Microcontroller Control System for Heart Valve Bioreactor

A Design Project Report

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Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title: Microcontroller control system for heart valve bioreactor

Author: Kang Li (kl694)

Abstract:

The project team of Butcher Lab has developed a bioreactor culture system to mimic the cardiac cycle for the invitro conditioning of 3D printed tissue engineered heart valve conduits. I designed a microcontroller control system to control the flow of the whole system and collect data sent from transducers. This will help the bio-print team to investigate cell and construct function under dynamic, physiological conditions and do further research.

I designed a microcontroller control system for the heart valve bioreactor using ATmega 1284P microcontroller. It can control the flow of the whole system based on the specified parameters and collect data in MATLAB. This will help Butcher Lab do further analysis.

Executive Summary

This project continues the design and development of a cyclic flow heart valve bioreactor for use in culturing and conditioning of tissue engineered heart valves in the Butcher Lab in BME department. The bioreactor can simulate the flow between left ventricle and aorta of the heart to mechanically stimulate the cells of the tissue engineered aortic semi lunar heart valve.

My part in this project is to design a microcontroller control system for the heart valve bioreactor. It can control the flow of the whole system based on the specified parameters and collect data in MATLAB.

I use the built-in ADC of ATmega 1284P microcontroller. The microcontroller reads the signal of four pressure transducers: high tank, low tank, ventricle, and aorta. And the microcontroller has to control one pump and one solenoid valve. The pump is turned on/off based on the pressure difference between high tank and low tank: if the pressure difference exceeds the upper threshold, the pump will stop working; if the pressure difference is smaller than the lower threshold, the pump will start working. The two-way solenoid valve is controlled based on the pressure of aorta. If the pressure of aorta exceeds the threshold, the valve will be open; otherwise it will be closed. And I built two junction boxes for controlling the pump and the two-way solenoid valve. The junction boxes can connect the low power and the high power by using relay switch. It can make the project safe to use. In this way, we can control the flow inside the microcontroller to mimic the actual flow in the heart valve system of human.

The values of the thresholds differ every time we run the bioreactor. I use MATLAB to communicate with the microcontroller. MATLAB sends different commands to the microcontroller and the microcontroller will give feedback based on the commands. The user can check the current state of the whole system, change the values of the parameters and collect data using MATLAB. During data collection, MATLAB will plot real-time wave forms of the four transducers. After finishing the data collection, MATLAB will store the data for further analysis.

The future work could be that we can design our own prototype board instead of using bread board so the whole system could be more compact. And also, we can build several parallel TEHV chambers instead of just one.

Content

Microcontroller Control System for Heart Valve Bioreactor

Kang Li (kl694)

Introduction

This project continues the design and development of a cyclic flow heart valve bioreactor for use in culturing and conditioning of tissue engineered heart valves in the Butcher Lab. The bioreactor has to simulate the flow between left ventricle and aorta of the heart to mechanically stimulate the cells of the tissue engineered aortic semi lunar heart valve.

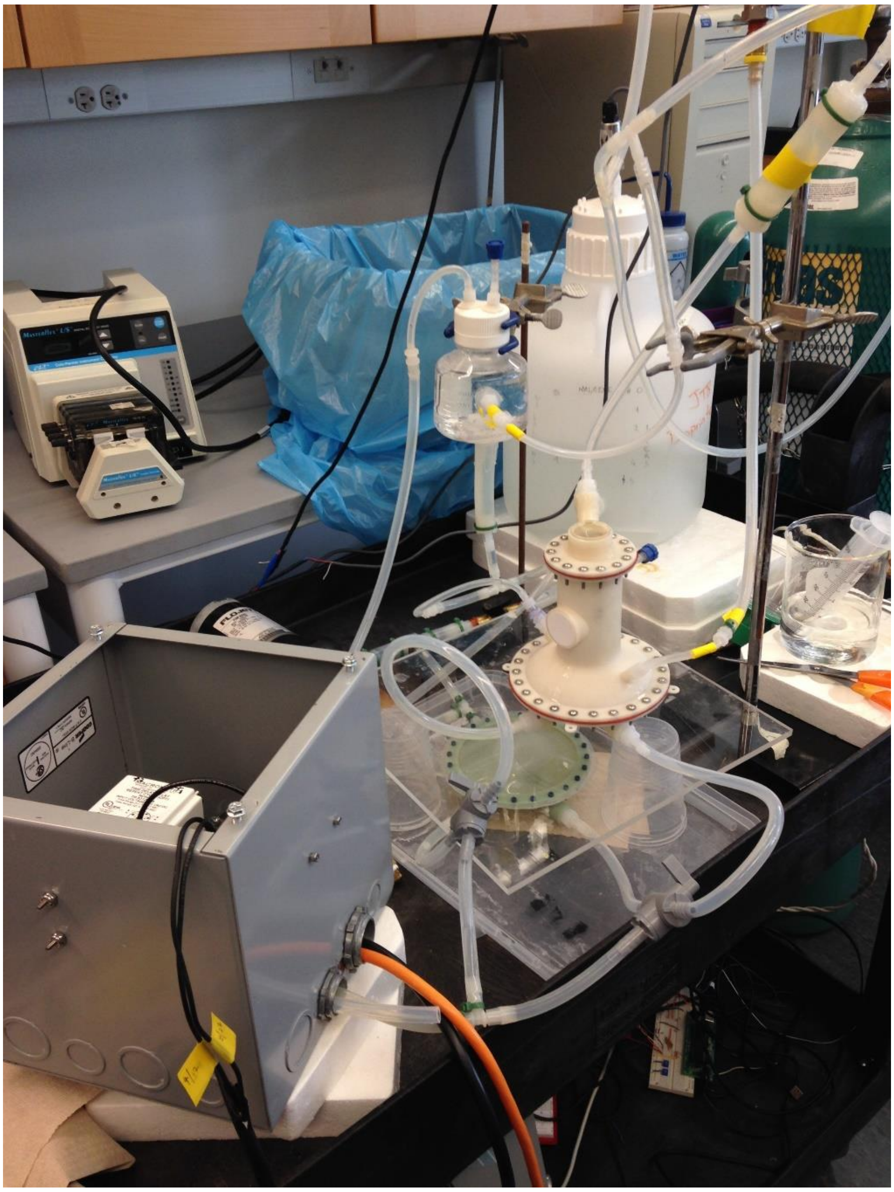


Figure 1. Heart Valve Bioreactor

The microcontroller system is needed for controlling the flow of the bioreactor. The flow diagram is shown in Figure 2.

The bottom circuit is composed of a chamber with the membrane, a pump, a high pressured tank and a low pressurized tank. There are two solenoid valves, which allow us to control the pulse rate. The pump is controlled by the pressure difference of the high pressured tank and the low pressurized tank. And the solenoid valve is controlled by the timer relay. Only water circulates in this bottom circuit.

The top circuit is composed of a chamber with the membrane, a Tissue Engineered Heart Valves (TEHV) chamber, an air tank, a media reservoir and a two-way solenoid valve. The air tank is used for pressurizing the TEHV chamber to maintain a constant value of aorta pressure. The two-way solenoid valve is controlled by the pressure of aorta. If the pressure of aorta reaches the threshold value, the valve will be open.

