Development of a Microcontroller-based Brushless DC Motor Control System for an Total Artificial Heart

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Abstracts A microcontroller-based DC motor control system for a total artificial heart(TAH) was developed. Using a one-chip microcontroller, 87C196KB, the design of digital motor speed control system and servo control system is demonstrated. Functionally, the control system consists of a position control unit, a speed control unit, and a communication unit. The performance and the reliability of the developed control system were assessed through a series of mock circulation system experiments.

Key Words : Microcontroller-based control system, Total artificial heart.

1. INTRODUCTION

For use in patients with severe forms of heart disease for which no surgical repair is possible, artificial hearts have been under development for the past 30 years and human survival over a year has become possible with artificial heart as demonstarted in the United States and in Europe[1]. Since 1984, we also have been developed an electromechanical total artificial heart(TAH) typified by the pendulous moving actuator mechanism and implanted in several animals for clinical applications[2].

Fig. 1 shows a perspective view of the TAH. A brushless DC motor as an energy converter is assembled in a moving actuator, which is intervened between a left and right artificial ventriclular blood sac. Most research groups developing the motor-driven TAH use a brushless DC motor as an energy converter based on the property that the motor has a high reliability and high output torque to weight ratio. The pendulous motion of this moving actuator pumps out the blood filled in a right or left blood sac alternatively. The moving actuator and the blood sacs are enclosed by polyurethane housing. Each artificial blood sac has two ports with artificial valves for a unidirectional circulation of blood.

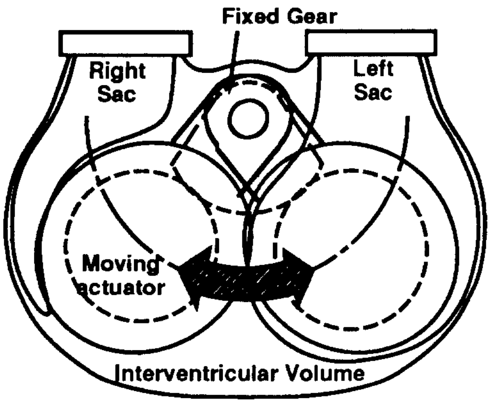


Fig. 1 A schematic diagram of the TAH

A control system for this motor-driven TAH has been also developed. The control objective of the total artificial heart is to supply enough cardiac output within a physiological range by controlling the moving actuator's pendulous motion[3], that is, by controlling the speed and the position of the brushless DC motor assembled in the moving actuator. In recent years, with the advancement of cheaper and more versatile microcontroller system, many industrial control applications involving microcontrollers have evolved. Applications of microcontroller-based control range from step motors[4], PWM controllers[5], process controllers[6], and automotive engine control system[7].

In this paper, an implantable microcontroller-based brushless DC motor control system with the implantability, reliability, and stability is introduced. The developed control system for the artificial heart has the following advantages: (1) It is possible to be implanted in a body by realizing the fundamental function such as a motor speed detection, proportional-integral control, timer, and PWM generation through a software programming. (2) Thus, the power consumed in the controller is reduced. (3) The reliability and stability are improved through the reduction of electronic parts and line connections at the controller.

Functionally, the control system consists of *a position control unit, a speed control unit, and a communication unit.* Minimum energy consumption and reduction of the inertia effect of the moving actuator are the main objectives of the speed control unit.

The performance and the reliability of the developed control system were assessed through a series of mock circulation system experiments and animal experiments.

2. MATERIALS AND METHODS

2.1 Description of Control System

The control system for a TAH is composed of an internal controller, which is implanted in abdominal region so as to drive and control a three phase, four pole brushless DC motor of the TAH, and an external controller for the purpose of monitoring the status of the implanted TAH including a control system and transmission of exogenous commands of a human operator. A block diagram of the control system is depicted in **Fig 2**.

