Design of portable 3-axis filament winding machine with inexpensive control system

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ABSTRACT

Filament winding technology is one of the fundamental fabrication methods in composite material fields, which has a high degree of automation. It is the process in which continuous strands or filament of fibres is wound on the mandrel, which is suitable for high-pressure vessels, pipes, shaft and ducts. The present filament winding machines have existed in enterprises or factories, which are high costs, heavy, complex control system and machine structure. The objective of this study is to design a 3-axis filament winding machine, which has portable, lightweight, low costs, high efficient and inexpensive control system features compared to the previous and present machine. The control system relates hardware section and software section, which can meet three axes movement principle. The 3-axis prototype filament winding machine has also been developed. Arduino Uno and CNC v1 shield module are applied as hardware section. Universal G-Code Sender (UGS) and Grbl codes are adopted as software section. In conclusion, a 3-axis portable, lightweight and low-cost filament winding machine have been successfully developed, which can fabricate filament wound carbon/epoxy tubes with a proper inexpensive control system.

Keywords: 3-axis filament winding machine; arduino uno; UGS; Grbl.

INTRODUCTION

Filament winding process is an expanding composite manufacturing process based on the introduction of advanced lightweight mass production items, which has increased the performance requirements of this manufacturing process [1]. Fibre reinforced composite materials have widely used in various industries, from relatively simple civil applications [2]. To meet the technology requirements, many composite material companies have improved the performance of cost-effective, high-grade quality,

recyclable products. In short, the composite material has excellent corrosion resistance, good resistance to temperature extremes compared to traditional material [3, 4]. Composite materials have been generally used in many fields including aerospace, chemical, automotive, civil engineering, military, motorsports and offshore industries [5-7].The composite material is a material system composed of a mixture or combination of two or more micro or macro-constituents that differ in form and chemical composition, which are essentially insoluble in each other [8]. Normally, reinforced-plastic composite materials are made with synthetic fibres such as glass, carbon and aramid fibres, since these materials have a high strength to weight ratio, corrosion resistance and low density, fibre-reinforce plastic is generally used in construction, automotive, marine and aerospace industries [9-11].

In recent twenty years technique development, many researchers have focused on the development and improvement of composite material structure and mechanical properties, more practically-oriented mandrel design and the influence of manufacturing progressive failure of filament wound cylindrical pressure vessels [12-14]. Some researchers have concentrated on dry winding method, winding tension experiment and some other factors, which affect filament wound composite products about mechanical properties [15-17]. Filament wound components are produced by a filament winding machine where resin-impregnated fibres pass through a pay-out eye and are wound on a rotating mandrel. The manufacture of filament wound composite products by filament winding consists of many parts, the main parts of filament winding machine are mandrel, machine structure and control system [18]. Figure 1 shows the classic manufacturing flowchart of filament wound structure.
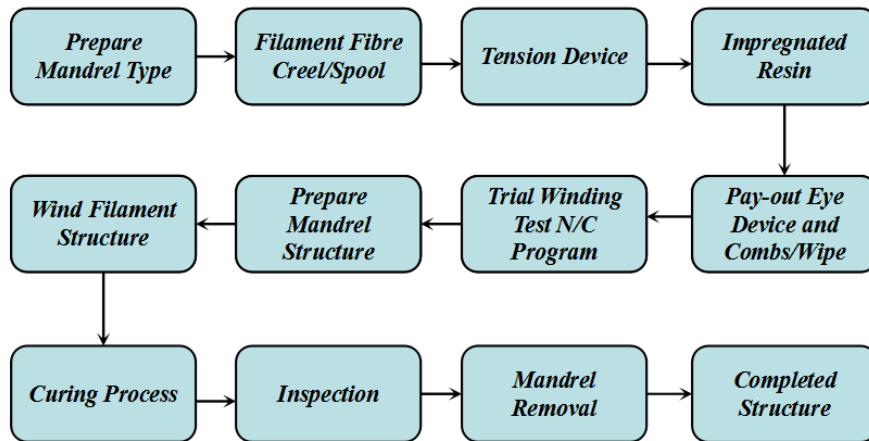

Figure 1: Typical manufacturing flow chart for filament wound structure [18]