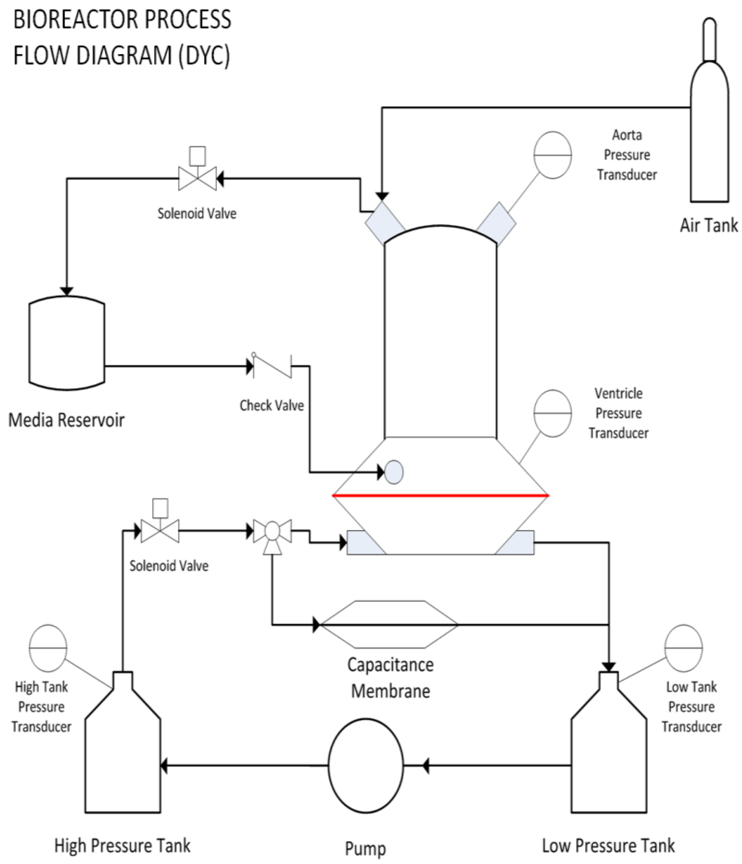


Figure 2. Bioreactor Process Flow Diagram

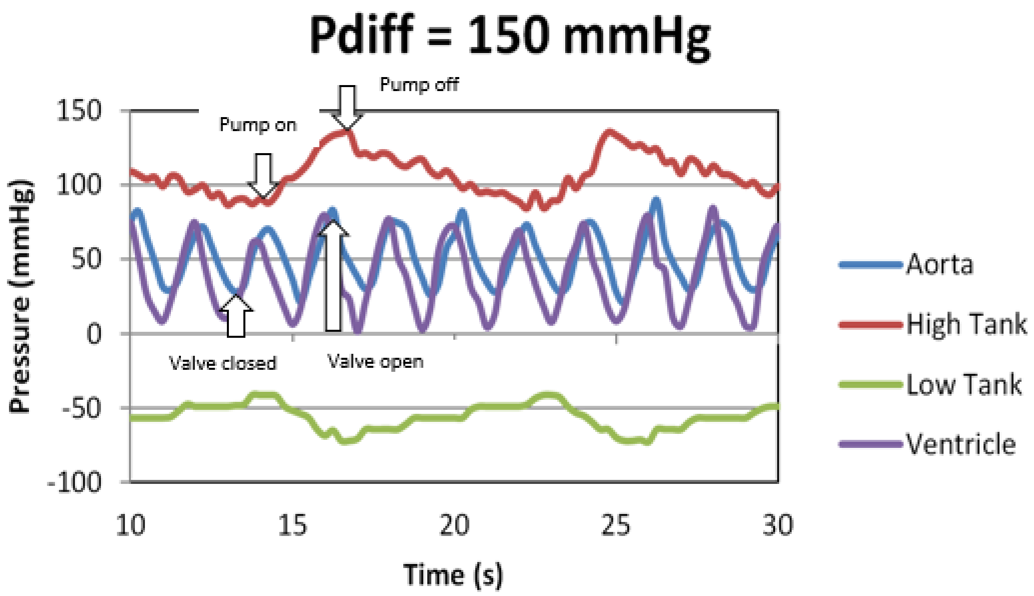


Figure 3. Example of Pump and Solenoid Valve control procedure

We can see one example of pump and solenoid valve control procedure in Figure 3. The pump is turned on/off based on the pressure difference between high tank and low tank: if the pressure difference exceeds the upper threshold, the pump will stop working; if the pressure difference is smaller than the lower threshold, the pump will start working. The two-way solenoid valve is controlled based on the pressure of aorta. If the pressure of aorta exceeds the threshold, the valve will be open; otherwise it will be closed.

High Level Design

I use ATmega 1284P microcontroller in this project. I use the built-in Analog to Digital Converter to read the signal from the four transducers and control the pump based on the pressure difference of high tank and low tank and control the two-way solenoid valve based on the pressure of aorta. I also use MATLAB to communicate the microcontroller with the PC. I collect data and plot real-time waveforms using MATLAB. I also use TRT (Tiny Real Time) to implement multitasking on the microcontroller. The High Level Design diagram is shown in Figure 3.

There are several variables I need to change or monitor in this project. Parts of them are calculated for calibrating the bioreactor by using MATLAB. And the rest of the variables are set every time we want to change the state of the bioreactor. They are as follows:

Name	Description	Need to change?
P_diff	This is the pressure difference between high tank and low tank, which is used for controlling the pump.	Y
dP_MA	Moving Average of the pressure. This parameter and “delta” help P_diff to determine the upper and lower pressure thresholds for the pump.	N
Bias	Pressure bias. This is calculated by the former designer for eliminating the noise.	N
thres	The threshold pressure of the aorta pressure. When the pressure of aorta pressure reaches this value, the valve will open.	Y
delta	This variable is multiplied by dP_MA every time when the microcontroller compares the pressure difference.	Y
Gain	This variable is multiplied by the measured pressure difference by Microcontroller for comparing the expected P_diff.	N

Table 1. Key variables and the descriptions

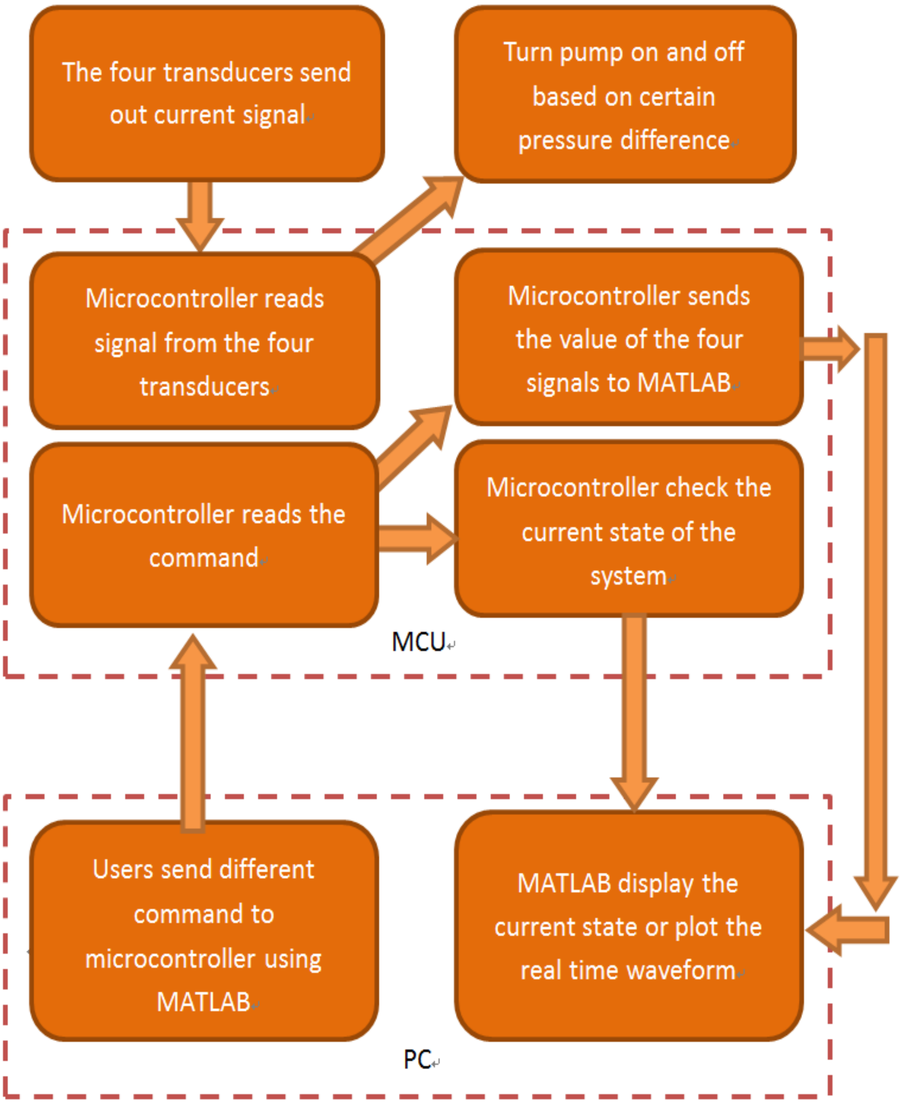


Figure 4. High Level Design

Hardware design

Junction Box

I need to use microcontroller to control the pump and solenoid valve, which are both driven by 110V wall AC. But the output of the microcontroller is 5V DC. So I need junction boxes which contain a relay switch to control the AC circuits.

Figure 5. Junction boxes

The major parts of the junction box include solid state relay, wall switch and wall socket. The circuit diagram is shown as in Figure 6.

The junction has a power plug which can be put in any wall socket. This plug provide the power of the junction box. The wall socket and wall switch are on the surface of the junction box. The plug of the pump or the solenoid can be put in the wall socket. And the wall switch can cut off the AC circuit in case of emergency situation. In this way, we can energize the pump or the two-way solenoid valve.

Inside the junction box, the AC live line first goes into one exposed lead of the wall switch. Then it comes out from the other lead of the wall switch and goes into one exposed lead of the AC output of the solid state relay. After coming out from the other lead of the AC output of the solid state relay, the live line connects one of the exposed lead of the wall socket, eventually. And the neutral line of the power plug directly connects the other exposed lead of the wall socket. And the ground line of the power plug connects both of the ground lead of the wall switch and the wall socket. The low-voltage input side of the solid relay switch connects the microcontroller through a 3.5mm audio cable. So if the microcontroller signal is high (5 volts), the AC output of the solid state relay conducts. So the load (the pump or the two-way solenoid valve) of the AC circuit can be energized.

