DESIGN AND DEVELOPMENT OF A CONTROL SYSTEM FOR NANOFIBER ELECTROSPINNING

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Abstract

This paper describes the development of a control hardware and software for a nano-fiber electro-spinning system. The hardware consists of motor driver boards, a high DC voltage board, and a main control board. The user interface software on PC is developed using Visual Studio C # 2010 express edition. The motor driver boards are controlled by an ATmega8 microcontroller IC, while the main board is controlled by an ATmega 128 microcontroller IC. Communication between the main board and the motor driver boards uses the inter integrated circuit (I2C), while communication between PC and the main board uses a serial communication at a baud rate of 9,600 bps. The high DC voltage generator is designed to have an output of 0-25 kV. High DC voltage output is configurable by giving a combination of low logic and high impedance into a six bit input. The result show that maximum output of high DC voltage is 25.025 kV with formula of curve is $y = 1x - 0.0244$ with $R2 = 0.9998$ and PC software interface can work very well. Polymer flow rate can be configured from PC interface software via I2C connected to the main board. The flow rate y follows the RPM setting x, according to the formula $y = 0.954x - 0.0099$ with $R2 = 1$. The results of scanning electron microscope (SEM) for morphology analysis of PVDF copolymer composite nano-fiber shows that the average diameter of the resulted fiber is 136.43 nm, when output high DC voltage is set to 15 kV and speed of syringe pump is set to 5 RPM.

Keywords: electrospinning, high DC voltage, I2C, motor driver, microcontroller, PC interface software.

I. INTRODUCTION

Polymer nanofiber can be applied in several areas such as biomedical, textile industry, filtration, and others [1-3]. One technique to make nanofibers is electrospinning. Electrospinning technology is chosen because it has several advantages such as ease of use, adaptability, and the ability to fabricate fibers with diameters on the nanometer size scale. The principle of electrospinning is giving high DC voltage source to form a polymer solution jet and arrested at the collector [4, 5].

A typical electrospinning setup consists of a capillary through which the liquid to be electrospun is forced, a high voltage source with positive or negative polarity, which injects charge into the liquid, and a grounded collector (Figure 1) [6]. Control system for nanofiber electrospinning is developed to control and to monitor electrospinning system by PC. The main parts of electrospinning system are High DC voltage and motor driver for syringe pump. High DC voltage controller is designed to control and to monitor the output voltage by microcontroller. Motor driver is designed to drive stepper motor with four phase and maximum current of 1 A. The inter integrated circuit (I2C) is used for communication between main board and motor drivers, while USB to serial protocol is used for communication between main board and PC software. I2C allows an ATMega128 microcontroller IC to be connected to up to 128 motor driver's board with different address [7].

This paper discusses the development of control system for electrospinning nanofiber based on interface software installed on a PC and microcontroller IC.

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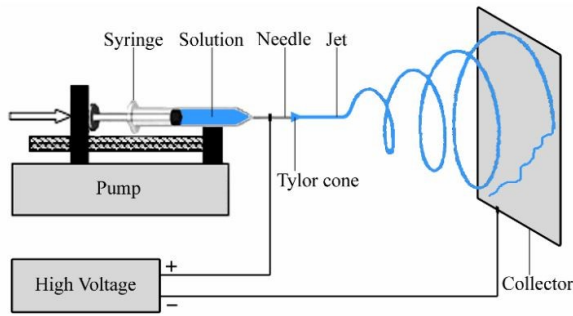E-mail: daysdk63@gmail.com
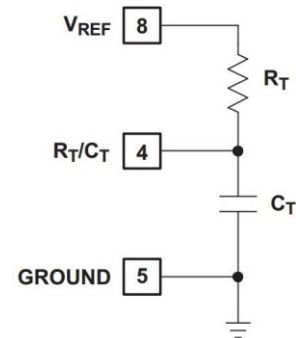
Figure 1. Electrospinning system setup [6]

Figure 3. Oscilator using UC3842 IC [9]

II. DESIGN

A. System Architecture

The system consists of electronic boards and software installed on a PC. The electronic boards are a main board, a high DC voltage board, and some motor driver boards. The main board is controlled by ATmega128 microcontroller, while the motor driver boards are controlled by ATmega8. Communication between the main board and the motor drivers uses I2C protocol, while the main board communicates with PC using a USB to serial converter.

The main board is configured as master and motor driver are configured as slave. The number of motor drivers that can be connected to this I2C bus is 128 with different slave addresses [7]. Microcontroller ATmega128 IC in the main board has function to extract data from PC and then send it to motor driver boards to control stepper motors, like speed, on/off and direction. Another function of the ATmega128 is to regulate and monitor the output voltage of the high DC voltage.

PC software interface is also equipped with the ability to monitor the movement of the syringe pump using a webcam and have a time schedule facility to configure output voltage of the DC high voltage, the speed of stepper motor, also the system start and stop. Block diagram of the system is shown in Figure 2.