Filament winding technique and filament wound composite product completely depend on filament winding machine types and axes. Multi-axial filament winding machine is the adequate processing technology to fabricate composite products at industrial level [19-21]. The maximum available number of the axis on filament winder is seven, which can have the highest motion axes [22]. Filament winding

machine with 2 axes is a classical prototype filament winding machine, which can have mandrel rotation and carriage movements [23-25]. Filament winding with four axes movement is designed with related four axes filament winding machine structure [26]. Filament winding machine with more than four axes can be used for advanced composite applications, which can have 3 linear movement axes and 3 rotation axes [27]. New axes filament winding machine is properly designed to fabricate axisymmetric and non-axisymmetric parts [28-30]. For the development of computer software controlled filament winding machines with high axes, which can automatically apply the software to generate the winding pattern methods [31]. With the software control system and computer numerical control technique has been applied to the manufacturing sector, industrial robots have been employed to replace the traditional filament winding machine [32-34]. For industrial winding robots, some detailed knowledge of the robot work principle and the robot language use the RAPID language [35-37], which can meet the winding operation. There are many industrials to produce the winding robot with different methods and types in the industrial robot marketplace.

Based on previous and existing limitations, the main problem in filament winding process is that filament winding machine has high cost, heavy, complex control system and machine structure. The research gap is that Arduino Uno is selected to use in the portable filament winding machine with 3 axes. The aim of this study is to design a 3-axis filament winding machine with inexpensive control system on hardware and software sections. Figure 2 clearly shows research problem statement and objectives, which also can highlight machine structure and control system contributions in filament winding technique.
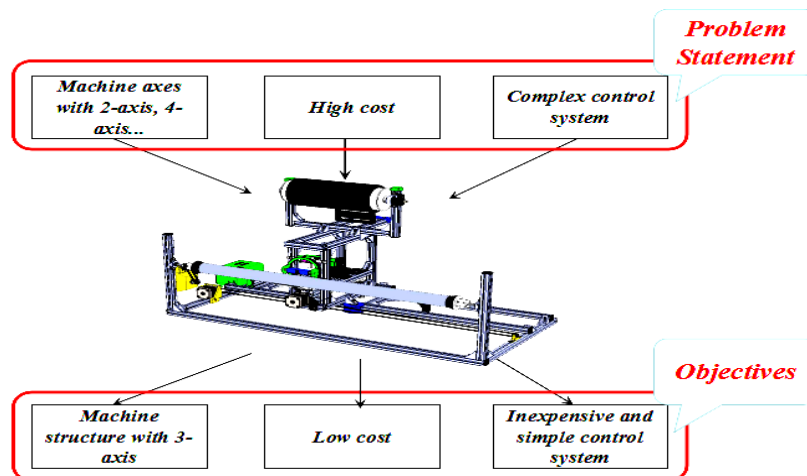

Figure 2: Previous problem and objectives

Filament Winding Methods and Patterns

There are two different methods to make it which is wet and prepreg winding. Wet winding, in which the fibres should be passed through a resin bath and wound on the rotating mandrel. Prepreg winding, in which the pre-impregnated fibre tows are

placed on the rotating mandrel, it should supply superb quality control, reproducibility of resin contents, bandwidth, and uniformity. These parameters can be well satisfied the filament winding process, which demonstrates the two basic winding patterns diagram in Figure 3.
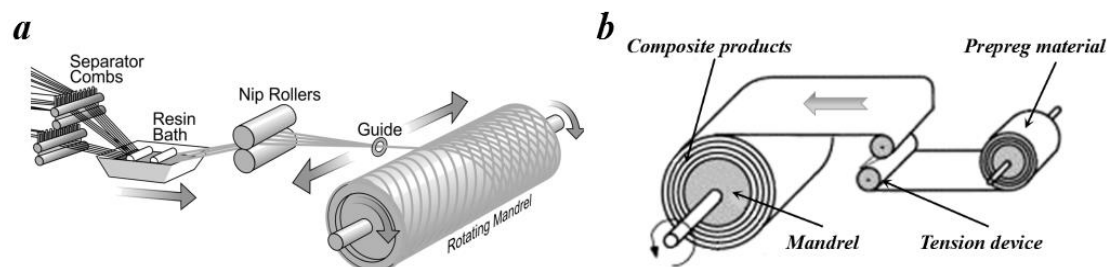