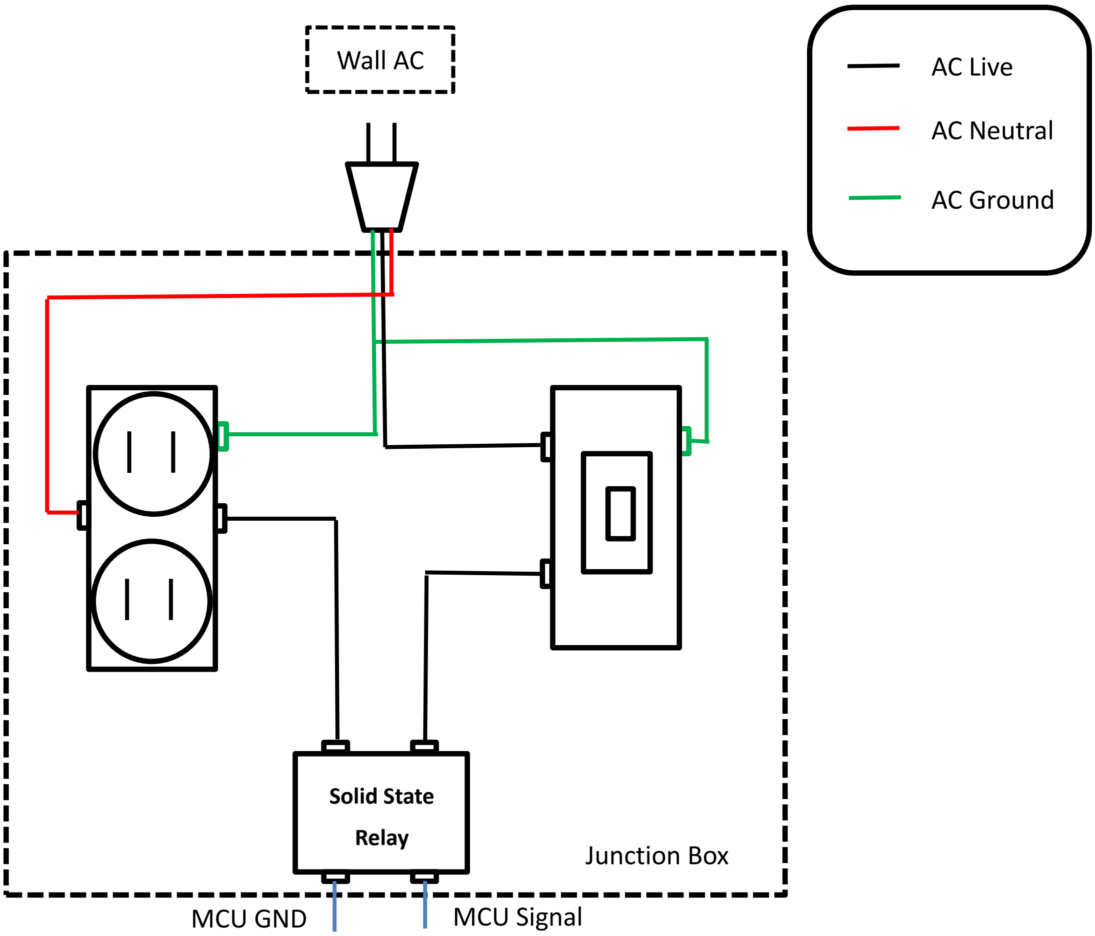


Figure 6. Circuit Diagram of Junction Box

In this way, I keep all the high power circuit inside the junction box so that the system is very safe. And also the wall switch can cut the circuit off in case of dangerous situation.

Hardware for microcontroller

The outputs of the four transducers are all currents which are in the range of 4-20 mA. But the built-in ADC of ATmega 1284P can only convert voltage to digital signal. So I put a 250 Ω resistor in serial with each transducer. The microcontroller measures the voltage drop between the two leads of the resistor.

I need four ADCs in this project. So the GND of the microcontroller should connect one lead of each resistors and PIN A0 ~ PIN A3 connects the other lead of each resistor. PIN D2 connects the junction box which controls the pump and PIN C0 connects the junction box which controls the two-way solenoid valve.

The whole setup is shown in Figure 7.

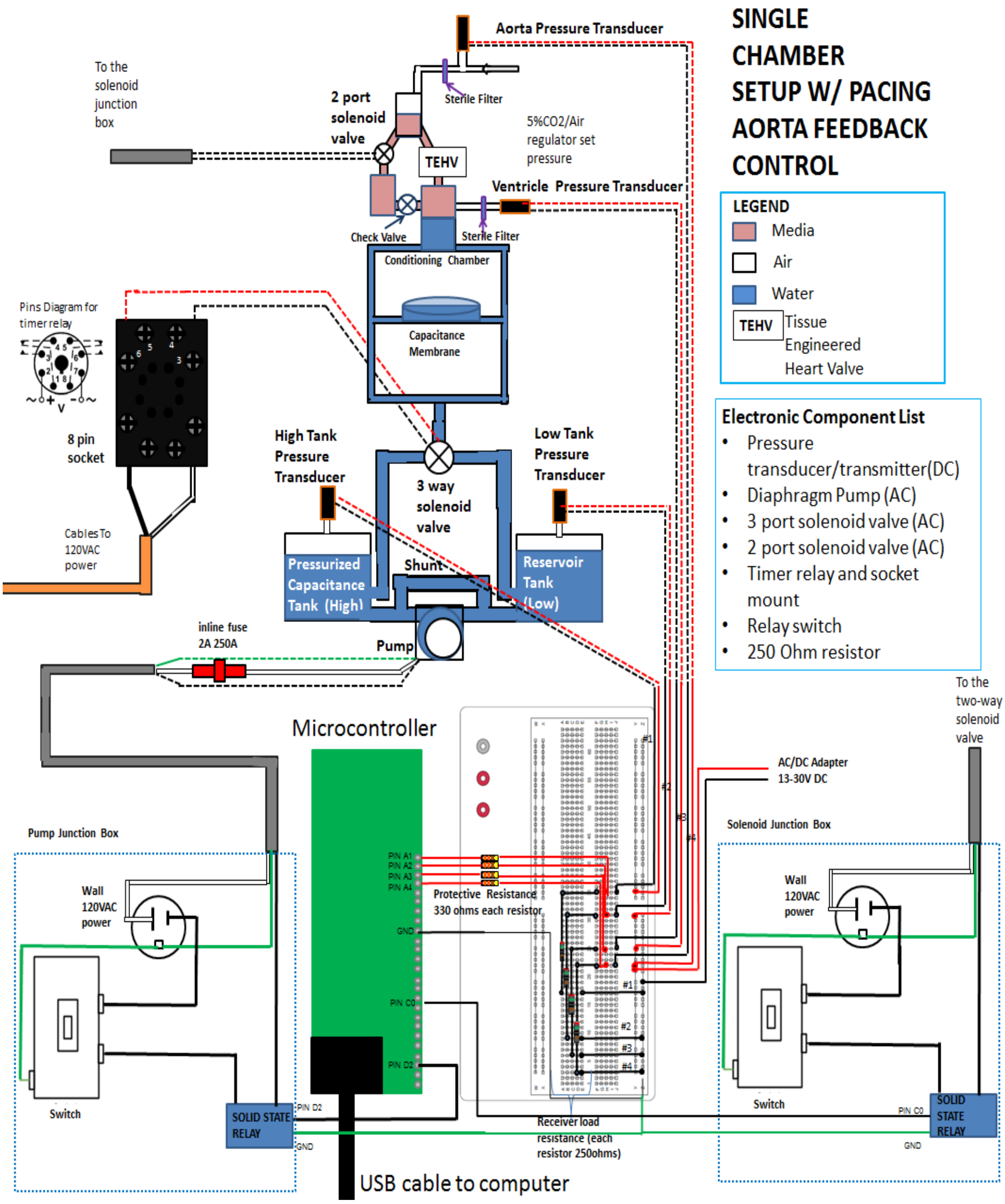


Figure 7. Hardware setup for Heart Valve Bioreactor

Software design

Microcontroller Part

1. TRT (Tiny Real Time)

I use TRT (Tiny Real Time) to implement the multi-tasking on the microcontroller. TRT is a real-time kernel which was written by Dan Henriksson and Anton Cervin (technical report). Aso see the ECE 4760 webpage about TRT. This kernel has some characteristics which make it very suitable for this project.

Multitask can run on the same ATmega 1284P microcontroller chip.

Every task has its own release and dead time. The scheduling algorithm is Earliest Deadline First (EDF).

There are semaphores to protect shared resources (e.g. memory, or the UART) which are used by more than one task.

In this project, I create two task using Tiny Real Time: pump_control and PC_communication. The task pump_control is reading the signal sending from the four transducers continuously. And it control the pump based on the pressure difference between high tank and low tank. And it also controls the two-way solenoid valve based on the pressure of the aorta transducer.

The task PC_communication is reading the serial port. If it receives command sending from the serial port, it will parse the command and react correspondingly. There are three different commands based on the first character of the string. They are as follows:

1) "c": If the first character of the string is "c" (check), which means the PC want to check the current state of the microcontroller, PC_communication will send back a string which contains the value of P_diff, dP_MA, delta, Gain, Bias, and threshold of the aorta pressure transducer. The format is "P_diff%fdP_MA%fdelta%fGain%fBias%fThres%d". This string will be parsed in MATLAB.
2) "o": If the first character of the string is "o" (operation), which means the user wants to change the value of the key variables, PC_communication will parse the following string of the command and load the value to the corresponding variables which are used in the pump_control task.
3) "s": If the first character of the string is "s" (send), which means the PC is collecting data

and needs the microcontroller to send the data of the four transducers and the pump signal, PC_communication will package the demanding data into a string and send it back to PC through serial port. The format of the string is "H%3dL%3dV%3dA%3dU%1d" and it will be parsed in MATLAB on PC.