B. High DC voltage

High DC voltage generator is designed to produce output in the range of 0-25 kV. The main component of high DC voltage is UC3842 IC and flyback transformer. The principle of high DC voltage is giving signal with certain frequency and duty cycle in order to drive the flyback transformer to generate output of 0-25 kV. The operating frequency of the flyback transformer is from 1.5 kHz to 82.5 kHz [8]. The operating frequency generated by UC3842 IC depends on the CT and RT values which are connected to pin 8, 4, and 5 as shown in Figure 3 [9]. Operating frequency about 36 kHz is to be used in this design. This value is the optimum frequency of the flyback transformer used in this design. The output frequency can be calculated by equation (1) [9].

$$for R_T > 5K$$

$$fout = \frac{1.72}{C_T * R_T} \tag{1}$$

To obtain f_{out} = 36 kHz, R_T = 10 K and C_T = 4.7 nF can be used.
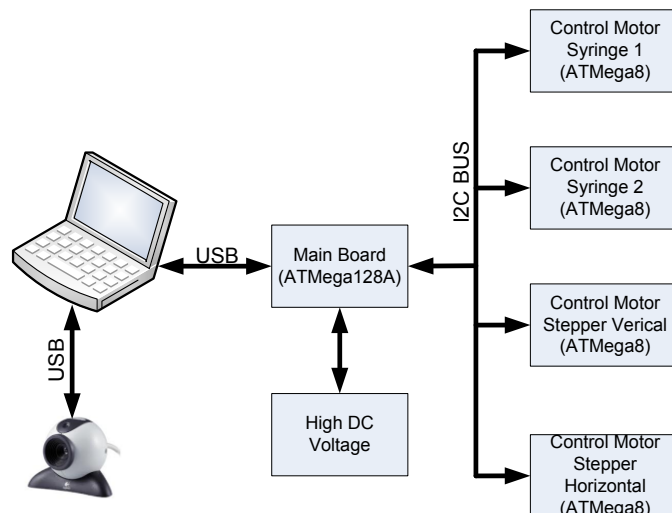

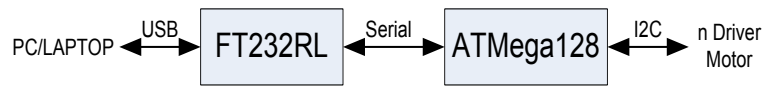Figure 2. Electrospinning system block diagram

Figure 4. Communication system of microcontroller ATMega128 IC

C. Main board

The main board extracts data from PC and then sends it to driver motor board to control the speed of stepper motor. It also controls and monitors the output voltage of the high DC voltage generator. The main component of main board is microcontroller ATMega128 IC. Microcontroller ATMega128 IC has some feature such as 128 kByte of flash program, 4 kByte EEPROM, 4 kByte internal SRAM, about 48 I/O pin, 16 bit Timer/Counters, 6 PWM channels, 8 channel 10 bit ADC, two wire serial interface (TWI/I2C), dual programmable serial USART and so on [7].

Communication between microcontroller ATMega128 IC and PC uses serial port. For simple operation reason, the FT232RL IC used in this design as converter from serial to USB port PC. Serial communication is set to a baud rate of 9,600 bps, one stop bit, and none parity. After receiving data from the PC, microcontroller ATmega128 IC will extract motor data and then send it to the motor driver or extract high voltage setting and set the high DC voltage generator output.

Communication between microcontroller ATMega128 IC and motor driver board uses I2C protocol, where ATMega128 is set as a master and motor driver boards are set as slaves. The communication system of microcontroller ATMega128 is shown in Figure 4.

D. Motor Driver Board

The motor drivers control motor speed, direction and on/off state. The main component of the motor driver boards are microcontroller ATMega8 IC and UCN5804B IC. The microcontroller ATMega8 has some feature such as 8 kByte of flash programming, 512 of kByte EEPROM, 1 kByte of internal SRAM, three PWM Channel, timer/counter, two wire serial interfaces (TWI/i2C) and so on. UCN5804B IC is a BiMOS II unipolar stepper motor translator/driver which has the ability to control and drive a four phase unipolar stepper motor with continuous output current ratings to 1.25 A per phase (1.5 A startup) and 35 V [10]. The motor speed can be adjusted with giving signal with different frequency for different speed on pin 11 of UCN5804B IC. On/off motor can be done by giving logic low/high on pin 15 while the direction of motor on pin 14 of UCN5804B IC.