Figure 3: Basic winding pattern diagram; (a) wet winding method; (b) prepreg winding method [25]

Basically, three types of winding patterns: circumferential, helical, and polar winding. The three winding patterns diagram are shown in Figure 4. The circumferential winding is a high helical winding angle that approaches almost 90 degrees. In helical winding, mandrel rotates at a constant speed while the fibre feed carriage transverses back and forth at speed to generate the desired helical winding angle. In polar winding, fibres are wrapped from pole to pole, as the mandrel arm rotates around the longitudinal axis.
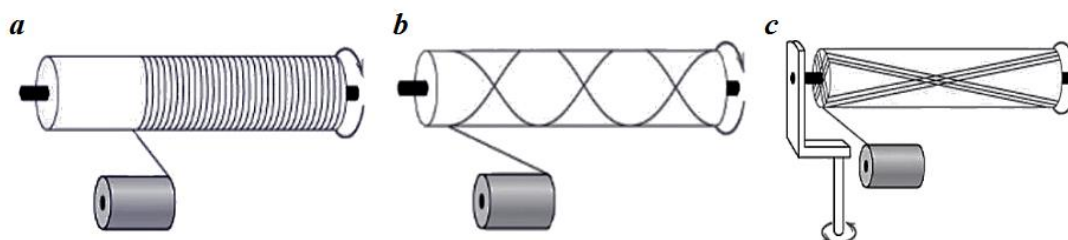

Figure 4: Schematic representation of three types of winding patterns; a) circumferential winding; b) helical winding; c) polar winding [20]

METHODOLOGY

Methodology section is provided with 3-axis filament winding machine design procedure, control system and filament wound composite products, which can have some related research results [38-40].

Methodology in this research paper can be briefly divided into three phases:

Phase 1: Literature review and purchase related components

> i. It is necessary to define problems and acquire the basic knowledge about filament winding technology, winding patterns.
> ii. Related components need to be purchased in this project such as 3 NEMA 17 stepper motors, Arduino Uno microcontroller, CNC shield v1 module, aluminum profile accessories etc.

Phase 2: Develop a 3-axis filament winding machine on prototype draft drawing

    i. It is difficult to start the preliminary design of the filament winding machine, the previous and existing filament winding machine prototype structure can be consulted from other researchers' findings [41-43].

    ii. Then main machine structure needs to define, which includes the rotation unit, the carriage unit and the control unit.

Phase 3: Design hardware and software sections in control system.

    i. Hardware section is to design winding process with related components, which can implement machine movement condition. Wiring connection diagrams are shown in details.

    ii. Software design is an essential section, which can send G-codes to hardware to control the machine movements. Universal G-Code Sender software can be successfully installed and performed.

DESIGN AND SCHEMATIC DIAGRAM

Schematic layout of a 3-axis filament winding machine can be divided into three main units: the rotation unit, the carriage unit and the control unit. These units are essential elements to develop the 3 axes filament winding machine, which can also refer to more than 3 axes filament winding machine [25-27].

The Rotation Unit

The rotation unit consists of a 690 mm length of the mandrel, which is held on the horizontal line by two mandrel holders, and a NEMA 17 stepper motor for y-axis rotation movement. Figure 5 illustrates the rotation unit front view. The hollow mandrel diameter is 38 mm, which is made of aluminum alloy material. It is totally adequate for stepper motor y to supply the mandrel rotation torque and speed. Inside the mandrel, an optical steel lever is designed to support the mandrel and the mandrel holders, which can fix on profile accessories.
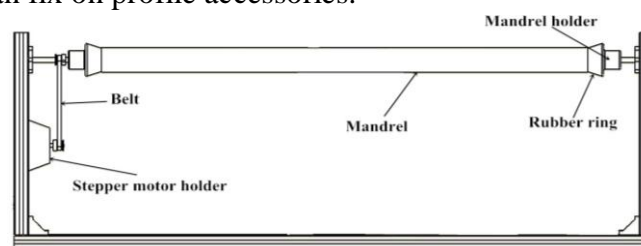