These two tasks may access the same variables at the same time. So the TRT will manage these accesses by using semaphore. The main functions I use in this project is as follows:

Function	Description
void trtInitKernel(uint16_t idletask_stack)	Sets up the kernel data structures. The parameter is the desired stack size of the idle task. For a null idle task, a stack size of 80 should be sufficient.
void trtCreateTask(void (*fun)(void*), uint16_t stacksize, uint32_t release, uint32_t deadline, void *args)	Identifies a function to the kernel as a thread. The parameters specify a pointer to the function, the desired stack size, the initial release time, the initial deadline time, and an arbitrary data input structure. The release time and deadline must be updated in each task whenever trtSleepUntil is called. The task structures are statically allocated. Be sure to configure MAXNBRTASKS in the kernel file to be big enough. When created, each task initializes 35 bytes of storage for registers, but stack size minimum is around 40 bytes. If any task stack is too small, the system will crash!
uint32_t trtCurrentTime(void)	Get the current global time in timer ticks.
void trtSleepUntil(uint32_t release, uint32_t deadline)	Puts a task to sleep by making it ineligible to run until the release time. After the release time, it will run when it has the nearest deadline. Never use this function in an ISR. The (deadline) - (release time) should be greater than the execution time of the thread between trtSleepUntil calls so that the kernel can meet all the deadlines. If you give a slow task a release time equal to its deadline, then it has to execute in zero time to meet deadline, and nothing else can run until the slow task completes.
void trtCreateSemaphore(uint8_t semnumber, uint8_t initval)	Creates a semaphore with identifier semnumber and initval initial value. Be sure to

	configure MAXNBRSEMAPHORES in the kernel file to be big enough. The identifier number is 1-based, so the first semaphore you define should be numbered 1.
void trtWait(uint8_t semnumber)	Adds one to the semaphore. If another thread is waiting on the semaphore, and has a nearer deadline, a context switch will occur. You can use this function in an ISR.
void trtSignal(uint8_t semnumber)	Returns the count of the specified semaphore (before it is decremented). If the semaphore has a nonzero value, the value is decremented. Your task must check the return value. This function does not block. You can use this function in an ISR.

Table TRT function and description (from TRT introduction page of ECE 4760)

2. Internal ADC of ATmega 1284P

I use the built–in Analog to Digital Converter of ATmega 1284P. This ADC is a 10-bit successive approximation ADC. In this project, I only use the first 8-bit for the ADC. I use four input pins of the chip (A0~A3) and the internal reference voltage is 5V. I use single-ended conversion for all the four

By the external circuits, I make the voltage of the input pin is in the range 0~5V. So the calculation of ADC is as follows:

$$\text{ADC} = \frac{V_{in}}{5V} \times 255$$

For example, if the input voltage of Pin A0 is 3.4V, the microcontroller will store $(173)_{10}$ which is $(10101101)_2$ in register ADCH after the Analog to Digital Conversion.

I need to set some of the registers to implement this ADC. The first register is ADMUX. I set the first two bits to "01" which means the reference voltage is 5V. And I set Bit 5 to "1" to left adjust the result of the conversion. And for Bits 4~0, I set 0b00000 to 0b00011 in the state machine because I need to use channel 0 to channel 4 and I don't need to add gain to the output. The second register which is also very important is ADCSRA. The most significant bit of ADCSRA is ADEN. I set it to "1" to enable the ADC. The second most significant bit of ADCSRA is ADSC. I set this bit to "1" to indicate the start of ADC. When the conversion is complete, it returns to zero. So I can also use this bit to test if the conversion is done and then start the next conversion. After the conversion, the data is stored in ADCH. I load the value to the corresponding variable after the conversion.

The ADC procedure is implemented in pump_control subroutine. I design a state machine to read four channels of the ADC and send out the pump control signal. The state machine is as follows:

DIFFERENCE:

In this state, we measure the values of the pressure of high tank and low tank. I use a while-loop "while (ADCSRA & (1<<ADSC));" to wait for ADC. After this loop, the value in ADCH can be used. So I load the value to variable P_tank_H which stores the value of high tank pressure. Then I set the ADC registers as follows:

```
ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00001;
ADCSRA |= (1<<ADSC) ;
```

The first line indicates the channel is changed to channel 1 (Pin A1) and the reference voltage is 5V and the result is left adjusted. The second line starts another ADC procedure.

Then I load the value of ADCH to P_tank_L which stores the pressure of the low tank. After that, I also need to set the channel to channel 2 (Pin A2). I also set two variables called HighTank_total and LowTank_total to eliminate the noise of the ADC. I set a count and every time we enter this state (DIFFERENCE) the count will increment by 1. If the count reaches 50, the microcontroller will compare the value of HighTank_total and LowTank_total by this sentence: deltaP = ((float)HighTank_total - (float)LowTank_total) / 50 * Gain; (See Table 1 for details).

The value of variable "Gain" is set from the MATLAB and protected by TRT since it is used in two tasks. After this calculation, I can use deltaP to control the pump. If(deltaP < P_diff - delta * dP_MA) , we should turn on the pump. The variables "P_diff", "delta", and "dP_MA" are also set from MATLAB and protected by TRT. If(deltaP >= P_diff + delta * dP_MA), we should turn off the pump.

VENTRICLE:

This state only reads the data of Pin A2. And the microcontroller will load the value of ADCH to variable "P_ventricle" and change the channel to channel 3 (Pin A3).

AORTA:

This state reads the data of Pin A3. The microcontroller will load the value of ADCH to variable

"P_aorta" and change the channel to channel 0 (Pin A0). And also, the microcontroller will control the two-way solenoid valve in this state. If P_aorta is bigger than the threshold value (variable "thres"), the microcontroller will send an open signal to the valve. Otherwise, the microcontroller will send a close signal. In this state, the microcontroller also put the four variable in a page whose format is H%3dL%3dV%3dA%3dU%1d. This is used for sending data to MATLAB.

MATLAB Part

I use MATLAB to communicate with the microcontroller and collect data. It is fairly easy to set up the serial port in MATLAB. The basic steps of the MATLAB code are as follows:

1. Load the calibration parameters of the bioreactor

   These parameters which are essential for the bioreactor control were created by the former students during the calibration time of the whole bioreactor system. They are in the form of mat file. So we can load them directly.

2. Close all the peripheral of the computer and open the serial port

   Before we open the serial port of the computer, we need to make sure all the instruments are deleted by using "delete(instrfindall);". Then we can open the serial port by the command:

   ```
   fid = serial("com8");
   fopen(fid);
   ```

   Otherwise, MATLAB may get the runtime error.

3. Check the current state of the microcontroller

   After we open the serial port, we can communicate with the microcontroller through USB cable. First thing we want to know is what kind of state the microcontroller or the bioreactor is. So we can send a check signal which is a single character "c" in my design to the microcontroller. The microcontroller receives the check signal and sends back a piece of information containing the current state. The format of the information is "P_diffXXXdP_MAXXXdeltaXXXGainXXXBiasXXXThresXXX". Then MATLAB parses the information by using "strfind" function. And finishing parsing this information, MATLAB will print out the parsed information in the command window. So the user will check the current state of the whole system (Please check User Manual for screen captures).

4. Set the value of the key variables through user interface and send them to microcontroller

Since we get the information of the state, we might want to change it to satisfy the demand of this period of data collection. After printing out the state of the microcontroller, MATLAB will ask the user "Do you want to change the current values?" If the user types in 0, the state won't change and the MATLAB starts collecting data; If the user types in 1, MATLAB will prompt the user to change the state of the system. After finishing changing the value, MATLAB will print out the value which the user just typed in and ask the user "Please type in 1 or 0 (1 for correct)". If the user types in 0, the whole procedure of changing values will start over again; if the user types in 1, MATLAB will send the new value to the microcontroller and starts to collect data. The format of the string which MATLAB sends to the microcontroller is "oPXXXfCXXXDXXXGXXXBXXXTXXX" and this string will be parsed in microcontroller.

5. Start to collect data and plot the real-time waveform of the four transducers

After changing the value of the key variables, we can collect data now. I use a for-loop to do the data collection. Instead of letting the microcontroller send data continuously, I design a simple "handshaking" protocol because MATLAB is very bad at dealing with memory control and it may flush the memory if we don't control the data transfer. The first thing is that MATLAB sends a character "s" to the microcontroller. The microcontroller recognizes the character and then sends back a string whose format is "HXXXLXXXVXXXAXXXUX". This string contains the value of the four transducers (High tank, Low tank, Ventricle, Aorta) and the pump signal (high or low). MATLAB will parse the string and send values to the corresponding variable. And then MATLAB plots the points in the figure. After finishing plotting, MATLAB will send "s" again and start the whole procedure again until it reaches the length of the time period we set.

In this way, the whole procedure of data collection is under control. Notice that we have to use pause() function between sending "s" and receiving the string, even when we only need a really short pause. Otherwise, the real time waveform will stuck and the whole waveform will appear after we finish collecting data.

6. Save the data of the four transducers for further analysis

The last step is that we save the data to a mat file for further analysis. The data we want to save is High_tank, Low_tank, Ventricle, and Aorta. And then we delete all the other internal variables. At last, MATLAB will print a pink information telling the user what format of the saved data is.

Result and Analysis

The microcontroller system is used for collecting data in out lab. We can use these data to do further analysis. This is just a simple example. Figure 8 shows the porcine heart valve pressure when P_diff equals 150 mmHg and the applied aorta pressure equals 0. Figure 9 shows the 3D printed heart valve pressure when P_diff equals 150 mmHg and the applied aorta pressure equals 0. We can compare these two figures to check if the printed valve satisfies our demand.

