HardwareX 14 (2023) e00434

Contents lists available at ScienceDirect

HardwareX

journal homepage: www.elsevier.com/locate/ohx

Tension controlled hollow-fiber winding machine for blood oxygenator prototypes

Easa AliAbbasi [a], Anil Akseki [b], Azmat Ullah [c], Kerem Pekkan [b,c,*]

[a] Department of Computational Sciences and Engineering, Koc University, Istanbul, Turkey
[b] Department of Mechanical Engineering, Koc University, Istanbul, Turkey
[c] Department of Biomedical Sciences and Engineering, Koc University, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 15 January 2023
Received in revised form 1 May 2023
Accepted 22 May 2023

Keywords:
Blood oxygenator
Cardiovascular devices
Composite materials with fibers
Winding
Hollow-fiber
Tension
PID
Control

ABSTRACT

Blood oxygenators involve a complex network of hollow fibers for efficient gas exchange with blood. The optimal microstructural arrangement of these fibers is an ongoing research interest. While the fiber systems of commercial oxygenators are manufactured to address mass production, the research oxygenator prototypes demand more flexibility so that different design parameters can be tested. Here a hollow-fiber assembly system is designed and built for winding research grade extracorporeal blood oxygenator mandrels at different layout dimensions so that these different configurations can be evaluated for mass transfer capacity and blood damage. The hardware design and manufacturing details of this system presented together with its impact on the prototype oxygenator device assembly process. This in-house built system can wind thin fibers, having outer diameters ranging from 100 µm to 1 mm, at any specified winding angle continuously. A control system for fiber stress is also incorporated to eliminate fiber damage. Our system consists of three main units: (1) unwinding, (2) accumulator, and (3) winding systems, integrated together via the control software. The unwinding unit has a PID controller to maintain the position of the accumulator motor on the reference point by tuning the velocity of feeding fibers to the accumulator unit. Another PID controller preserves the desired tension value of the fibers by adjusting the position of the accumulator motor. Desired tension value is defined by the user and typically obtained through uniaxial testing of fibers. The control unit employs a "cascaded" PID controller since the PID controller in the accumulator unit maintains the tension and the PID controller in the unwinding unit controls the position of the accumulator motor. Finally, the winding unit utilizes two motors to wind the fibers over the outer diameter of a mandrel at the desired winding angle. The first motor drives the translational movement, and the second one provides mandrel rotation. The desired angles are achieved by tuning the synchronous movement of the winding motors. While the system is designed to produce assembled blood oxygenator mandrel prototypes, this concept is also applicable for producing cylindrical fiber-reinforced composite materials with specified fiber angles and stents winded on jigs.

---

* Corresponding author at: Department of Mechanical Engineering, Koc University, Istanbul, Turkey.
E-mail address: kpekkan@ku.edu.tr (K. Pekkan).

https://doi.org/10.1016/j.ohx.2023.e00434
2468-0672/© 2023 The Author(s). Published by Elsevier Ltd.

Specifications table

Hardware name	Tension Controlled Hollow Fiber Winding Machine for Blood Oxygenator Prototypes
Subject area	• Medical (Cardiovascular) and Composite Materials
Hardware type	• Biomedical device • Sensor • Electronics
Closest commercial analog	Winder
Open-source license	CC BY-NC-SA 4.0
Cost of hardware	*5729 Euro*
Source file repository	https://doi.org/10.5281/zenodo.7882884

1. Application and need

Hollow fiber oxygenators have been a critical component in extracorporeal membrane oxygenation (ECMO) and cardiopulmonary bypass (CPB) procedure for several decades. The early studies in the literature [1–3] demonstrated the feasibility of using membrane oxygenators for CPB in neonates and infants with congenital heart disease. These early oxygenators were limited in their design and function but served as a foundation for future research and development. In recent years, researchers have explored the use of novel designs and materials to improve oxygenator performance and minimize the invasiveness of CPB procedures. Fraser et al. [4] developed a compact oxygenator design for use in minimally invasive cardiac surgery, which could potentially reduce the need for sternotomy and improve patient outcomes. Zhang et al. [5] optimized a hollow fiber oxygenator using computational fluid dynamics simulations to improve mass transfer efficiency and minimize pressure drop.