The function of microcontroller ATMega8 IC on the motor driver board are to communicate with the main board, to generate frequency to control motor speed, and to give low/high logic to control on/off or direction of the motor. Microcontroller ATMega8 uses timer/counter that was operated in Clear Timer on Compare Match (CTC) mode to generate frequency. Motor driver circuit uses UCN5804B IC is shown in Figure 5.
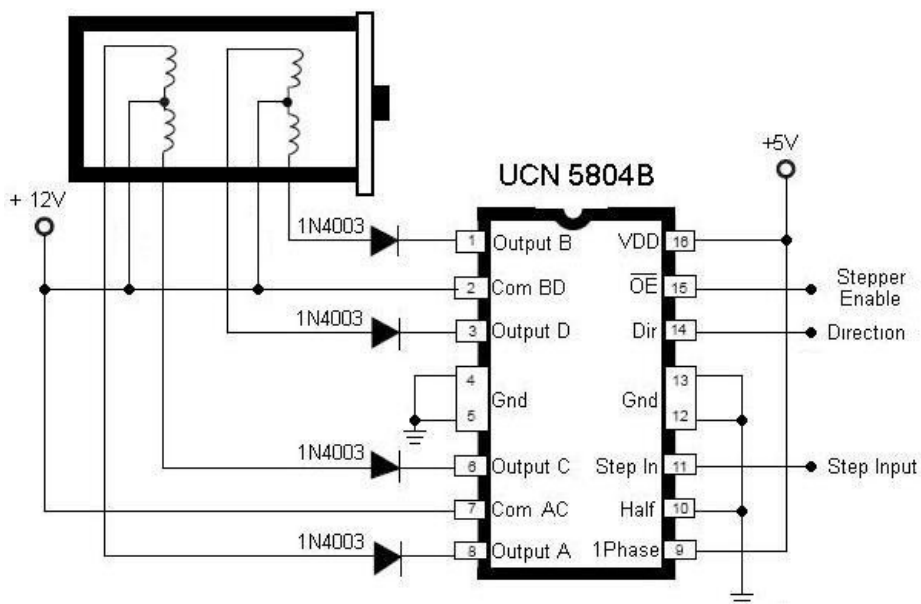

Figure 5. Motor driver uses UCN5804B IC [10]

E. PC Software Interface

PC interface software serves as a graphical user interface (GUI) to control the electrospinning system through computer. Visual C# 2010 Express Edition used to develop this GUI. A packet data sent from this GUI to main board through USB port to control motor speed and high DC voltage output. Format packet data is shown in Figure 6.

Where:

- Header → 1 Byte, contain "@" character
- ID → 1 Byte data, contain ID address of driver motor board
- Function → 1 Byte, describes function of motor control like speed, direction, on/off or function of regulating high DC voltage
- Data → n Byte data
- Tail → 1 Byte, contain "#" character

III. IMPLEMENTATION

A. High DC voltage

High DC voltage output is configurable by setting a combination of low logic and high impedance into a six bit input. The combination input and output high DC voltage is shown in Table 1. 0 represents 0 V and 1 represents high impedance. High DC voltage input circuit is shown in Figure 7. The input of high DC voltage is connected to port C.0 to port C.5 of the

Table 1.
Combinations of input and output

Combinations (MSB-LSB)	Output Voltage (kV)
000000	0
000001	1
000010	2
000011	3
000100	4
000101	5
000110	6
000111	7
001000	8
001001	9
001010	10
001011	11
001100	12
001110	13
001111	14
010000	15
010001	16
010010	17
010011	18
010100	19
010101	20
010110	21
010111	22
011000	23
011001	24
011010	25

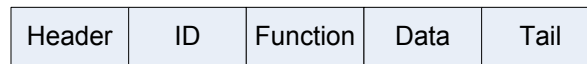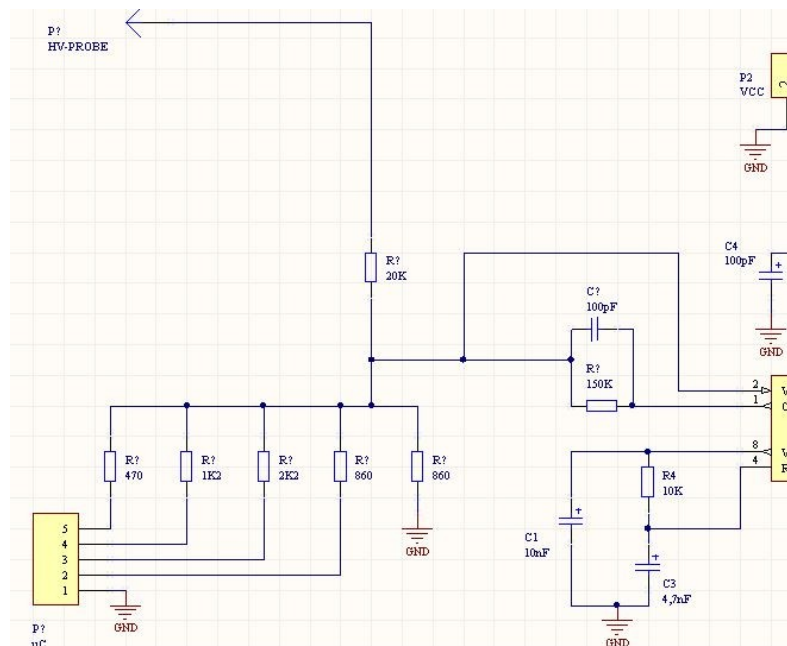| Header	ID	Function	Data	Tail