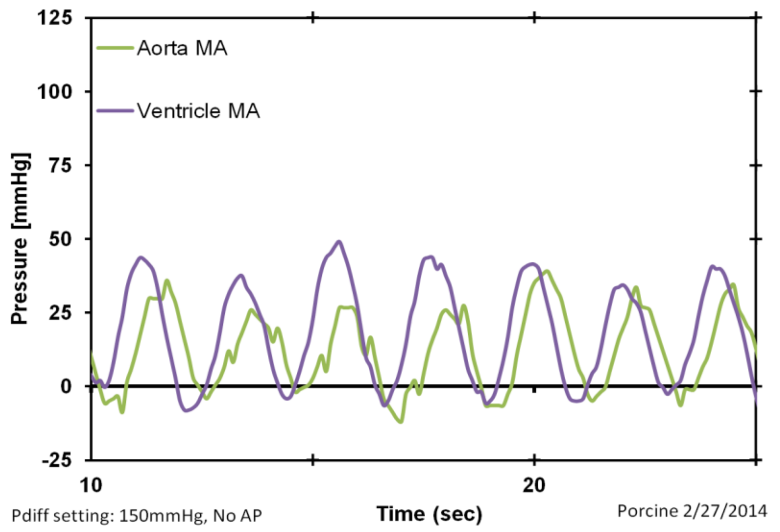


Figure 8. Porcine heart valve pressure waveform when P_diff = 150 mmHg

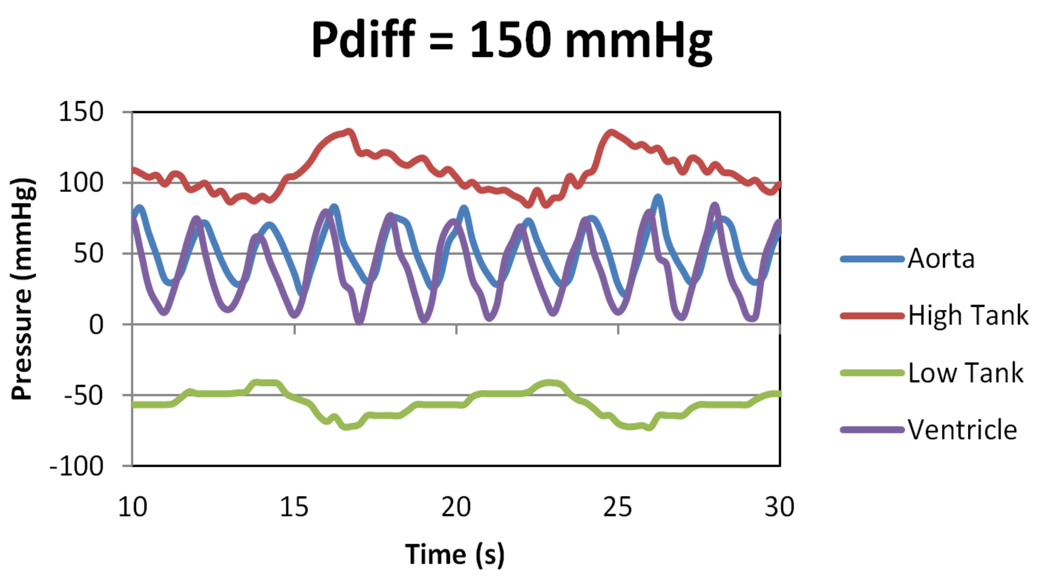


Figure 9. 3D printed heart valve pressure waveform when P_diff = 150 mmHg

Conclusion

I designed a microcontroller control system for the heart valve bioreactor. It can control the flow of the whole system based on the specified parameters and collect data in MATLAB.

The future work could be that we can design our own prototype board instead of using bread board so the whole system could be more compact. And also, we can build several parallel TEHV chambers instead of just one.

Acknowledgement

I would like to thank my advisor Bruce Land for all his instruction. His advice of junction box really make the project much safer. And he taught me how to change the clock frequency to make the TRT run for much longer time. All these things make the project much easier for me to accomplish.

And I also want to thank all the team members in our bio-print team, especially Laura. She is always so patient and kind. When I started to participate in this project, I know nothing about the machenism of heart valve and the bioreactor. She told me how to start and what goal we should achieve. When I have questions, she always explains to me no matter how stupid the question is. And also for Alain, Dan, and Duan, you guys are always helping me when I have problems.

APPENDIX A

User Manual

1. Hardware setup

   Currently, I put all the wire connections on the bread board so all the circuit should be set up as in Figure. And then we should connect the microcontroller and the PC through USB cable.

2. Run MATLAB code

   Before we run the MATLAB code, we should check “Device Manager” to see which serial port we are using to connect the microcontroller. Then we should go to the fifth line of the MATLAB scripts and change “com8” to the serial port we are using.

   After that, we can run our MATLAB code. The first thing we can see is the time length of this experiment, as shown in Figure 10.

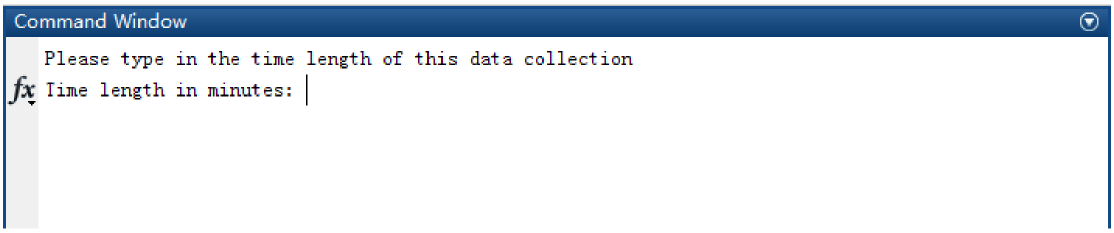
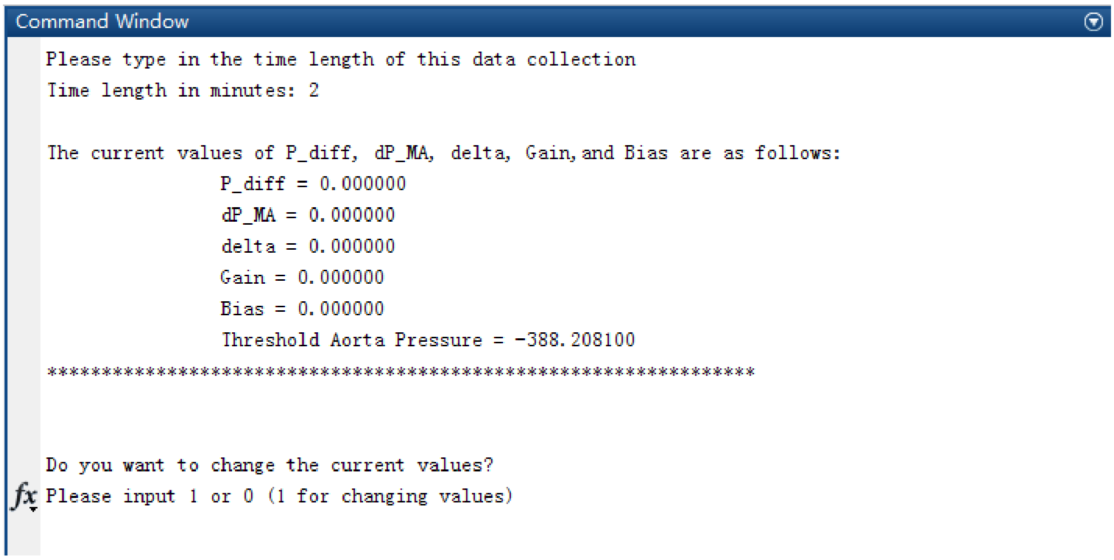


Figure 10. Prompt line of time length

   We should type in how long we want to collect data. Notice that the user must type in an integer in this procedure.

   Then the MATLAB will send the current state of the whole system, as shown in Figure 11.



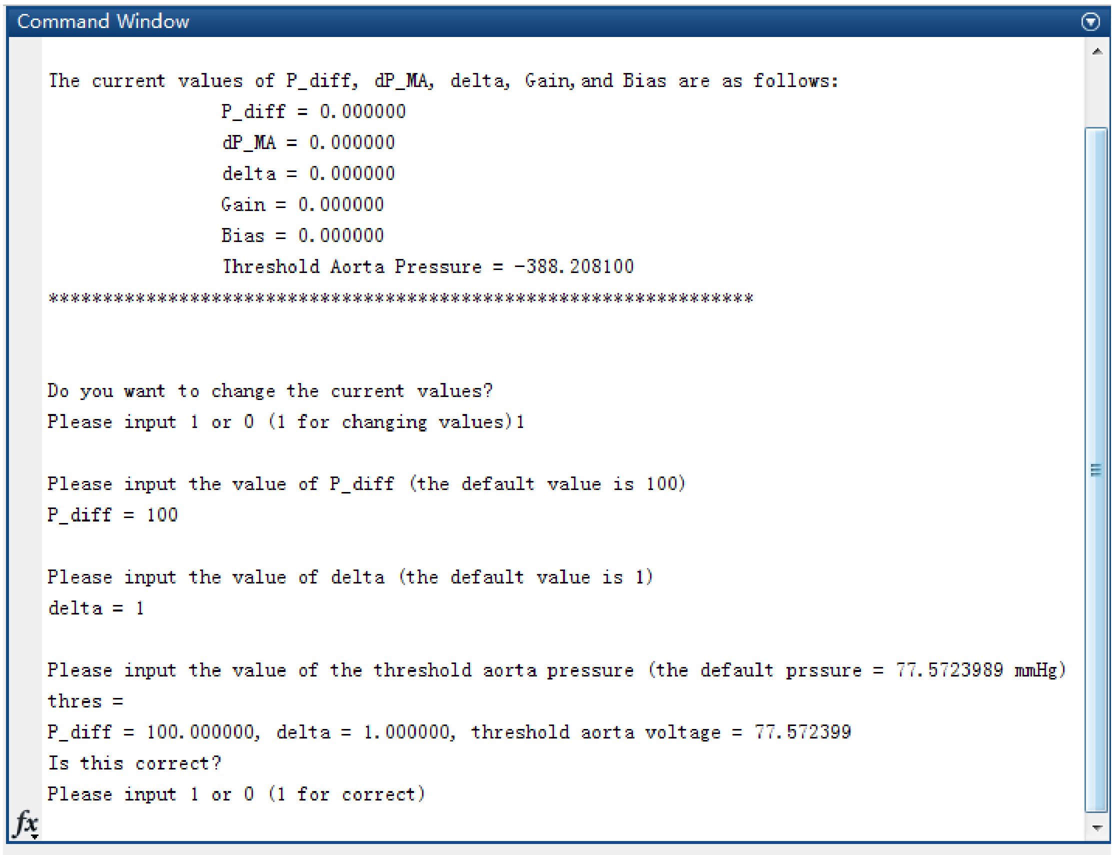
```
Command Window
Please type in the time length of this data collection
Time length in minutes: 2

The current values of P_diff, dP_MA, delta, Gain, and Bias are as follows:
                P_diff = 0.000000
                dP_MA = 0.000000
                delta = 0.000000
                Gain = 0.000000
                Bias = 0.000000
                Threshold Aorta Pressure = -388.208100
******************************************************************


Do you want to change the current values?
Please input 1 or 0 (1 for changing values)
```