The use of fiber winding systems played an important role in manufacturing of hollow fiber blood oxygenators. Li et al. [6] developed a fiber winding method for producing fiber-reinforced plastic pressure vessels with improved strength and durability. Sorrentino et al. [7] described the use of a robotic fiber winding system for the production of carbon fiber composite pressure vessels, which could potentially improve the precision and speed of the manufacturing process. Ellul et al. [8] investigated the effect of winding angle on the mechanical properties of fiber-reinforced plastic pressure vessels, providing insight into the optimal winding parameters for oxygenator production. In addition to oxygenators, fiber winding systems have also been used in the manufacturing of high-strength and lightweight pressure vessels for various applications. Baldwin et al. [9] developed a fiber winding process for producing pressure vessels for hydrogen storage, while Mlýnek et al. [10] developed a continuous fiber winding process for producing pressure vessels for use in fuel cell vehicles. Quanjin [11] presented a novel method of fabricating high-quality polymer composite frames and demonstrates its potential applications in various fields, providing valuable insights into the development of new methods for producing high-quality polymer composite materials. Moreover, Kadir et al. [12] described the development of a 2-axis winding machine for the production of for composite material and Srivastava et al. [13] described the use of a 3-axis winding machine for the production of composite pressure vessels.

Geometric design parameters of hollow fiber blood oxygenators, such as the fiber diameter, angle of winded fibers and their spacings play a critical role in the mass transfer performance. To discover the optimal design parameters a versatile extracorporeal oxygenator prototype production system with programable winding speed, pattern and fiber tension is aimed. This will allow rapid manufacturing of custom oxygenator prototypes with different design parameters. The commercial computer-controlled fiber winding machines that employ accurate fiber winding with robust tension controllers are intended for large-scale structural applications such as for laying carbon fibers in composite pressure vessel manufacturing. Unfortunately, these fiber winding machines are very sophisticated, costly, and not versatile enough for research use. Their complex structures and specialized software algorithms require skilled personnel for maintenance and operation.

In addition to the hollow-fiber mass transfer devices, the in-house fiber winding device presented in this article can also be utilized in a wide variety of industrial applications where directional fiber layouts are desired. For example, previous efforts focused on finding the ideal winding angle for pressure vessel systems [14–18]. Generally, in the process of winding fibers, a carriage arm moves horizontally over a stationary rotating mandrel. The arm has a winding pay-out eye that gathers and distributes fibers. The carriage rate and the mandrel's rotating speed determine the precise direction of the composite winding process [19]. Different types of fiber winding machines are available in literature based on their performance and specific requirements. For example, 2-axis machines are mostly suitable for pipe fabrication purposes [20]. On the other hand, 4-axis machines have better performance in lightweight pressure vessels like CNG containers [21]. More complicated machines such as 6-axis ones have 3 rotational and 3 linear motions. The more we increase the number of axes, the more capability we acquire in winding non-symmetrical mandrels. However, increasing the number of axes increases the costs and requires high accuracy in design and manufacturing.

The development and optimization of hollow fiber oxygenators and fiber winding systems have been critical in advancing the field of extracorporeal blood circulation support. The use of novel designs and materials, along with advancements in manufacturing processes, have the potential to improve patient outcomes and make ECMO and CPB procedures more accessible and less invasive.

2. Hardware description

Fiber winding machines have been widely adopted in various industries for producing composite materials due to their efficiency, cost-effectiveness, and ability to create complex structures. The demand for high-strength and lightweight materials has fueled the development of these machines, resulting in significant advancements over the last years [21,22]. Despite its long-standing history, filament winding technology still attracts a significant amount of interest from the scientific community. Moreover, improvements in software and control systems have enhanced the precision and repeatability of the winding process, resulting in more consistent and reliable production.

Several reports have underscored the practicality of in-house laboratory equipment for assessing new filament winding techniques and for the experimental fabrication of advanced composite materials. For example, a 5-axis filament winding machine, including a numerical control unit and liner, has been presented by Ateba et al. [23]. It is also suggested to increase the fiber volume ratio and decrease the void volume ratio of the composite casing [24]. An environmentally friendly filament winding machine, without any discernible loss of quality, was devised by initially separating the resin components with their controllable feeding to a conventional static mixer and subsequently to a custom-designed resin impregnation unit [25,26]. While many research papers have focused on specific scientific problems and engineering solutions related to filament winding technology, only a few have presented details regarding the cost-effective design of the filament winder, its control system, and winding technique. One of the first attempts to design a low-cost computer-operated wet filament winding system for manufacturing cylindrical and conical parts or a combination of components is outlined by Lye and Boey [27]. The associated system is accompanied by software written in the AUTOLISP parametric programming language for the visualization of the winding patterns. Another innovative lathe-type machine based on a wet winding method is reported by Abdalla et al. [19]. The cost of the system is low due to the implementation of a rigid automation. Their control system is not computer-controlled but based on relays, limit switches, a timer, and a counter. Similar low-cost design solutions have been presented, which are based on the speed control of two motors [28].