Figure 5: The rotation unit front view

The Carriage Unit

Figure 6 provides the carriage unit front view and side view. The carriage unit consists of ring steering gear, composite fibres, resin bath, two guide shafts, stepper motor z and stepper motor x with belts, which transfer the velocity by carriage belt holder in carriage basement. Ring Steering gear configuration looks like a ring, which can be properly controlled by stepper motor z when x movement direction is altered. Ring

steering gear can rotate a certain angle with the carriage moves back and forth. An optimum tension force can be applied in this process, which can be easily measured. It is necessary to generate tension force before resin bath when the composite fibres are well wetted to reduce the damage of composite fibre tow surface.
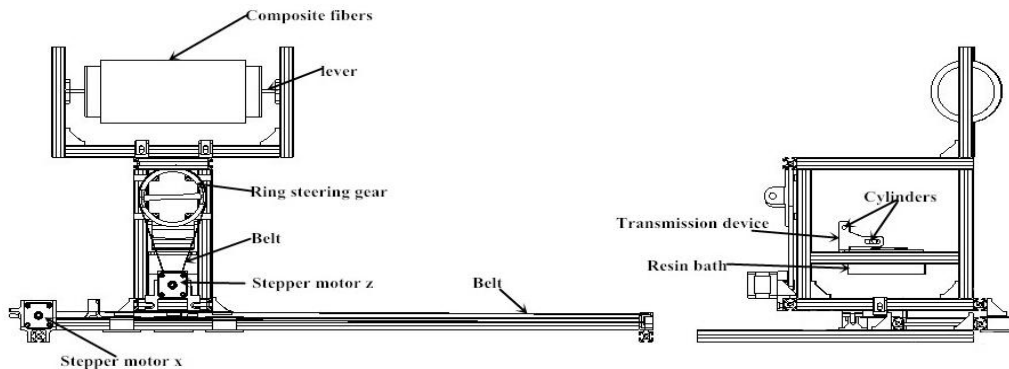

Figure 6: The carriage unit front and side view

The Control Unit

The control unit consists of an Arduino Uno microcontroller, a CNC shield module, a voltage regulator, a bluetooth module, a limit switch and a small fan. All components can be put in the control box. The control system wiring diagram is illustrated in Figure 7, which is shown more details in control box in Figure. The machine working principle is based on G-Code, which applies the CNC machine working principle to this 3-axis filament winding machine. Another control unit function is to control the winding process in order to get the proper winding sequence, which is difficult to implement manually. The limit switch position can define machine home position, which can design machine structure and product dimension size.

Control system   control unit
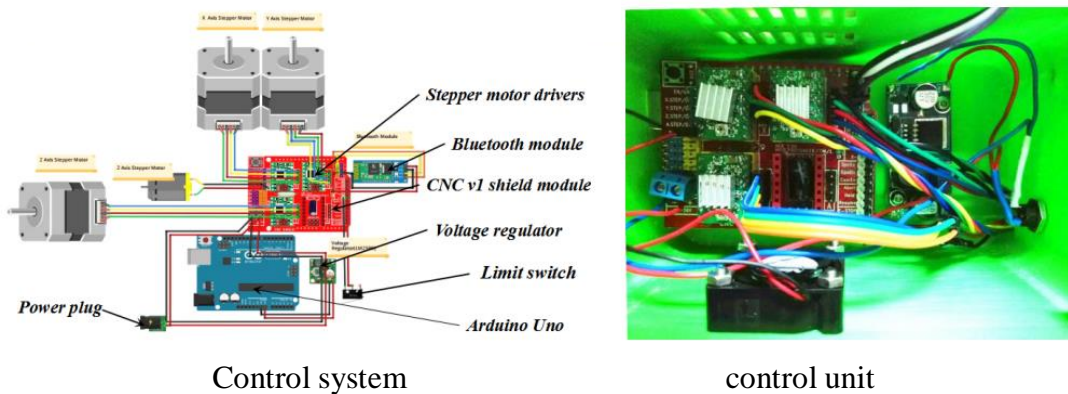
Figure 7: Control system diagram; control system wiring diagram and control unit in control box