Figure 6. Serial data packet format

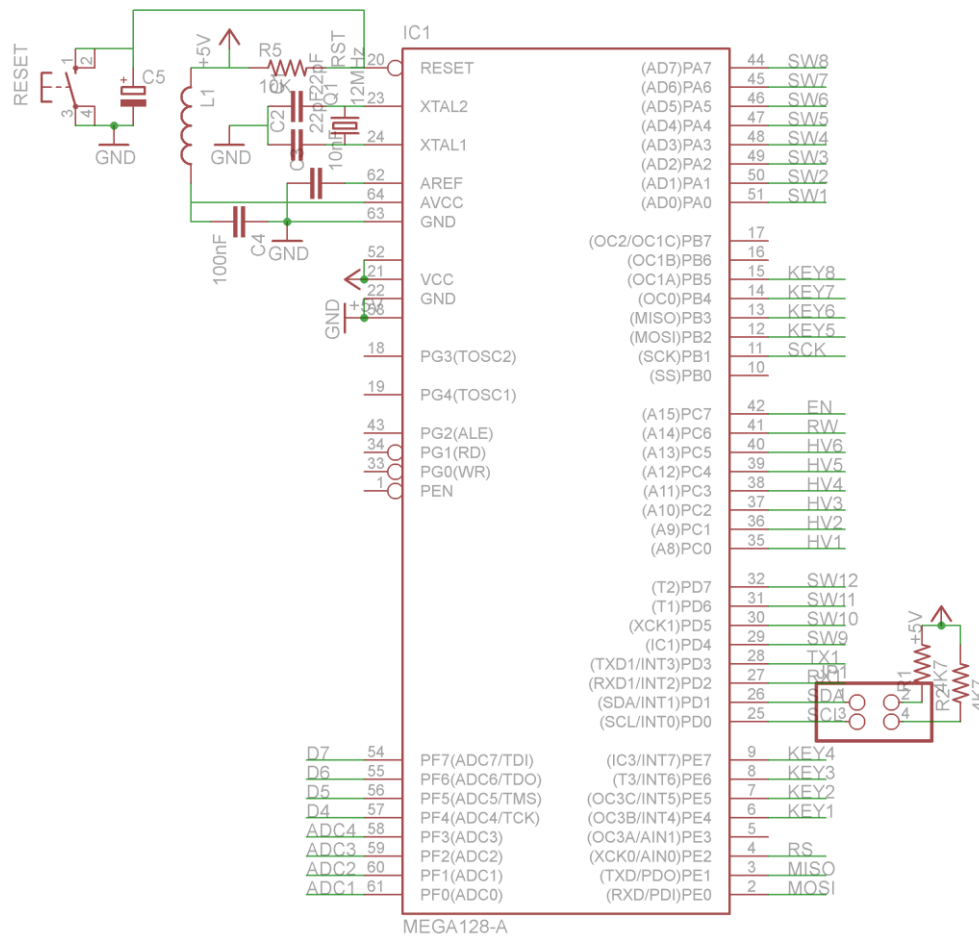Figure 7. High DC voltage input circuit

Figure 8. Minimum system of main board

ATMega128 microcontroller IC.

B. Main Board

Microcontroller ATMega128 IC has enough I/O to connect with other peripheral in this system such as Liquid Crystal Display (LCD), keypad, max232 IC, FT232RL IC and the other. Minimum system of the main board is shown in Figure 8. Port A.0-7 is connected to limit switches of syringe pump, horizontal, and vertical motors. Port B.2-5 are connected to keypad while Port C.0-5 are connected to high DC voltage control input I2C bus using port D.0 as clock signal and port D.1 as data.

Serial data communication uses port D.2 as receiver and port D.3 as transmitter. LCD control input is connected to port F.4-7. Port F.0-3 is used as ADC for monitor of high DC voltage output. The program flowchart implemented in the ATMega128 is shown in Figure 9.

C. Motor Driver

The motor drivers consist of microcontroller ATMega8 IC and UC5804B IC. Communication between ATMega8 and ATMega128 microcontroller ICs uses I2C protocol. In this
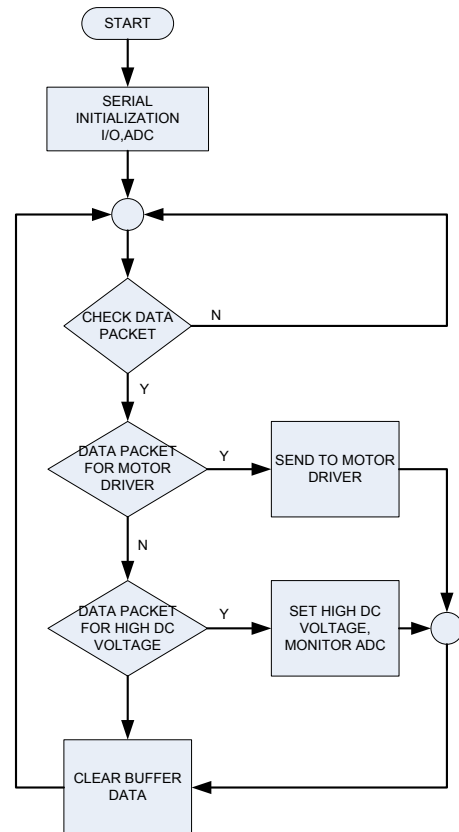

