporally decreased, 4. the negative pressure on the inflow side was released after c was drawn into c, 5. A increased because of recovery of the flow and c also increased tentatively, and 6. the flow reached the target value again. Similarly, the target flow was achieved throughout 10-time attempts, even though the results varied widely (24.1±16.4 sec) because of the sucking degrees and noise effects.

IV. Discussion

As tasks of this trial, a rotation speed increase and temporary decrease were required when the blood flow decreased because of a circulatory resistance increase and sucking, respectively. Flow maintenance and sucking release could be realized by other means; however, in this method, different behaviors were required for the same flow-decrease phenomenon. Therefore, the self-adjusting behaviors observed in this study should be significantly useful to develop more flexibly adaptive ventricular assist device control, because those results were obtained without the provision of any additional sensor for sucking detection as well as the design of behavioral rules based on some models or experiences. Furthermore, this study demonstrated that the method was able to cope with dynamic objects and first or low-frequency events regardless of the disadvantages of accuracy and speed. However more detailed behaviors should be investigated for severe conditions on the circulation.

At clinical sites in which continuous flow VADs are used, sucking on the ventricle insert site of an inflow cannula is acknowledged as a problem; thus, this method which can solve sucking automatically is likely useful. In this trial, the probe of the ultrasonic flow meter used was connected to the outflow tube to determine the pump flow. A general continuous flow VAD has a function to estimate flow from current or other values. Nevertheless, it is difficult to provide accurate data in situations such as sucking. Some ultrasonic flow meter probes are able to be used with blood vessel prostheses for VAD blood supply; however, long-term stable measurements of flow are likely difficult in implantable continuous flow VAD patients. As many researchers have pointed out, development of long-term stable flow measurements is a major task with respect to implantable continuous flow VADs [19-22], and this is also essential for this flow control algorithm. Meanwhile, testing under pulsatile pressure must be performed to investigate the behaviors of this algorithm, in consideration of blood inflow from the patient's native heart. With the exception of c, the parameters, constant a, b, d of $U(x)$, control cycle, e & f corresponding to the weight of A, and bias of noise η were set by trial and error approach. To establish the evaluation and design methods to optimize these parameters is another task.

In this trial, the control to maintain flow was executed using the feedbacks of pump flow measurements. This algorithm is able to be applied not only to flow control but also other processes. A and x can be respectively independent in regard to this method. Therefore, if further technical developments enable macroscopic index sensing such as judging on VAD patients' circulation conditions or comfort, pumps using this method may cope with sensing situations easily even if the relationship between the indices of evaluation function A and pump flow is not clear. In addition, combinatory use of this proposed method with currently-used VAD control methods may enable stable VAD systems to behave without algorithm errors, because this method is able to help to adapt other control algorithms to the human body.

V. Conclusion

In this study, we proposed a searching control method and performed axial flow pump flow control using a mock circulation loop. As a result, the control to maintain the target flow determined at the design phase was successfully achieved. When sucking, an unexpected event, occurred, the target flow was recovered via the self-adjusting behavior without designing the detailed control rule based on the experience or the model of the control target.

Accordingly, this method was proved useful with respect to autonomous VAD control.

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