Based on the above three units design principles, the prototype of the 3-axis filament winding machine has been assembled. Figure 8 exhibits the mechanical drawing of the 3-axis filament winding machine, where modification and position profile has been considered. On hardware inspection, it spends much time checking

the wire connection and other components connection. On software inspection, the software needs to be confirmed, which is the latest version and compatibility in a different computer system. Two different inspections are completely necessary, which can eliminate the errors in control system. The picture of machine object is given in Figure 9, which demonstrates a brief filament winding machine structure.
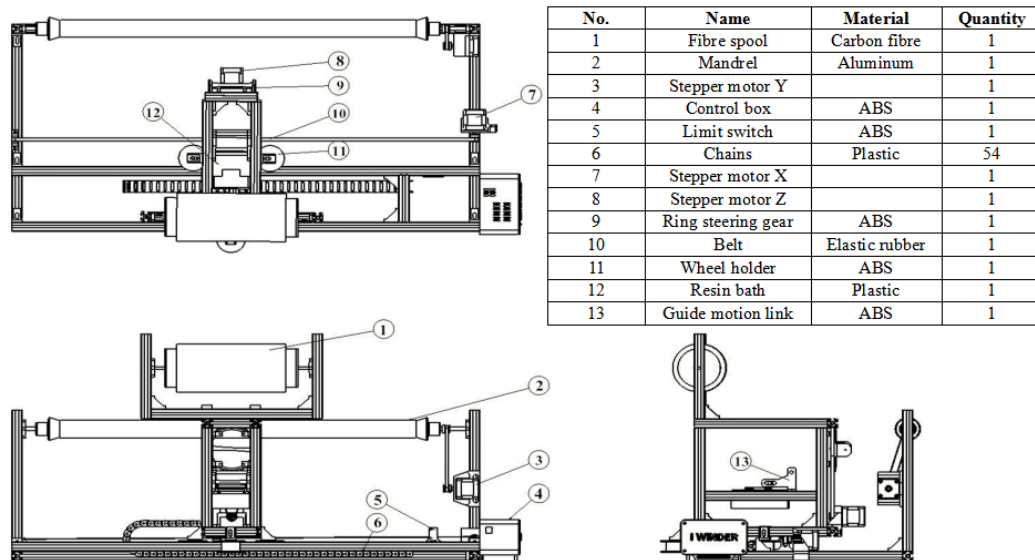
No.	Name	Material	Quantity
1	Fibre spool	Carbon fibre	1
2	Mandrel	Aluminum	1
3	Stepper motor Y		1
4	Control box	ABS	1
5	Limit switch	ABS	1
6	Chains	Plastic	54
7	Stepper motor X		1
8	Stepper motor Z		1
9	Ring steering gear	ABS	1
10	Belt	Elastic rubber	1
11	Wheel holder	ABS	1
12	Resin bath	Plastic	1
13	Guide motion link	ABS	1

Figure 8: The orthographic view of the 3-axis filament winding machine
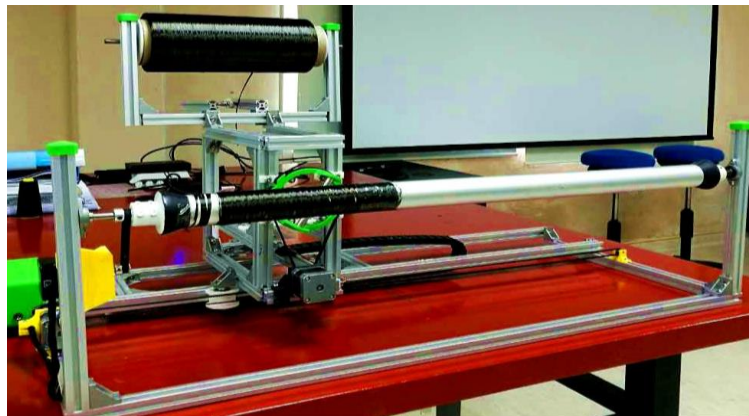
Figure 9: The 3-axis filament winding machine fabrication result

DESIGN INEXPENSIVE CONTROL SYSTEM

Arduino Uno is an open-source electronics platform based on easy-to-use hardware and software. The user can make board by sending a set of instructions codes to the microcontroller. Compared to other kinds of microcontrollers, Arduino Uno simplifies the process of working and fabrication process. Figure 10 presents the brief advantages of Arduino Uno microcontroller