Figure 11. The current state of the whole system

These information is sent back from the microcontroller. If we want to change the state, we should type in “1”; otherwise we should type in “0”. After we type in “1”, the MATLAB will guide us to change the values of some key variables, as shown in Figure 12.



```
Command Window

The current values of P_diff, dP_MA, delta, Gain, and Bias are as follows:
                P_diff = 0.000000
                dP_MA = 0.000000
                delta = 0.000000
                Gain = 0.000000
                Bias = 0.000000
                Threshold Aorta Pressure = -388.208100
******************************************************************


Do you want to change the current values?
Please input 1 or 0 (1 for changing values)1

Please input the value of P_diff (the default value is 100)
P_diff = 100

Please input the value of delta (the default value is 1)
delta = 1

Please input the value of the threshold aorta pressure (the default prssure = 77.5723989 mmHg)
thres =
P_diff = 100.000000, delta = 1.000000, threshold aorta voltage = 77.572399
Is this correct?
Please input 1 or 0 (1 for correct)
```

Figure 12. Change the values of key variables

After we check the desired value of the key variables, we should type in “1” if all the values are correct; otherwise we should type in “0” and start the whole procedure over again.

After we determine the value of the key parameters, MATLAB will start to collect data. MATLAB will plot the real-time waveforms of the four transducers, as shown in Figure 13.

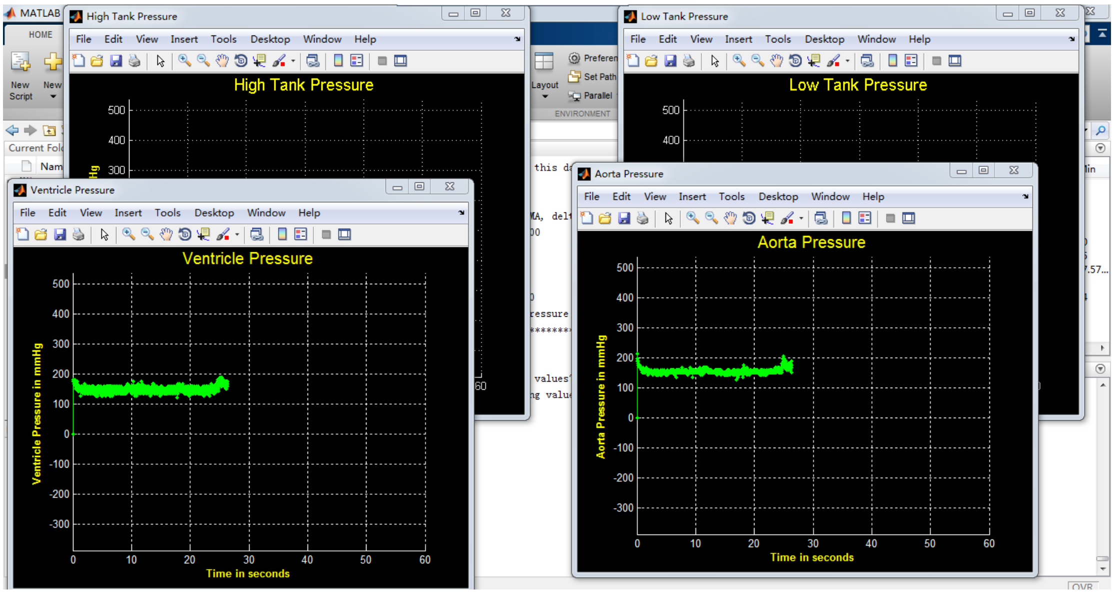


Figure 13. Real-time Waveforms of four transducers

We can monitor the pressures by these real-time waveforms.

After we reached the time length of this experiment, MATLAB will store the four vectors of the values of the four pressures in a mat file and prompt a pink line to tell the user what format of the saved data is, as shown in Figure 14.

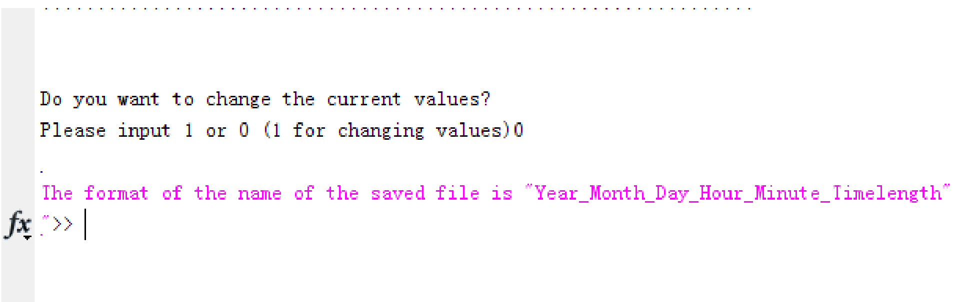


Figure 14. File format

In this way, we can guarantee that there will never be two files which have the same name and we can use the data to do further analysis.

APPENDIX B

Parts Number

Microcontroller (All from lab)

Part Name	Quantities
ATmega 1284P chip	1
Prototype Board	1
Resistors	Several
USB cable	1

Junction Box × 2 (Parts number are all from Grainger)

Quantities	Parts Number	Part Name
2	6X063	LEVITON Wall Switch,1-Pole,Toggle,Brown
2	6A702	LEVITON Receptacle,20A,125V,5-20R,2P,3W,1PH
2	6XC61	RACO Box, Plastic 2 Gang
2	1LXT1	HUBBELL WIRING DEVICE-KELLEMS Wall Plate,2Gang,Nylon,Ivory
2	6C900	OMRON Relay, Solid State
4	5XFP9	NO BRAND NAME ASSIGNED Extension Cord,6ft,16/3,13A,SJT,Black