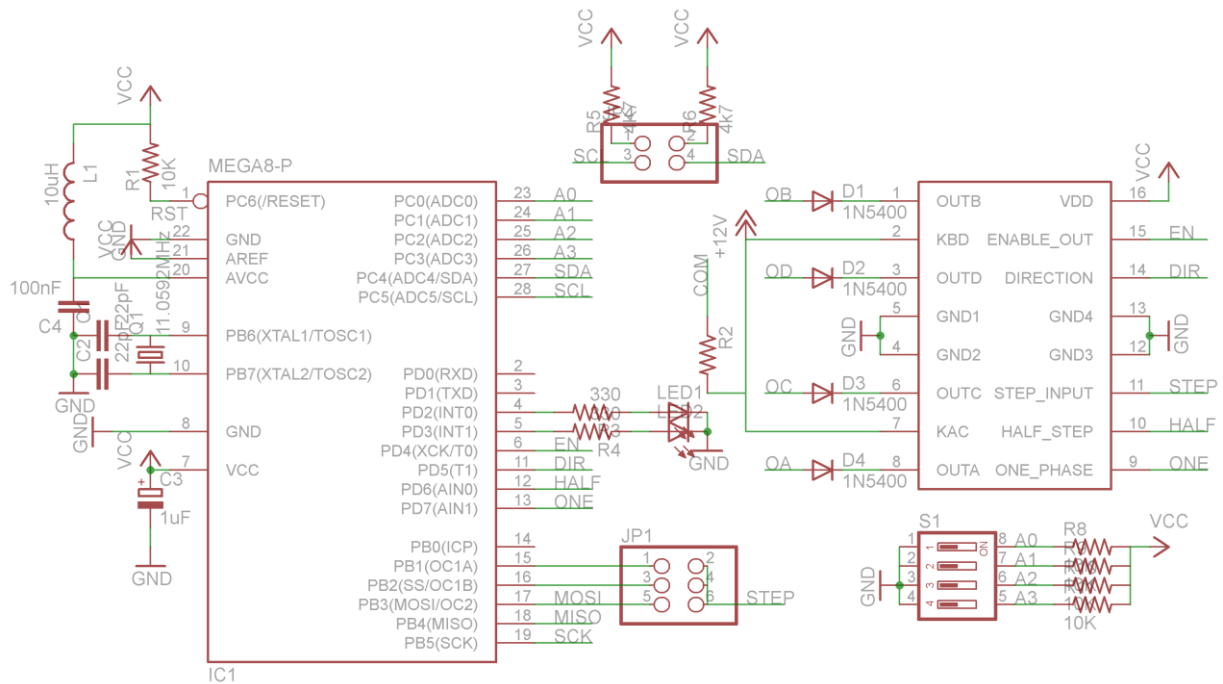Figure 9. Program flowchart of ATMega128

Figure 10. Minimum system of motor driver board

system, ATMega8 are configured as slaves. The slaves addresses configured by giving logical low or high on port C.0 – port C.3. Port D.4 is connected to pin 15 of UCN5804 IC which is used to control of on/off motor. Port D.5 is connected to pin 14 of UCN5804B IC which is used to control the motor direction. Port B.1 is connected to pin 11 of UCN5804B IC which is used to control motor speed.

Port B.1 is configured as output of timer/counter 1 A which is configured in CTC mode. Port C.4 is used as data signal of I2C while port C.5 is used as clock signal. The minimum system of motor driver board is shown in Figure 10.

ATMega8 microcontroller ICs will extract data from the main board before controlling motors. It is done by comparing address data from main board with ATMega8 own address data. For monitoring the control mode of ATMega8 microcontroller IC, two LED, which connected to port D.2 and port D.3, are used.