The CNC shield v1 module is designed to control maximum 4 motors at the same time, which can connect Arduino Uno board with pins. Based on CNC shield v1 module properties, it is easy to control the machine movements on G-code program

language [45]. Grbl is a basic program code to control the machine movements, which can be used for three axes machines: X, Y and Z. Figure 11 shows an overview flow chart of hardware and software sections, which can interpret two sections relationship. Filament winding code is clearly shown in Figure 12, which can perform this winding process.
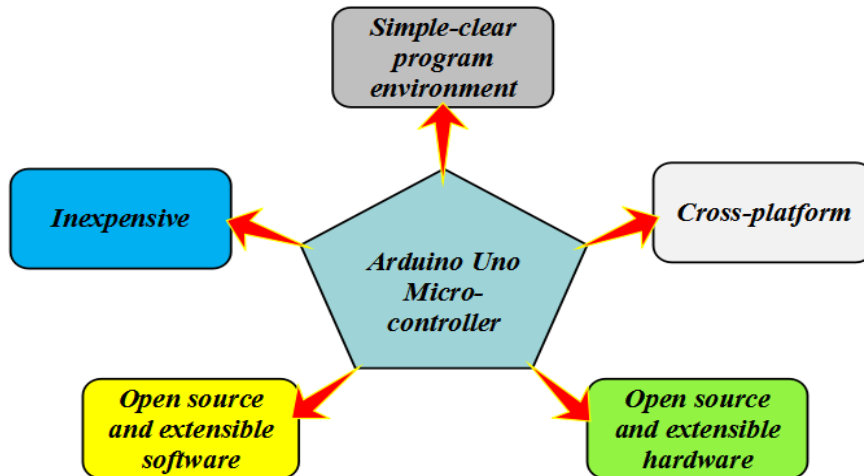
Figure 10: The advantages of Arduino microcontroller [44]

Some basic and useful G-codes programming language is shown as follows:
- G91(Incremental programming): Position defined with reference to the previous position.
- G01(Linear interpolation): The common linear movement code.
- X (axis): Absolute or incremental position of X-axis
- Y (axis): Absolute or incremental position of Y-axis
- Z (axis): Absolute or incremental position of Z-axis
- F (feed rate): which is defined as velocity of axis travelling from point to point, the unit is rpm (revolutions per minute)
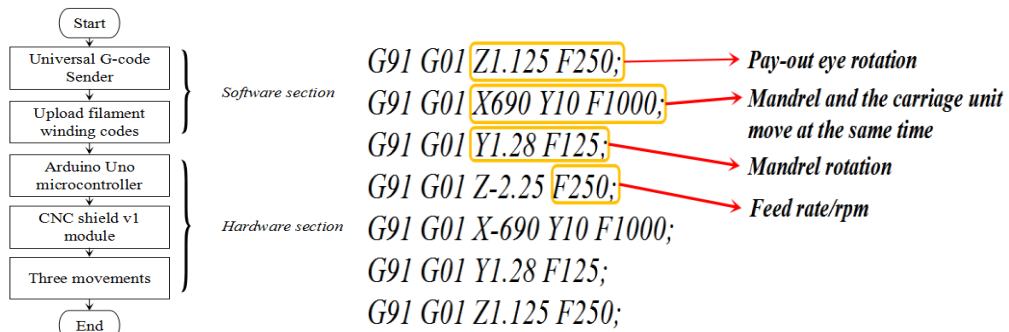
Figure 11: The flowchart between hardware and software sections

Figure 12: The winding code example

Hardware Section

An inexpensive control system has been chosen, which includes Arduino Uno microcontroller, CNC shield v1 module, stepper motor driver, limit switch and others. As follows, Figure 13 shows basic pins and connection schematic of Arduino Uno and CNC v1 shield module. Pins and connection schematic are shown in Figure 14. The control system needs three stepper motor drivers, which type is A4988 or DRV8825. The limited switch enables pins on the driver align with enable pins on the shield, which is illustrated in Figure 15.