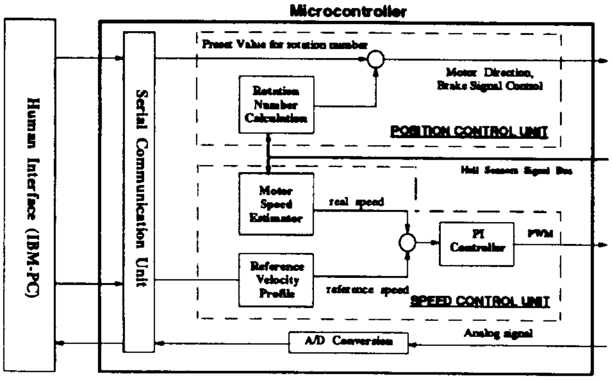


Fig. 2 A block diagram of the control system for the TAH

2.2 Description of an Internal Controller Hardware system

The hardware system of an internal controller consists of a microcontroller, a feedback circuitary of motor position, a motor drive circuitary, a motor current sensing circuitary, and a serial communication circuitary as shown in **Fig 3**.

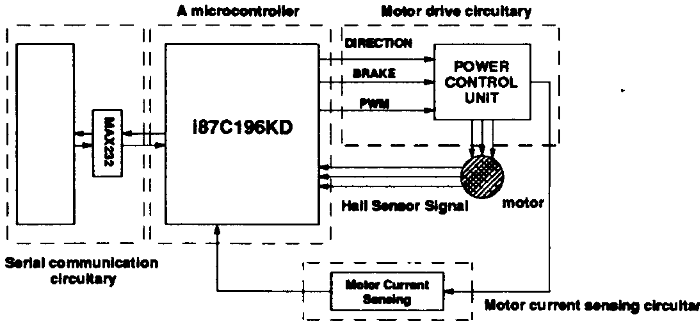


Fig. 3 A block diagram of the hardware of the internal controller

The 87C196KB (Intel Co., USA), a high performance member of the 8096 microcontroller family, is a 16-bit microcontroller with 8 Kbytes of on-chip EPROM. Four high-speed capture inputs are provided to record times when events occur. Also provided on-chip are an 8 channel 10-bit A/D converter, serial port, watchdog timer, and a pulse-width-modulated output signal.

To commutate a brushless DC motor three Hall effect sensors are utilized and activated in the form of rectangular pulse signal by the flux of the rotor magnet. These sequential pulses of Hall sensors, which are fedback to the high-speed capture input ports of the microcontroller via a motor position feedback circuitary that is composed of low pass filtering circuitary for rejecting high frequency noise and schmitt trigger circuitary, are also available for the position and speed control as well as the motor commutation.

In the motor drive circuitary, a high performance brushless DC motor controller, MC33035 (Motorola Inc., USA) is used to switch six power MOSFETs. The MC33035 contains all of active functions required to implement a full featured open-loop, three or four phase motor control system especially such as Hall sensor pulses decoder for proper commutation, pulse width modulator comparator, three open collector top drivers, and three high current totem pole bottom drivers.

And also, the motor current signal detected on the drive circuitary is converted to digital data by an embeded A/D converter in the microcontroller and transmitted to the external controller for screen panel monitoring through an RS-232C serial protocol.

2.3 Description of an Internal Controller Software System

Functionally, there are three main units: (1) position control unit, (2) speed control unit, and (3) communication unit.

2.3.1 Position Control Unit

The position control unit is required to guarantee the maximum stroke volume as well as the stable operation and to instantaneously control stroke volume of each ventricle. The major process of the position control unit is a Hall sensor counting procedure performed by an interrupt proces supported by the microcontroller. When the value of the counter is equal to the preset value from the external controller, the control unit generates a brake signal and exchanges the direction of motor through the input/output port of the microcontroller.

2.3.2 Speed Control Unit

A speed control unit is composed of three modules: (1) optimal reference velocity profile, (2) motor speed estimation, (3) digital PI controller and PWM generation module.

In order to make the position control assured, the optimal reference velocity command to the motor is designed as a function of the motor position. In the open loop system, the reference velocity command will be directly input to the motor in the form of pulse width modulated signal. There may be many optimalities for the reference command such as minimal inertia effect and/or minimal energy consumption. In this paper, we designed an optimal velocity profile for the nominal plant system to minimize energy consumption because it is a critical factor of the implanted system in a body.

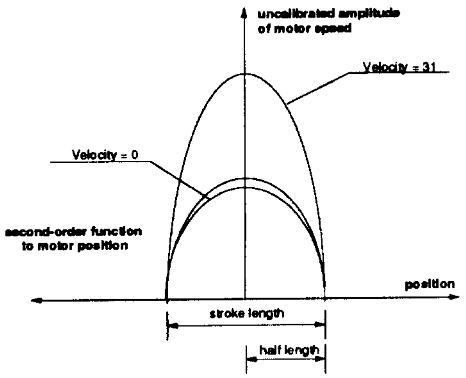


Fig. 4 Segmented reference velocity profiles

A parabolic reference velocity profile as a function of position is adopted and total 32 profile sets with different amplitude as shown in **Fig. 4** are stored in the EPROM of the microcontroller. To control the heart rate of the TAH on a beat by beat basis, we just select a suitable profile.