Despite all the developments in fiber winding machines, the high cost of composite structures with unique shapes and dimensions limits their accessibility to small companies, which are often forced to seek alternative solutions. University teams, on the other hand, may benefit from the sponsorship of equipment manufacturers [29]. Hence, further research is needed to overcome the challenges associated with the accessibility and cost-effectiveness of fiber winding machines. In this paper, we present the design and manufacturing of a low-cost fiber winding machine that can be used in research and development sections. In particular, the system's focus is more aligned to the winding of fibers on mandrels used in extracorporeal hollow fiber blood oxygenators. The efficiency of these oxygenators could be improved by experimenting with different layouts or designs of mandrels and winding patterns. Hence, the proposed system could facilitate the testing and development of research grade oxygenator products.

Operation and main components of the final system acquired from multiple synchronous videos are presented in "Fiber_Winding_Machine.mp4" video file. Likewise, as shown in Fig. 1, the system comprises three main units. Each unit is designed to work as a stand-alone system, meaning that it is possible to replace a unit with a new one to enhance the system's functionality. This is advantageous as it gives flexibility for other possible fiber winding applications. The first unit is named the unwinding unit (see Fig. 2). It has a NEMA 23 stepper motor that serves in unwinding the fibers from a storage bin typically placed on a shaft. The accumulator unit shown in Fig. 3 is a critical piece as it maintains the tension of the fibers at a fixed and desired tension value. Inspired by Ref. [30], five sets of pulleys are designed, machined, and utilized in this unit as tension levelers. A 24-bit tension load cell with an analog 5 V isolated signal converter is used to measure the tension of the fibers during the winding process. The third unit is named the winding unit (see Fig. 4), which completes the system operation by winding the fibers from the accumulator unit on a custom-made oxygenator mandrel. It has two NEMA 34 stepper motors, and each motor is connected to a GSTD2860 stepper driver. One of the motors provides translational movement, and the other provides rotational movement for the mandrel. As such, a deep groove ball bearing supports the translational movement of the mandrel.

The hollow fiber winding machine is controlled via a custom-designed and built extension board (ANAKS Extension Board, Anaks Inc., Turkey). This board utilizes a "Teensy Board 3.6" but the number of PWM (Pulse Width Modulation) pins providing 5 V of voltage signals was increased to satisfy the required PWM pins of the stepper motors' "step" and "direction" commands. The board is ultra-compact and designed to increase the number of PWM pins. Since the system requires stable, soft, and accurate functionality, the "TeensyStep" library is used in the driver code.

A cascaded Proportional-Integral-Derivative (PID) controller has been implemented on unwinding and accumulator units to preserve a stable fiber winding mechanism (see the schematic of our cascaded PID controller in Fig. 5). The cascaded PID controller consists of two individual PID controllers, each with a unique function. The first PID controller is responsible for regulating the stepper motor in the unwinding unit. This motor plays a crucial role in maintaining the initial position of the accumulator unit's stepper motor. The PID controller achieves this by changing the velocity of the unwinding motor. Hence,