D.   PC Software Interface

Communication between PC and the main board uses serial port. Interface software will check all active serial ports and then show them to combo box dialog. The program syntax is shown in listing program 1.

```csharp
privatevoid Form1_Shown(object sender,
EventArgs e)
{ // Get Com port available
comboBox9.Items.Clear();
foreach (string s inSerialPort.GetPortNames())
{ comboBox9.Items.Add(s);}
 comboBox9.SelectedIndex = 0;}
```

Serial data communication is set to a baud rate of 9,600 bps, with 8 data bits, 1 stop bit, no parity, and no handshake. Transfer data rate can be increased by changing the baud rate to a higher value than the default, such as 115,200 bps. The same serial port setting must be used by ATMega128. ATMega128 IC will not receive valid data if serial port settings are not the same. The program syntax is shown in listing program 2.

```csharp
serialPort2.PortName = comboBox9.Text;
//get id comport
Com = comboBox9.SelectedIndex;
serialPort2.BaudRate =
int.Parse("9600");
serialPort2.DataBits = int.Parse("8");
serialPort2.StopBits =
(StopBits)Enum.Parse(typeof(StopBits),
"One");
serialPort2.Parity =
(Parity)Enum.Parse(typeof(Parity),
"None"); serialPort2.Handshake =
(Handshake)Enum.Parse(typeof(Handshake),
"None"); serialPort2.Open();
```
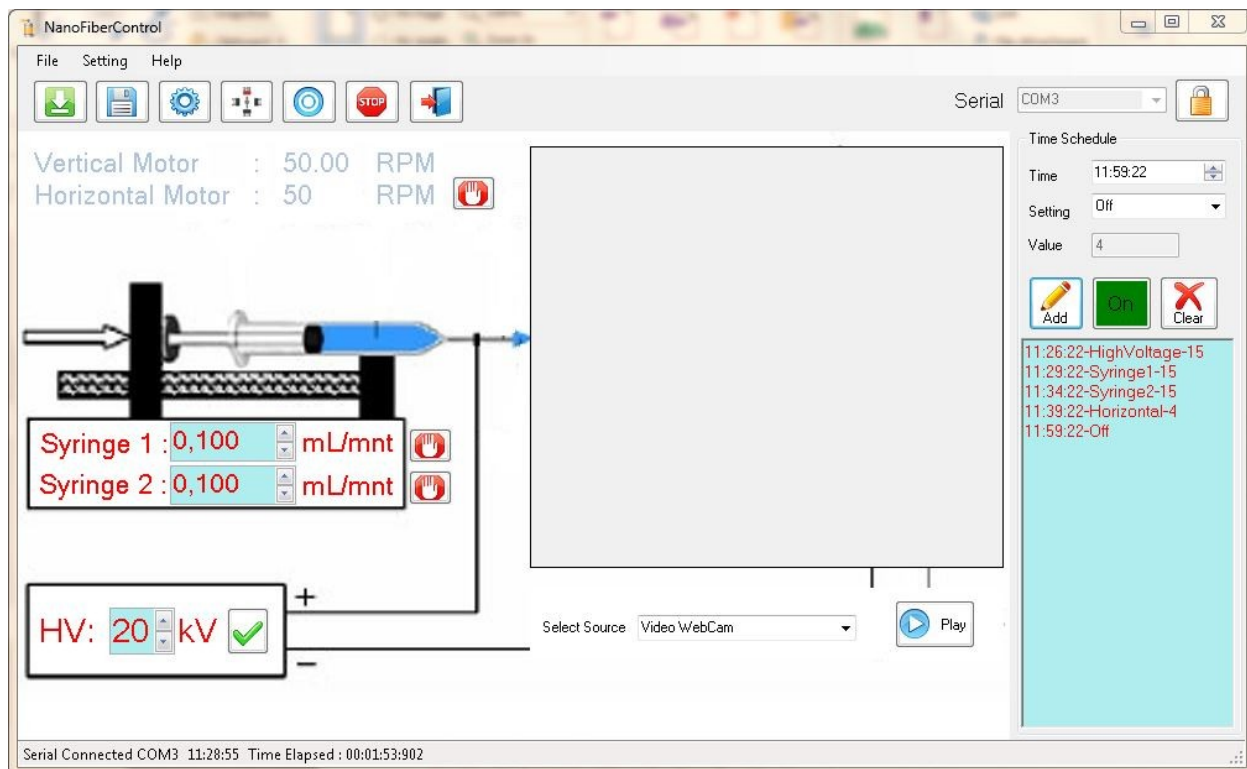
Figure 11. Display of PC software interface

A control command is sent to the main board in the form of data packet. Data packet has header, id, function, data and tail as describe in previous section. The program syntax is shown in listing program 3.

```
publicvoid speedM2()
{
char function = 'a';
//send to serial data
if (main_form.serialPort2.IsOpen){
doublenilai =
Convert.ToDouble(numericUpDown2.Value) *
speed_kali;
main_form.serialPort2.Write("@B" + function +
Convert.ToString(nilai) + "#");
speed2 =
Convert.ToString(numericUpDown2.Value);}}
```

User interface consists of a start/stop button, a motor speed control form, a high DC voltage button, a video webcam form, and an automatic setting form. Figure 11 show the display of the user interface.