Using the Hall sensor pulses instead of the commercially available electronic frequency-to-voltage(F/V) converter, it is possible to estimate the actual speed of rotating motor by simple calculation as following. **Fig. 5** shows a method to estimate an actual speed of the motor.

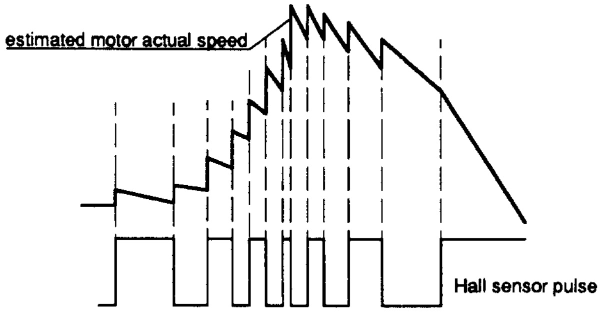


Fig. 5 A mechanism of the motor speed estimation

A time between each edge of Hall sensor pulses is measured by 12 Mhz clock of microcontroller as a timing source. Besides, until the next edge is detected, the estimated speed value decreases exponentially every 1.65 msec by the half amount of the value of one step previous state.

$$S[k] = \frac{C}{T[k]} - D[k]$$

$$D[k] = \frac{S[k]}{2} \qquad (1)$$

where S[k] is kth calculated actual speed of motor, C is constant angle between each Hall sensor, T[k] is kth time value between each edge of hall sensor pulses, and D[k] is kth one step decreasing amount. The constant value of angle between each hall sensor was selected empirically by a simple experiment using pulse generator.

Due to the characteristics of the DC motor, the speed of the motor would change as its load changes. In other words, an increase in afterload, the aortic pressure generated by the aortic resistance in the TAH, would cause a decrease in motor speed in the open loop system. By optimal tuning of the gains of the PI controller with a feedback loop, a motor velocity servomechanism, where the actual speed follows the reference command input, was achieved. The estimated actual speed of motor is compared with a reference velocity command and the resultant error amount is used as an input to the digital PI controller with a sampling time of 1.65 msec. The digital PI controller is derived from the well-known continuous-time PI controller as shown in **Fig. 6** by Tustin discretization method[8].

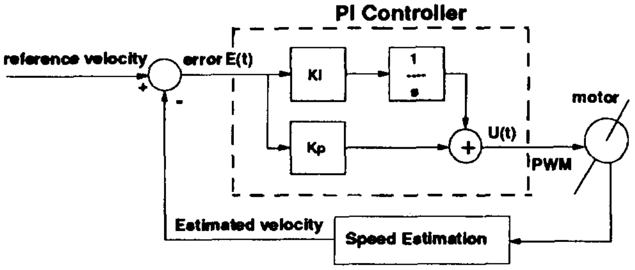


Fig. 6 A block diagram of the PI controller

The output of the PI controller is fed to the PWM generator processed by an interrupt service routine on the microcontroller and the resultant signal is transfered to the motor drive unit.

2.3.3 Communication Unit

In the communication unit, informations on the status of the implanted actuator of the TAH such as motor current, reference velocity command, estimated speed, and emergent situations are transmitted to the external controller for the real-time monitoring. Reversely, the control variables such as preset value of stroke angle of the moving actuator and amplitude of reference velocity profile are transfered from external controller as a command of human operator. The bidirectional communication is performed with error coding via an RS232C protocol.

2.4 Description of an External Controller

Fig. 7 shows a developed real-time external human interface panel in the IBM-PC monitor screen. A physician will use this panel to monitor the status of the implanted artificial heart system, command the control variables, and store all data. In addition to these functions, these panel alarms the unexpected emergent situations. TAH dynamics displayed in the screen are calculated by the informations transfered from the internal controller.