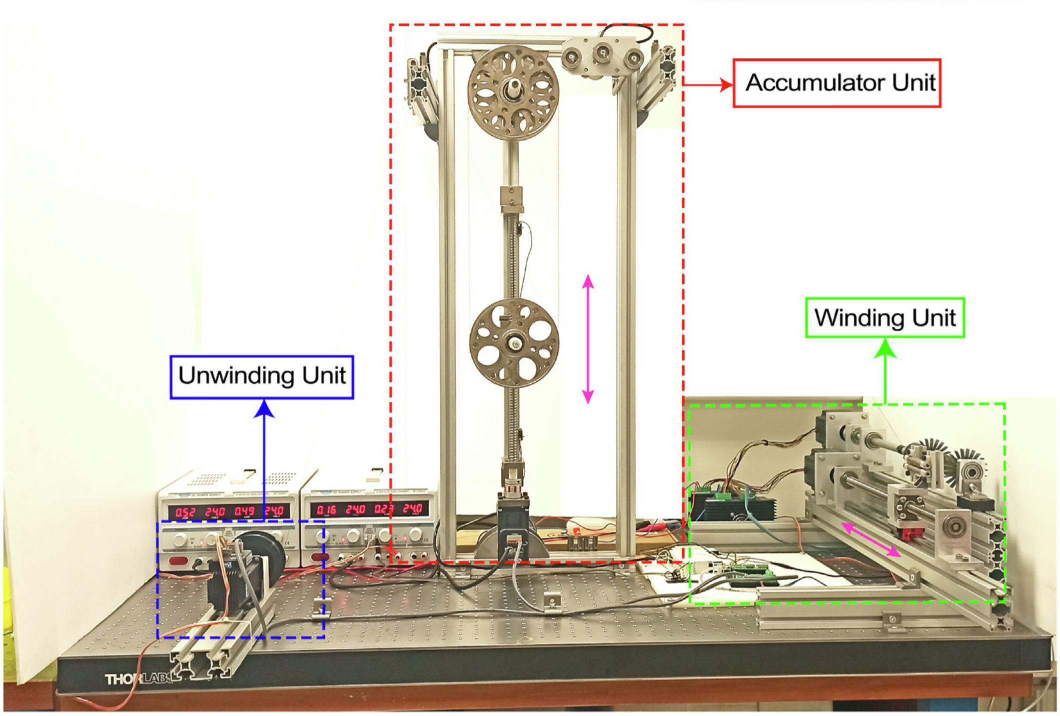

Fig. 1. Overview of the fiber winding machine. The system has three main parts: the unwinding, accumulator, and winding unit. Two DC power supplies are used to provide the required power for the motors and the tension sensor. The machine winds the fibers on the outer diameters of a specifically designed mandrel. The whole machine is placed on a firm table to reduce the vibrations caused by the movements of wagons. The movements are shown by the arrows.

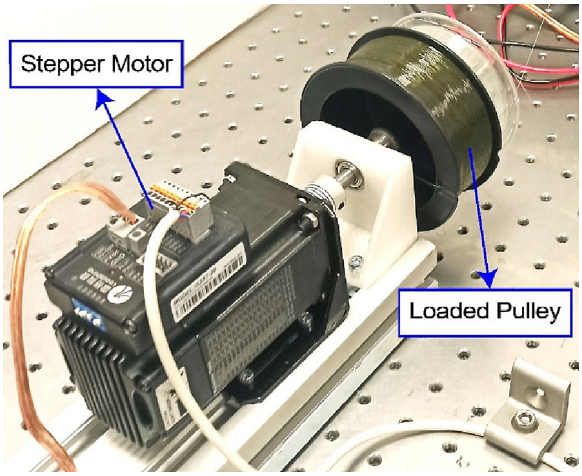

Fig. 2. The unwinding unit that releases the fiber from a loaded pulley controlled by a stepper motor. A PID controller maintains the position of the accumulator motor on the reference point by tuning the velocity of feeding fibers to the accumulator unit. The loaded pulley is typically supplied by fiber manufacturers.

the position of the accumulator unit's stepper motor can be held constant and stable around its initial position to avoid crushing the two ends of the rails. The second PID controller in the cascaded system is tasked with preserving a constant and desired tension value during the winding process. This is accomplished by modulating the position of the accumulator unit, which in turn controls the amount of tension exerted on the fiber during winding. By adjusting the position of the accumulator unit through the second PID controller, the tension on the fiber can be regulated and kept at a desired and consistent level throughout the winding process. Fig. 6 shows the data collected from a) the tension sensor and b) the encoder of the stepper motor in the accumulator unit. In Fig. 6a, the cascaded PID controller tries to keep the tension value at the desired