APPENDIX C

Source Code

pump_trt_28.c

```
/*------------------------------------------------------------*/
/*This script is written for MENG Project: Heart Valve Bioreactor
   by Kang Li (kl694), Cornell University*/
#define F_CPU 16000000UL
#include "trtSettings.h"
#include "trtkernel_1284.c"
#include <avr/interrupt.h>
#include <avr/pgmspace.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <avr/sleep.h>

#define begin {
#define end }

// serial communication library
// Don't mess with the semaphores
#define SEM_RX_ISR_SIGNAL 1
#define SEM_STRING_DONE 2 // user hit <enter>
#include "trtUart.h"
#include "trtUart.c"

#define DIFFERENCE 11
#define AORTA 12
#define VENTRICLE 13

#define READ(U, N) ((U) >> (N) & 1u)
#define SET(U, N) ((void)((U) |= 1u << (N)))
#define CLR(U, N) ((void)((U) &= ~(1u << (N))))
#define FLIP(U, N) ((void)((U) ^= 1u << (N)))

#define SEM_SEND 3
#define SEM_INPUT 4
#define SEM_SQUARE 5

#define T_OVERFLOW 500
// UART file descriptor
```

```
// putchar and getchar are in uart.c
FILE uart_str = FDEV_SETUP_STREAM(uart_putchar, uart_getchar, _FDEV_SETUP_RW);

int args[2];
unsigned char    P_tank_H, P_tank_L;
double P_diff;
int count;
double deltaP;
double delta;
double time_squarewave, dP_MA, Gain, Bias;
int thres,T;
float P, C, D, G, B;
unsigned char P_aorta, P_ventricle;
unsigned char channel_flag ;
long HighTank_total, LowTank_total;
int pumpSignal;
char sendData[14];


void initialize(void);

int main(void)
begin
	initialize();
	set_sleep_mode(SLEEP_MODE_IDLE);
	sleep_enable();
	while (1)
	begin
		CLR(PORTD,1);
		sleep_cpu();
	end
end

void pump_control(void * args)
begin
	uint32_t rel,dead;
	while(1)
	begin
		switch(channel_flag)
		begin
			case (DIFFERENCE):

				// wait for ADC done
				while (ADCSRA & (1<<ADSC));
```

```
            P_tank_H = ADCH;
            ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00001;
            ADCSRA |= (1<<ADSC) ;
            HighTank_total += P_tank_H;
            // wait for ADC done
            while (ADCSRA & (1<<ADSC));
            P_tank_L = ADCH;
            //Reference voltage is 5V; Write one to ADLAR to left adjust the result; Select the PINA1(ADC1) as analog input
            ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00010;
            ADCSRA |= (1<<ADSC) ;
            LowTank_total += P_tank_L;
            count++;
            if (count >= 50)
            begin
                count = 0;

                trtWait(SEM_INPUT);
                deltaP = ((float)HighTank_total - (float)LowTank_total) / 50 * Gain;
                trtSignal(SEM_INPUT);
                HighTank_total = 0;
                LowTank_total = 0;

                //load the values sent from MATLAB and protect the variables using TRT
                trtWait(SEM_INPUT);
                P_diff = P;
                dP_MA = C;
                delta = D;
                Gain = G;
                Bias = B;
                thres = T;
                trtSignal(SEM_INPUT);

                //if P_diff, dP_MA, delta are all zeros, don't start the pump
                if((P_diff > 0) || (dP_MA > 0) || (delta > 0))
                begin
                    if(deltaP < P_diff - delta * dP_MA)
                    begin
                        SET(PORTD, 2); // turn on the pump
                        trtWait(SEM_SEND);
                        pumpSignal = 1;
                        trtSignal(SEM_SEND);
                    end
                    if(deltaP >= P_diff + delta * dP_MA)
```

```
                begin
                        CLR(PORTD, 2); // turn off the pump
                        trtWait(SEM_SEND);
                        pumpSignal = 0;
                        trtSignal(SEM_SEND);
                end
        end
        else
        begin
                CLR(PORTD, 2);
        end
end

channel_flag = VENTRICLE;
break;
case (VENTRICLE):

        // wait for ADC done
        while (ADCSRA & (1<<ADSC));
        P_ventricle = ADCH;
        //Reference voltage is 5V; Write one to ADLAR to left adjust the result; Select
the PINA3(ADC3) as analog input
        ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00011;
        ADCSRA |= (1<<ADSC) ;
        channel_flag = AORTA;
        break;
case (AORTA):

        while (ADCSRA & (1<<ADSC));
        P_aorta = ADCH;;

        if(P_aorta >= thres)
        begin
                CLR(PORTC,0); // open the two-way solenoid valve
        end
        else
        begin
                SET(PORTC,0); // close the two-way solenoid vale (the valve is closed
when energized)
        end

        //Reference voltage is 5V; Write one to ADLAR to left adjust the result; Select
the PINA0(ADC0) as analog input
        ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00000;
```

```
                ADCSRA |= (1<<ADSC) ;

                trtWait(SEM_SEND);
                // put the four variables in a package
                sprintf(sendData, "H%3dL%3dV%3dA%3dU%1d",P_tank_H,P_tank_L,
P_ventricle, P_aorta, pumpSignal);
                trtSignal(SEM_SEND);
                channel_flag = DIFFERENCE;
                break;

        end


        rel = trtCurrentTime() + SECONDS2TICKS(0.01);
        dead = trtCurrentTime() + SECONDS2TICKS(0.011);
        trtSleepUntil(rel, dead);

    end
end

void PC_communication(void * args)
begin
    char cmd[40], P_str[10], C_str[10], D_str[10], G_str[10], B_str[10], T_str[10];
    int p, c, d, g, b, t;

    while(1)
    begin
        fscanf(stdin, "%s", cmd) ;

        if (cmd[0] == 'o') // change the value of the protected variables
        begin
            // parse the received string
            p = strchr(cmd,'P')-cmd;
            c = strchr(cmd,'C')-cmd;
            d = strchr(cmd,'D')-cmd;
            g = strchr(cmd,'G')-cmd;
            b = strchr(cmd,'B')-cmd;
            t = strchr(cmd,'T')-cmd;
            strlcpy(P_str, cmd + p + 1, c - p);
            strlcpy(C_str, cmd + c + 1, d - c);
            strlcpy(D_str, cmd + d + 1, g - d);
            strlcpy(G_str, cmd + g + 1, b - g);
            strlcpy(B_str, cmd + b + 1, t - b);
            strlcpy(T_str, cmd + t + 1, strlen(cmd) - t);
```

```
            trtWait(SEM_INPUT);
            //load the values to corresponding variables
            sscanf(P_str, "%f", &P);
            sscanf(C_str, "%f", &C);
            sscanf(D_str, "%f", &D);
            sscanf(G_str, "%f", &G);
            sscanf(B_str, "%f", &B);
            sscanf(T_str, "%d", &T);
            trtSignal(SEM_INPUT);
        end

        if (cmd[0] == 's') // send the package to PC
        begin
            trtWait(SEM_SEND);
            fprintf(stdout, "%s", sendData);
            trtSignal(SEM_SEND) ;
        end

        if (cmd[0] == 'c') // check the current state of the whole system
        begin
            trtWait(SEM_INPUT);
            fprintf(stdout, "\rP_diff%fdP_MA%fdelta%fGain%fBias%fThres%d\n", P_diff,
dP_MA, delta, Gain, Bias, thres);
            trtSignal(SEM_INPUT);
        end
    end
end

void initialize(void)
begin
    CLKPR = (1 << CLKPCE);
    CLKPR = (1 << CLKPS0) | (1 << CLKPS1); // set divide by 8

    //PINA is input
    DDRA = 0x00;
    PORTA = 0x00;
    //PIND is output
    DDRD = 0xff;
    PORTD = 0x00;
    //PINC is output
    DDRC = 0xff;
    PORTC = 0x00;

    ADMUX = (1<<REFS0) | (1<<ADLAR) + 0b00000;
```

```
    ADCSRA = (1<<ADEN) | (1<<ADSC) + 7 ;

    channel_flag = DIFFERENCE;
    P_tank_H = 0;
    P_tank_L = 0;
    P_aorta = 0;
    P_ventricle = 0;
    P_diff = 0;
    delta = 0;
    dP_MA = 0;
    Gain = 0;
    Bias = 0;
    time_squarewave = 0;
    thres = 0;
    count = 0;

    T=0;

    //ini uart
    trt_uart_init();
    stdout = stdin = stderr = &uart_str;

    trtInitKernel(300);
    trtCreateSemaphore(SEM_RX_ISR_SIGNAL, 0) ; // uart receive ISR semaphore
    trtCreateSemaphore(SEM_STRING_DONE,0) ;   // user typed <enter>
    trtCreateSemaphore(SEM_SEND, 1) ;
    trtCreateSemaphore(SEM_INPUT, 1) ;
    trtCreateSemaphore(SEM_SQUARE, 1) ;

    trtCreateTask(PC_communication, 300, SECONDS2TICKS(0.15), SECONDS2TICKS(0.25),
&(args[0]));
    trtCreateTask(pump_control, 300, SECONDS2TICKS(0.01), SECONDS2TICKS(0.015),
&(args[1]));
    sei();
end
```