Arduino Uno   CNC shield v1 module

Figure 13: Basic pins and connection schematic of Arduino Uno and CNC shield v1 module [44]

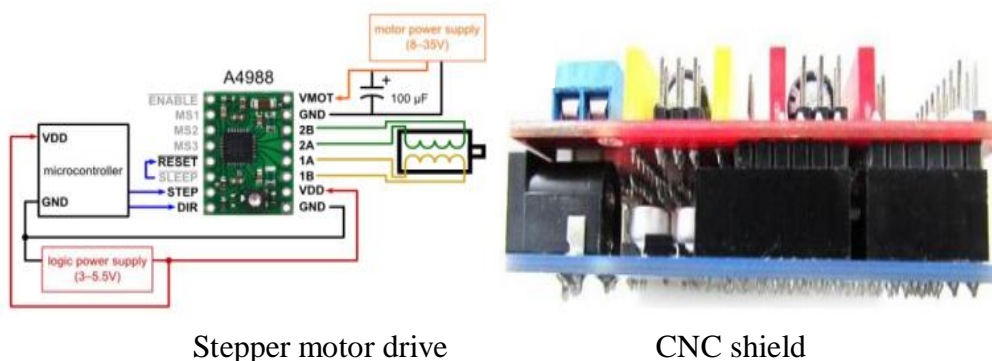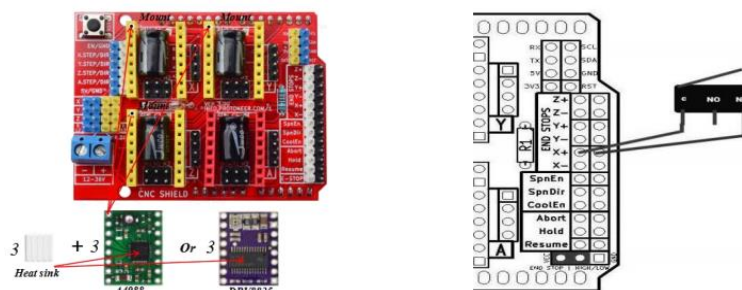Stepper motor drive   CNC shield

Figure 14: Pins and connection schematic of A4988 stepper motor driver and CNC shield v1 module and Arduino Uno setup


A4900 and DRV8825 Stepper motor driver   Limit switch

Figure 15: CNC shield v1 module connection diagram of A4988 &   DRV8825 stepper motor drivers diagram and limit switch connection

Software Section

In software section, Arduino Uno needs to connect with computer, firstly, download files and upload "grbl_v0_8c_atmega328p_16mhz_9600" using Arduino IED software to Arduino Uno board in order to communicate between 3-axis filament winding machine and Universal G-code Sender software. Universal G-Code Sender (UGS) software is an application used to send commands from your computer to 3-axis filament winding machine.

In the main interface of the UGS software, the user can set port number, baud and firmware, then click open button to initialize communication. Tabs Commands, File mode, Machine control and Macros are individually used for the commands tab testing single line of code typed inside text blank and send by pressing enter on the keyboard. UGS software and machine status setting are shown in Figure 16. When filament winding machine is ordered to "home position", it travels in three axes until it has reached each end stop. UGS software machine control setting is shown in Figure 17, which relates to machine home and manual jogging settings. Based on the setting value, the filament winding machine G-codes can be written to perform the winding process. The user can change the different setting values using software platform, which is convenient to write a single process code with the certain winding angle.
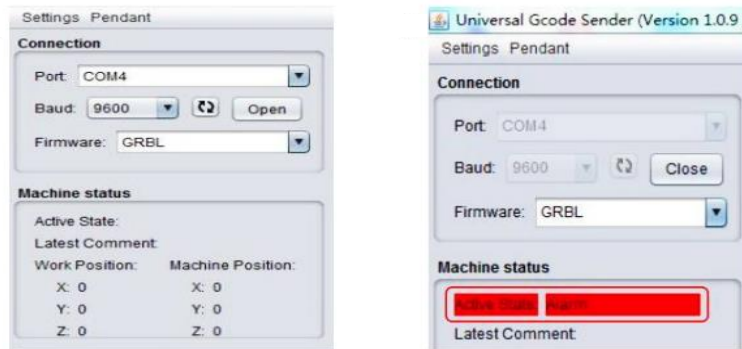
COM port   Machine setting