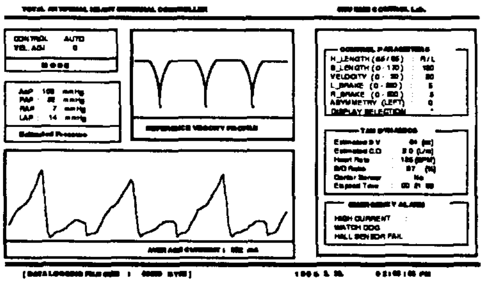
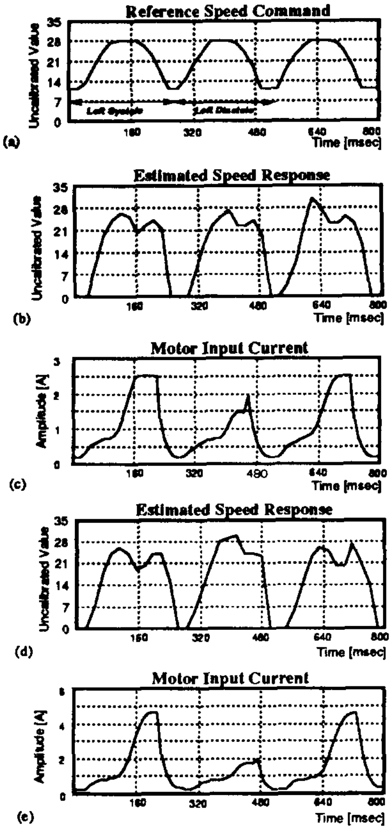


Fig. 7 A computer screen panel of the external controller

3. RESULTS AND DISCUSSION

Through a series of mock circulation experiments, the performance and the reliability of the control system were satisfactory. **Fig. 8** shows the experimental results.



(a) Reference velocity profile
(b) Estimated speed, when AoP = 70 mmHg
(c) Motor input current, when AoP = 70 mmHg
(d) Estimated speed, when AoP = 150 mmHg
(e) Motor input current, when AoP = 150 mmHg

Fig. 8 Performance results of the digital PI controller

When the TAH pumps out the blood from the left atrium to the aorta, the aortic pressure(AoP) due to the resitance of aorta acts on the motor as a load. Generally, around 70 mmHg of mean AoP is a low load to the motor of the TAH and about 150 mmHg may be a high load condition. The reference velocity command, estimated motor speed, and the motor current waveform at low, 70 mmHg and high, 150 mmHg of aortic pressure, load condition, respectively, are displayed in the figure. The speed response of motor tracks the reference command well even at high load condition with the increase of input current by dint of digital PI controller.

However, the speed response at decreasing phase of the waveform was not excellent due to the limit of the proposed motor drive system. In other words, despite the drive unit of control system has to support the negative power when the error amount between the reference and response speed is negative, the proposed motor driver can not generate the negative power but just brake the motor because the drive circuitary does not have a negative power supply. In the decreasing phase of speed, therefore, the reactive inertial force may cause a slight movement of motor even though the driver circuitary brake the motor. On the other hand, comparing the estimated with the motor speed response using a commercial F/V converter from the Hall sensor pulses as shown in **Fig. 9**, the proposed speed estimator has a good performance without respect to the load of motor. In addition, four sets of TAH including the controller were continuously operated for about 6 months in order to test the reliability of the system and there were not any failure. As the operation time was increased, the input motor current level was increased slightly.

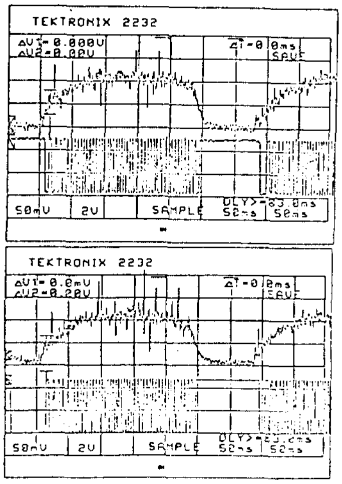


Fig. 9 Measurement of the motor speed by F/V converter

4. CONCLUSION

Using a microcontroller, the control system for the brushless DC motor-driven total artificial heart was developed. To achieve the reduction of power consumption, the enhancement of reliability and the stability, and the implantibility of control system, many a part of hardware system including the speed detector and PI controller was replaced by a simple assembly program. The performance and the reliability of the control system were satisfactory at the mock circulatory system experiments.

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