Heart_valve-MCU.m

```
clc;clear; % clean the screen and workspace
load CalibTransducer.mat; % load the calibration parameters
close all; % close all the figures
delete(instrfindall); % delete all the instruments
fid = serial('com8'); % open serial port
s.BytesAvailableFcnMode = 'byte'; % set the parameters of the serial port
s.InputBufferSize = 5000;
s.BytesAvailableFcnCount = 10;
s.BaudRate = 9600;
s.BytesAvailableFcn = @my_callback;
s.Timeout = 3000;
fopen(fid);
fprintf('Please type in the time length of this data collection\n'); % prompt the user to type in the
data length
timeout = input('Time length in minutes: ');
timeout_used = timeout * 60 ; % convert minutes to seconds
fprintf(fid,'c\n');
check = [];
scaler = 5/255* 393.3217; %convert the units to mmHg
sample_rate = 44; % samples/second
while ((isempty(check)) || (check(1) ~= 'P')) % check the current state of the whole system
    check = fscanf(fid, '%s');
    P_diff_location = strfind(check, 'P_diff'); % parse the string
    dP_MA_location = strfind(check, 'dP_MA');
    delta_location = strfind(check, 'delta');
    Gain_location = strfind(check, 'Gain');
    Bias_location = strfind(check, 'Bias');
    Thres_location = strfind(check, 'Thres');
    P_diff_current = str2double(check((P_diff_location + 6):(dP_MA_location - 1)));
    dP_MA_current = str2double(check((dP_MA_location + 5):(delta_location - 1)));
    delta_current = str2double(check((delta_location + 5):(Gain_location - 1)));
    Gain_current = str2double(check((Gain_location + 4):(Bias_location - 1)));
    Bias_current = str2double(check((Bias_location + 4):(Thres_location - 1)));
    Thres_current = str2double(check((Thres_location + 5):length(check))) * scaler - 388.2081;
end
fprintf('\nThe current values of P_diff, dP_MA, delta, Gain,and Bias are as follows:'); % display the
current state
fprintf('\n\t\t\t\tP_diff = %f', P_diff_current);
fprintf('\n\t\t\t\tdP_MA = %f', dP_MA_current);
fprintf('\n\t\t\t\tdelta = %f', delta_current);
fprintf('\n\t\t\t\tGain = %f', Gain_current);
fprintf('\n\t\t\t\tBias = %f', Bias_current);
fprintf('\n\t\t\t\tThreshold Aorta Pressure = %f', Thres_current );
```

```
fprintf('\n*************************************************************\n\r');
fprintf('\rDo you want to change the current values?\n') % ask the user to change value
check_flag = input('Please input 1 or 0 (1 for changing values)');
if(check_flag ~= 0)
    finish_input_flag = 0;
    while(finish_input_flag == 0)
        fprintf('\nPlease input the value of P_diff (the default value is 100)\n');
        P_diff = input('P_diff = ');
        if (size(P_diff) == 0)
            P_diff_used = 100;
        else
            P_diff_used = P_diff;
        end

        fprintf('\nPlease input the value of delta (the default value is 1)\n');
        delta = input('delta = ');
        if (size(delta) == 0)
            delta_used = 1 ;
        else
            delta_used = delta;
        end

        fprintf('\nPlease input the value of the threshold aorta pressure (the default prssure =
77.5723989 mmHg)\n');
        thres = input('thres = ');
        if (size(thres) == 0)
            Thres_used = 77.5723989 ;
        else
            Thres_used = thres;
        end

        fprintf('P_diff = %f, delta = %f, threshold aorta voltage = %f\nIs this correct?\n', ...
            P_diff_used, delta_used, Thres_used );
        finish_input_flag = input('Please input 1 or 0 (1 for correct)\n');
        if ((finish_input_flag ~= 0))
            clear delta P_diff finish_input_flag thres;
            break;
        end
    end
else
    P_diff_used = P_diff_current;
    delta_used = delta_current;
    Thres_used = Thres_current;
```

```
end
R_Use = 250;
Gain_total = a_Transducer * R_Calib / R_Use * 5 /255;
Bias_used = b_Transducer;
Thres_convert = round((Thres_used + 388.2081) / 393.3217 * 255 / 5);
send_packet = sprintf('P%06.2fC%06.3fD%dG%06.3fB%06.3fT%d', P_diff_used, dP_MA,
delta_used, Gain_total, Bias_used, Thres_convert);
fprintf(fid,'o%s\r', send_packet); % send the new value to microcontroller
clear P_diff_current dP_MA_current delta_current %clear the internal variables
clear Gain_current Bias_current
clear P_diff_location dP_MA_location delta_location
clear Gain_location Bias_location Thres_current

%initialize the vectors%initialize the vectors
Low_tank = zeros(timeout_used * sample_rate, 1);
High_tank = zeros(timeout_used * sample_rate, 1);
Ventricle = zeros(timeout_used * sample_rate, 1);
Aorta = zeros(timeout_used * sample_rate, 1);
PumpSignal = zeros(timeout_used * sample_rate, 1);
i_real = 1;

% set the figure handles
figureHandle1 = figure('NumberTitle','off',...
        'Name','High Tank Pressure',...
        'Color',[0 0 0],'Visible','on');
axesHandle1 = axes('Parent',figureHandle1,...
        'YGrid','on',...
        'YColor',[0.9725 0.9725 0.9725],...
        'XGrid','on',...
        'XColor',[0.9725 0.9725 0.9725],...
        'Color',[0 0 0],'xlim', [0, timeout_used], 'ylim', [0, 120] * scaler-388.2081);
hold on;
plotHandle1 =
plot(axesHandle1,i_real,High_tank(1,1),'g',i_real,PumpSignal(1,1),'r','Marker','.','LineWidth',1);
xlabel('Time in seconds','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
ylabel('High Tank Pressure in mmHg','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
title('High Tank Pressure','FontSize',15,'Color',[1 1 0]);

figureHandle2 = figure('NumberTitle','off',...
        'Name','Low Tank Pressure',...
        'Color',[0 0 0],'Visible','on');
axesHandle2 = axes('Parent',figureHandle2,...
        'YGrid','on',...
        'YColor',[0.9725 0.9725 0.9725],...
```

```
        'XGrid','on',...
        'XColor',[0.9725 0.9725 0.9725],...
        'Color',[0 0 0],'xlim', [0, timeout_used], 'ylim', [0, 120] * scaler-388.2081);
hold on;
plotHandle2 =
plot(axesHandle2,i_real,Low_tank(1,1),'g',i_real,PumpSignal(1,1),'r','Marker','.','LineWidth',1);
xlabel('Time in seconds','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
ylabel('Low Tank Pressure in mmHg','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
title('Low Tank Pressure','FontSize',15,'Color',[1 1 0]);


figureHandle3 = figure('NumberTitle','off',...
        'Name','Ventricle Pressure',...
        'Color',[0 0 0],'Visible','on');
axesHandle3 = axes('Parent',figureHandle3,...
        'YGrid','on',...
        'YColor',[0.9725 0.9725 0.9725],...
        'XGrid','on',...
        'XColor',[0.9725 0.9725 0.9725],...
        'Color',[0 0 0],'xlim', [0, timeout_used], 'ylim', [0, 120] * scaler-388.2081);
hold on;
plotHandle3 = plot(axesHandle3,i_real,Ventricle(1,1),'Marker','.','LineWidth',1,'Color',[0 1 0]);
xlabel('Time in seconds','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
ylabel('Ventricle Pressure in mmHg','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
title('Ventricle Pressure','FontSize',15,'Color',[1 1 0]);

figureHandle4 = figure('NumberTitle','off',...
        'Name','Aorta Pressure',...
        'Color',[0 0 0],'Visible','on');
axesHandle4 = axes('Parent',figureHandle4,...
        'YGrid','on',...
        'YColor',[0.9725 0.9725 0.9725],...
        'XGrid','on',...
        'XColor',[0.9725 0.9725 0.9725],...
        'Color',[0 0 0],'xlim', [0, timeout_used], 'ylim', [0, 120] * scaler-388.2081);
hold on;
plotHandle4 = plot(axesHandle4,i_real,Ventricle(1,1),'Marker','.','LineWidth',1,'Color',[0 1 0]);
xlabel('Time in seconds','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
ylabel('Aorta Pressure in mmHg','FontWeight','bold','FontSize',10,'Color',[1 1 0]);
title('Aorta Pressure','FontSize',15,'Color',[1 1 0]);

PropName1(1)={'YData'};
PropName1(2)={'Color'};
PropName1(3)={'XData'};
```

```
PropName2(1)={'YData'};
PropName2(2)={'Color'};
PropName2(3)={'XData'};
PropVal1(1,2)={[0 1 0]};
PropVal1(2,2)={[0 1 0]};
PropVal2(1,2)={[0 1 0]};
PropVal2(2,2)={[0 1 0]};

% start to collect data and plot the real-time waveform
for i = 2:(timeout_used    * sample_rate)
    fprintf(fid, '%c\r','s');
    pause(0.001);
    f_test = fscanf(fid,'%s');
    if ((~isempty(f_test)) && (f_test(1) == 'H'))
        i_real = i_real + 1;
        H = find(f_test == 'H');
        L = find(f_test == 'L');
        V = find(f_test == 'V');
        A = find(f_test == 'A');
        U = find(f_test == 'U');
        High_tank(i_real,1) = str2double(f_test((H + 1):(L - 1)))*scaler-388.2081;
        Low_tank(i_real,1) = str2double(f_test((L + 1):(V - 1)))*scaler-388.2081;
        Ventricle(i_real,1) = str2double(f_test((V + 1):(A - 1)))*scaler-388.2081;
        Aorta(i_real,1) = str2double(f_test((A + 1):(U - 1)))*scaler-388.2081;
        PumpSignal(i_real,1) = str2double(f_test((U + 1):(length(f_test) - 1)))*200;

        PropVal1(1,1)={High_tank(1:i_real)};
        PropVal1(1,3)={[1:i_real] / sample_rate};
        PropVal1(2,1)={PumpSignal(1:i_real)};
        PropVal1(2,3)={[1:i_real] / sample_rate};
        set(plotHandle1,PropName1,PropVal1);
        set(plotHandle2,'YData',Low_tank(1:i_real),'XData',[1:i_real] / sample_rate);

        PropVal2(1,1)={Low_tank(1:i_real)};
        PropVal2(1,3)={[1:i_real] / sample_rate};
        PropVal2(2,1)={PumpSignal(1:i_real)};
        PropVal2(2,3)={[1:i_real]/ sample_rate};
        set(plotHandle2,PropName2,PropVal2);

        set(plotHandle3,'YData',Ventricle(1:i_real),'XData',[1:i_real] / sample_rate);
        set(plotHandle4,'YData',Aorta(1:i_real),'XData',[1:i_real] / sample_rate);
    end
end
```

```
timelength = timeout_used / 60;
% savefile is the name of the saved file
savefile = sprintf('%d_%2d_%2d_%2d_%2d_%d',
year(now),month(now),day(now),hour(now),minute(now),timelength);
cprintf(-[1,0,1],'\n\rThe format of the name of the saved file is
"Year_Month_Day_Hour_Minute_Timelength"\n\r"');
% save the four vectors to a mat file
save(savefile, 'High_tank', 'Low_tank', 'Ventricle', 'Aorta');
%clear all the internal variables
clear f f1 H L A V over timelength timeout_used send_packet t_Average;
clear figureHandle1 figureHandle2 figureHandle3 figureHandle4;
clear plotHandle1 plotHandle2 plotHandle3 plotHandle4;
clear axesHandle1 axesHandle2 axesHandle3 axesHandle4;
clear i i_real check check_flag s savefile timeout f_test;
clear Square_current Square_used Square_location scaler;
clear Bias_used Gain_total P_diff_used PropName1 PropName2 PropVal1 PropVal2
clear R_Calib R_used U a_Transducer b_Transducer dP_MA dV_MA R_Use delta_used
% close the serial port
fclose(fid);
delete(fid);
clear fid
```