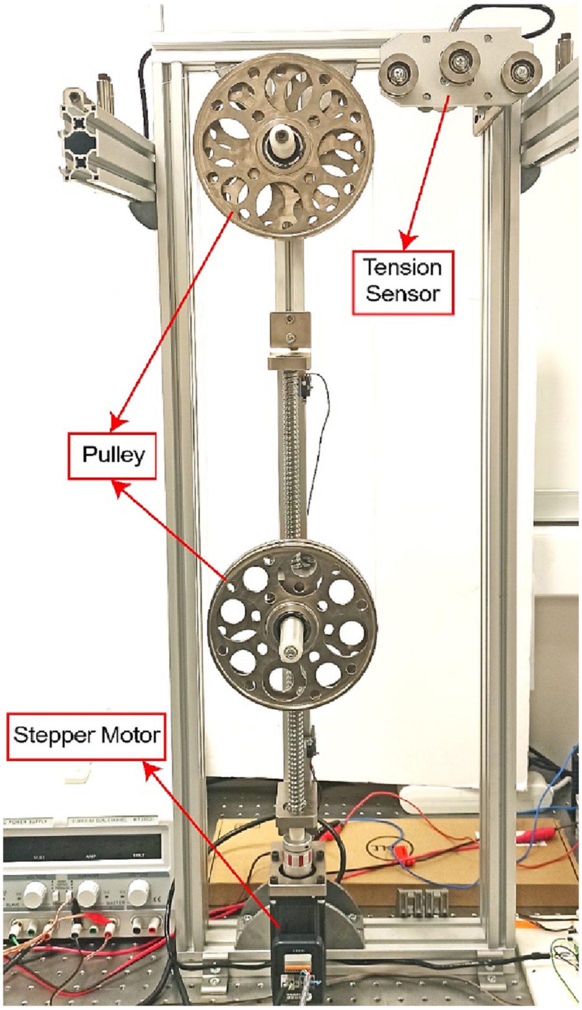

Fig. 3. The accumulator unit is shown in the figure. The tension sensor measures the tension values on fibers, and a PID controller maintains the tension at the desired value. The desired tension value can be changed based on the strength of the fibers, and the controller is capable of operating for a range of desired tension values.

user-defined tension (which is 2 N for our tests), and in Fig. 6b, the position of the accumulator unit's motor is controlled. The system tries to keep the motor position at zero.

Since the objective of this device is to produce a uniform fiber layout on the blood oxygenator mandrel, its design and manufacturing are also important. A tapered mandrel design is employed with circular holes and increasing diameter along the flow direction (Fig. 7). Inside the far end of the mandrel, an aerodynamic protrusion profile is introduced to keep the blood flow velocity constant through the oxygenator for low blood cell activation. This will also result in lower pressure drops through the device. This basic design configuration is employed in commercial hollow fiber oxygenator systems and evolved over time. The Sorin Cardiovascular Inc., Arvada, CO, Cobe Cardiovascular D901 and D902 Lilliput devices enhanced patient outcomes for pediatric patients in the late 1990s [31]. Specific recirculation ports, low blood volume, reduced surface area heat exchangers, and short tubing connections are features of these oxygenators. In 2012, Medtronic introduced the Affinity Pixie, having graded fiber bundle density which enabled the radial-radial blood flow channel.

The winding angle is an important parameter in the fiber winding process. Depending on the application, a low or high winding angle is prefered. Due to the complex structure of the mandrel, it is essential to have an accurate procedure for calculating the winding angle. Hence, we developed an algorithm in Matlab and provided it freely, which will help understanding of the geometrical operations. The angle of winding can be calculated by the following equation [32]:

$$\theta = \tan^{-1}\left(\frac{R\Phi}{L}\right) \tag{1}$$

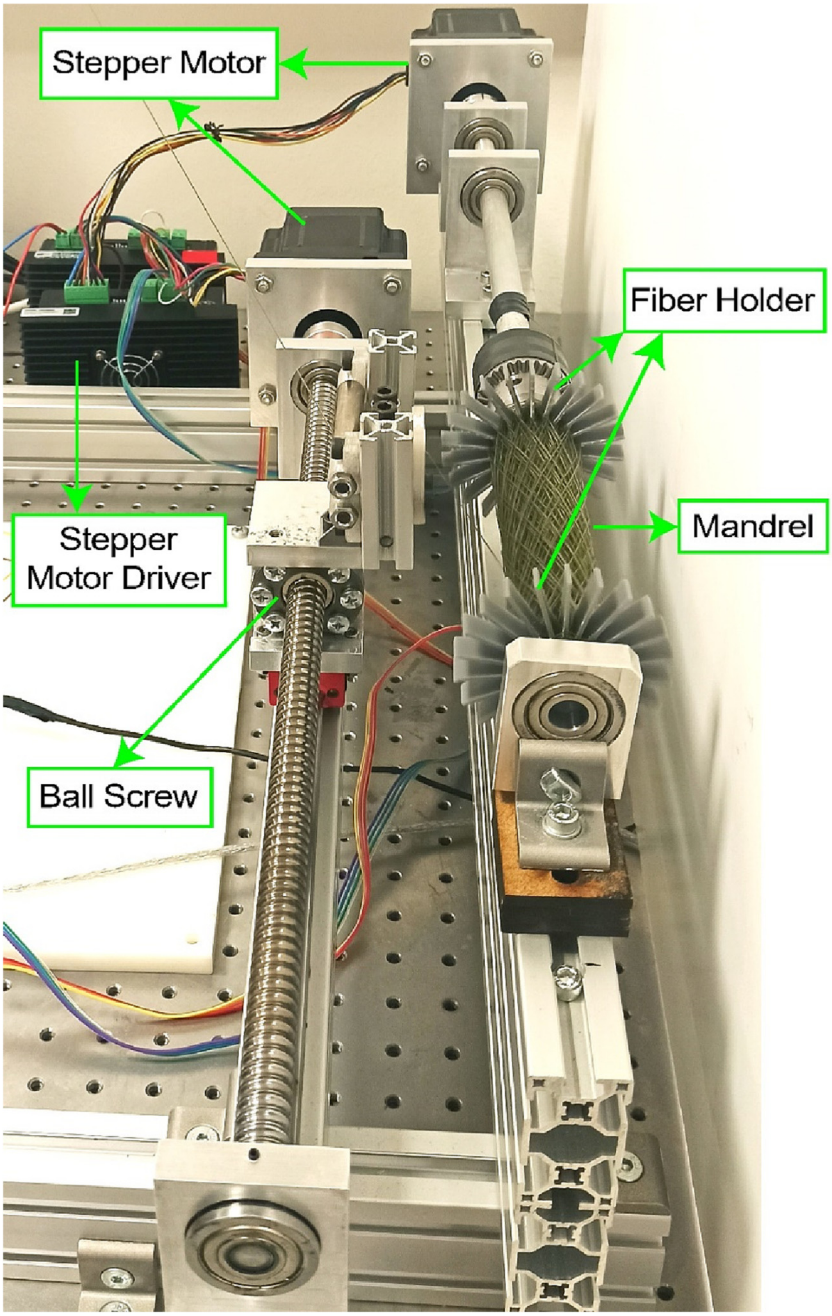

Fig. 4. A close-up photograph of the winding unit is provided. Two stepper motors provide translational and rotational movements for the mandrel, respectively. A deep groove ball bearing supports the translational movement of the mandrel. The system is also capable of winding tapered mandrels with modest conical angles, as installed here.

where, R, Φ, and L are the mandrel diameter, turn-around angle, and mandrel length, respectively. The diameter and length of the mandrel could be any value based on the designed geometry and the calculation of the turn-around angle requires complicated computations. Our Matlab algorithm calculates the turn-around angle and the corresponding winding angles for a desired mandrel geometry. The turn-around angle and the explanation regarding the angle index are appended as a supplementary file (“Matlab_Explanation.pdf“). This file is prepared with multiple examples to guide the user about the successful possibilities of winding patterns.

The user should run the Matlab function named “simulateAllConfig.m” in “Matlab_Winding.zip” file. The code asks for the geometry of the mandrel and calculate the possible fin numbers accordingly. Then, it asks the user to select the desired fin