IV. EXPERIMENT AND ANALYSIS

A. High DC Voltage

Testing for high DC voltage were conducted by connecting port C.0-5 of the microcontroller to the input of the high DC voltage board and connecting ADC channel0 (portF.0) of microcontroller ATMega128 IC to the high DC voltage output via a voltage divider. ADC readings show on LCD. Electronics configuration is shown in Figure 12. High DC voltage output is configured from PC interface software by clicking the high DC voltage button. Measurements of high DC voltage output are taken three times and the results are shown in Table 2. The high DC voltage output curves can
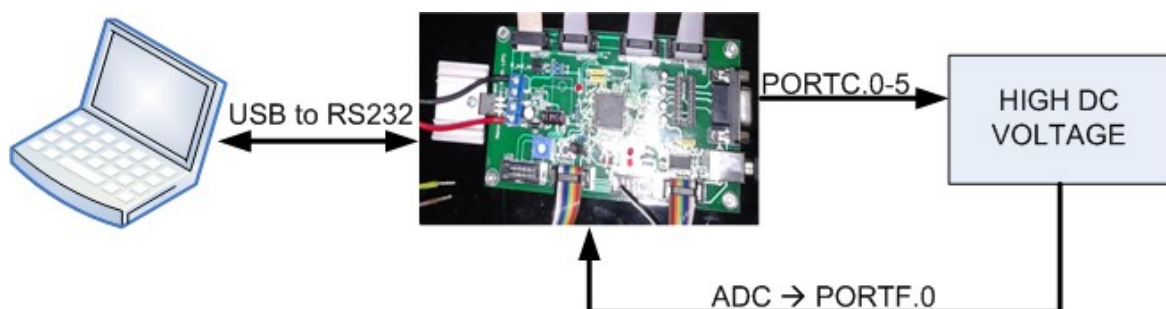

Figure 12. Electronics setup for high DC voltage test

Table 2.
ADC reading on high DC voltage output

Setting (kV)	ADC 1 (kV)	ADC 2 (kV)	ADC 3 (kV)
1,00	1,15	1,15	1,19
2,00	2,29	2,32	2,31
3,00	2,95	2,98	2,98
4,00	3,93	3,98	3,97
5,00	4,91	4,96	4,96
6,00	5,92	5,96	5,96
7,00	6,90	6,94	6,94
8,00	7,95	7,98	7,98
9,00	8,94	8,97	8,97
10,00	9,95	9,99	10,00
11,00	10,91	10,93	10,97
12,00	11,93	11,98	11,97
13,00	12,94	12,97	12,97
14,00	13,92	13,97	13,99
15,00	14,84	14,94	14,92
16,00	15,96	16,05	16,06
17,00	16,94	17,06	17,05
18,00	17,91	18,05	18,03
19,00	19,05	19,12	19,14
20,00	19,92	20,01	20,01
21,00	21,06	21,19	21,15
22,00	21,97	22,02	22,04
23,00	23,10	23,17	23,19
24,00	24,12	24,23	24,25
25,00	24,99	25,04	25,05

Table 3.
Polymer flow rate (mL/minute)

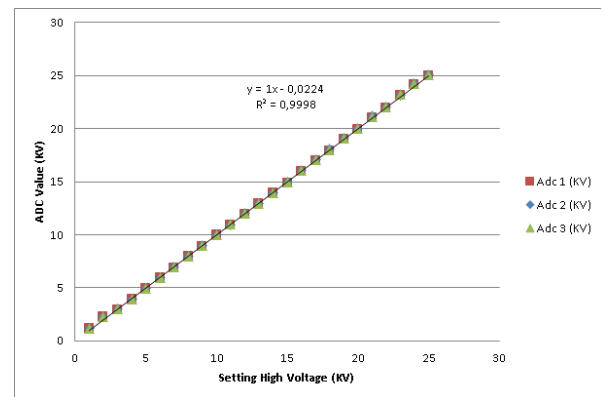| Motor Speed (RPM)	M1 (mL/minute)	M2 (mL/minute)	M3 (mL/minute)
1,00	0,9466	0.9460	0.9466
2,00	1.8986	1.8966	1.8962
3,00	2.8426	2.8439	2.8420
4,00	3.8128	3.8220	3.8138
5,00	4.7594	4.7553	4.7576

Figure 13. High DC voltage output curve

interface software by clicking the motor speed control button. Measurements are taken three times and the result is shown in Table 3.

The polymer flow rate curves are shown in Figure 15. The polymer flow rate (mL/minute) y follows the motor speed (RPM) setting x, according to the formula $y = 0.954x – 0.0099$ and $R^2 = 1$. This result shows that motor driver work as expected.

C.   SEM Analysis

A scanning electron microscope (SEM) is used to analyze the nanofibers produced in this experiment. The results of SEM for morphology analysis of PVDF copolymer composite nanofiber is shown in Figure 16. The average diameter of the fibers is 136.43 nm, when the high DC voltage is set to 15 kV and the syringe pump speed is set to 5 RPM. There are some

be seen in Figure 13. The output y follow the voltage setting x, according to the formula $y = 1x – 0.0224$ and $R^2 = 0.9998$. This result shows that high DC voltage generator and PC interface software work as expected.