Figure 16: UGS software and machine status setting of com port, baud & firmware setting and machine status setting
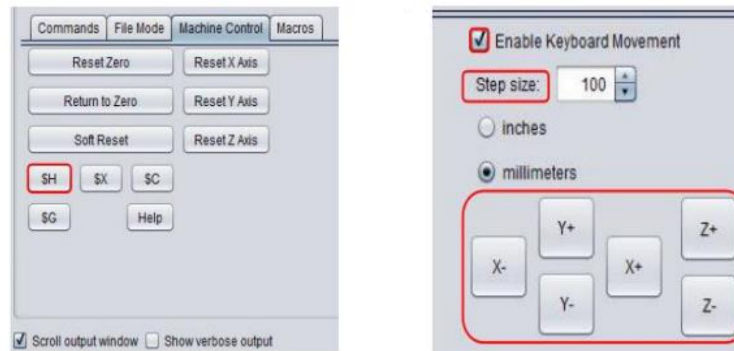
| Machine home setting | Manual jogging setting |

Figure 17: UGS software machine control function of machine home setting and manual jogging setting

RESULT AND DISCUSSION

The finding of the present study suggests that 3-axis filament winding machine has been designed and fabricated, which can be controlled using inexpensive control system. The machine has three units, which are rotation unit, carriage unit and control unit. Hardware and software sections can properly meet filament winding process requirements, which can wind with proper winding codes. Filament wound carbon/epoxy tubes can be produced using this machine, which can also fully prove the new 3-axis filament winding machine manufacturing capability. The main research findings are shown in Figure 18.

The contribution of this study is obvious as the result outcomes can be capitalized as guidelines to design a portable, low-cost filament winding machine with 3 axes, which can successfully combine inexpensive microcontroller and open software together. Compared to previous and existing filament winders, this machine is much better used in research purpose for filament wound products. The machine structure can also provide design reference and a successful extended example. Arduino Uno microcontroller can embed in control system based on its own advantages, which can provide more ideas for machine control system in future technology development.
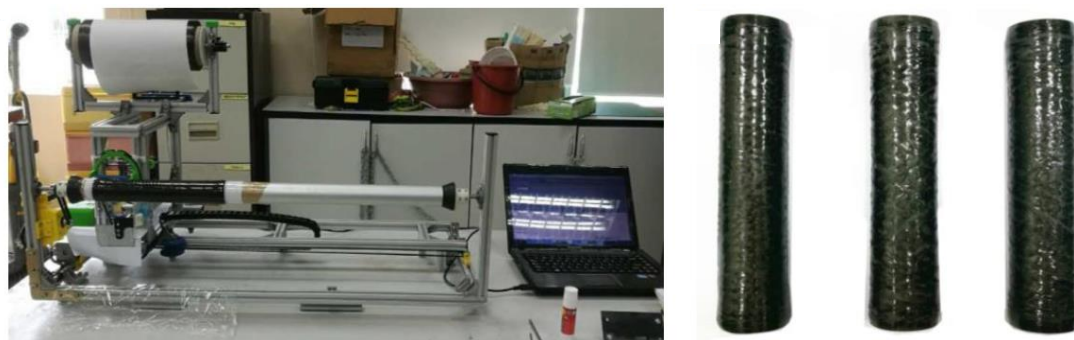

Figure 18: Research results the portable, low-cost, inexpensive 3-axis filament winding machine and filament wound carbon/epoxy tubes

CONCLUSION

The portable, low-cost, lightweight and automated filament winding machine has been effectively developed with 3 axes. Arduino Uno is used in this efficient and inexpensive control system, which controls the x, y and z movements. This filament winding machine can perform hoop and helical winding patterns, which should be written and uploaded proper winding codes. Filament wound composite products can be fabricated from this newly designed machine. The 3-axis filament winding machine has reached the main expected results, which solves the previous problems of filament winding machine costs and complicated operation. The inexpensive control system is another popular characteristic of this machine, which can mostly meet the filament winding process requirements.

RECOMMENDATION

Due to the limitation of research schedule and scope, it is suggested that the following improvements should be done for the future development.
a) Mandrel holder device

    The original mandrel holder should be changed to chuck device, which can hold different kinds of mandrel shape such as the elliptic mandrel. It can also promote the 3-axis filament winding machine manufacturing product capacity.

b) Add a separated comb device

    The 3-axis filament winding machine should wound more than two kinds of fibres at the same time, which need to separate different fibre tows using the comb device.

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