B.   Polymer Flow Rate

The control for polymer flow rate is done by configuring speed of motor stepper. Testing for relation between motor speed and polymer flow rate were conducted by connecting motor driver to main board via I2C, the syringe with 10 mL volume, a timer to show minute as in Figure 14. Polymer flow rate is configured from PC
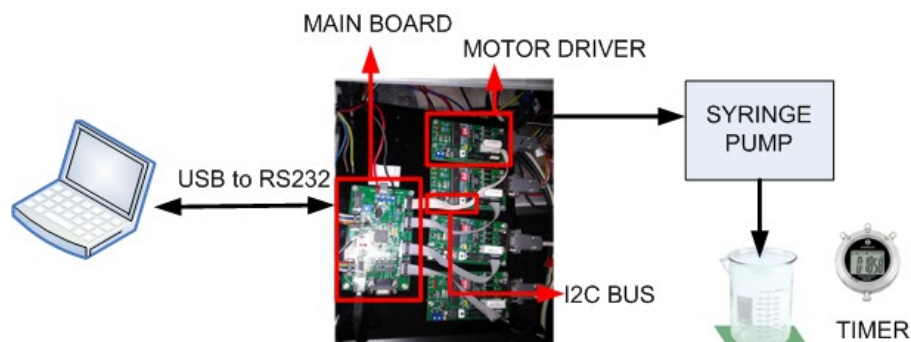

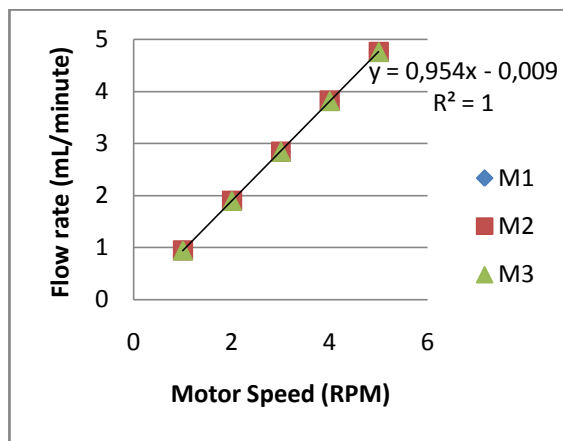Figure 14. Testing for polymer flow rate setup
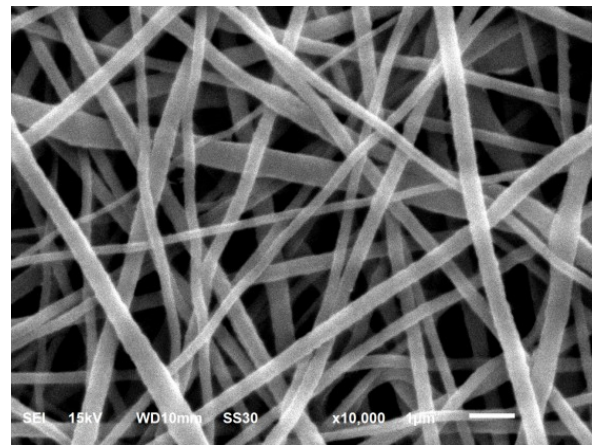
Figure 15. Flow rate curve

Figure 16. The result of SEM for PVDF copolymer composite and 15 kV high DC voltage

Table 4.
Effects of electrospinning parameters on fiber morphology[4]

Parameter	Effect on fiber morphology
Applied voltage ↑	Fiber diameter ↓ initially, then ↑(not monotonic)
Flow rate ↑	Fiber diameter ↑ (beaded morphologies occur if the flow rate is too high)
Distance between capillary and collector ↑	Fiber diameter ↓ (beaded morphologies occur if the distance between the capillary and collector is too short)
Polymer concentration (viscosity) ↑	Fiber diameter ↑ (within optimal range)
Solution conductivity ↑	Fiber diameter ↓ (broad diameter distribution)
Solvent volatility ↑	Fibers exhibit micro texture (pores on their surfaces, which increase surface area)

processing parameters that can greatly affect the fiber formation and structure on electrospinning system. These parameters are high DC voltage, polymer flow rate, capillary-collector distance, polymer concentration, solution conductivity, and solvent volatility [4, 11-15]. A number of general relationships between processing parameters and fiber morphology are shown in Table 4 [4].

V. CONCLUSIONS

PC interface software works as expected. High DC voltage output can be configured from PC interface software via serial communication. The maximum output of high DC voltage is 25.025 kV. The output y follows the voltage setting x, according to the formula $y = 1x - 0.0224$ and $R^2 = 0.9998$. Polymer flow rate can be configured from PC interface software via I2C connected to the main board. The flow rate y follows the RPM setting x, according to the formula $y = 0.954x - 0.0099$ and $R^2 = 1$. The results of scanning electron microscope (SEM) for morphology analysis of PVDF copolymer composite nanofibers show that average diameter of produced fibers is 136.43 nm, when high DC voltage is set to 15 kV and syringe pump speed is set to 5 RPM.

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