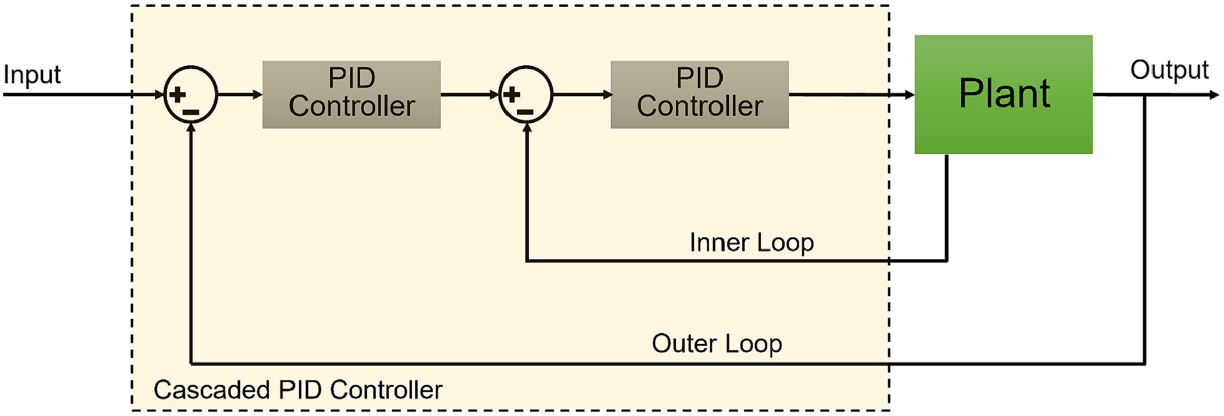

Fig. 5. Schematic of the controller design is presented. The cascaded Proportional-Integral-Derivative (PID) controller maintains the tension of fibers on a desired user-defined value.

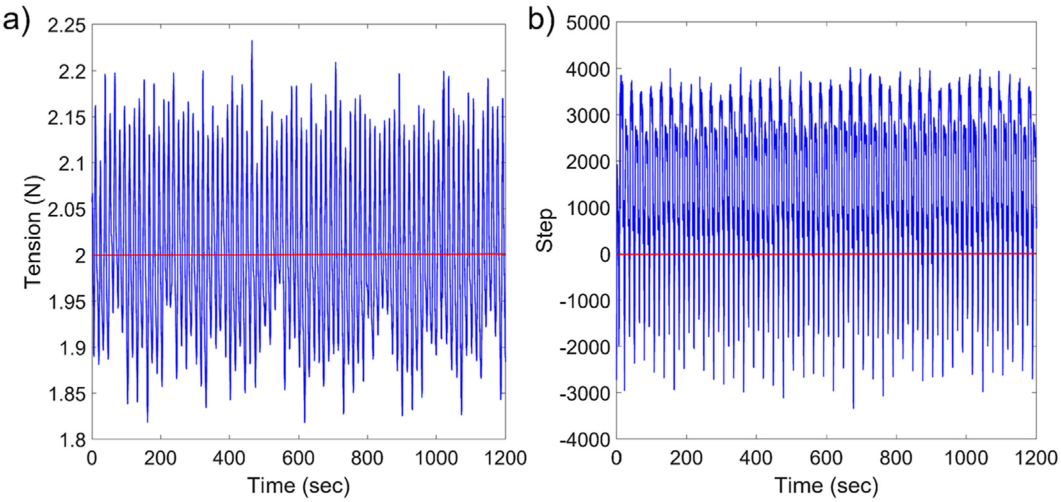

Fig. 6. Sample test data of (a) the tension on the fibers and (b) the steps traveled by the accumulator unit's motor is acquired over a relatively long period of time. In both graphs, the red line shows the target value fed to the cascaded PID controller. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

number. It calculates all possible winding patterns with multiple options of turn-around and winding angles and simulates all of them. The user can select any of the provided turn-around angles and enter the value to the "Arduino_final.ino" code. More information regarding the steps required for running the Matlab code is presented in a video file named "Matlab_Guide.mp4".

In particular, the general system specifications are,

- low-cost,
- easy to implement,
- safe,
- stable,
- easy to enhance,
- suitable for research and development,
- can create different fiber layouts easily for performance tests,
- and does not require skilled personnel for operation.

3. Design files summary

.

Design file name	File type	Open source license	Location of the file
AssemblyMandrel	CAD, STP	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
assemblyAll	CAD, STP	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Gerber_Files	Gerber File	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Arduino_final	INO	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Fiber_Winding_Machine	MP4	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Matlab_Winding	Matlab Functions	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Matlab_Guide	MP4	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705
Matlab_Explanation	pdf	CC BY-NC-SA 4.0	https://doi.org/10.5281/zenodo.7494705

assemblyMandrel: This file contains the CAD drawings of an novel conicalshaped mandrel with holes of varying diameters along the length. The shape of the mandrel is such that the pressure drop is low, and the blood flow is uniform.

assemblyAll: This file contains the CAD drawings and the assembly of the unwinding, accumulator, and winding units. CNC milling and lathe operations are used for machining the parts. Electroless Nickel Coating is also utilized for post-processing the machined parts. We created the CAD files for 3D parts with a general tolerance of ∓0.02 mm since it is the first prototype. For FDM parts, we used Prusa MK3S (Prusa Inc., Czech Republic) using Fillamentum PETG (Czech Republic) filaments.

Gerber_Files: This zipped file contains the PCB production files. It includes information about production and layers.

Arduino_final: Arduino code for embedded hardware setup.

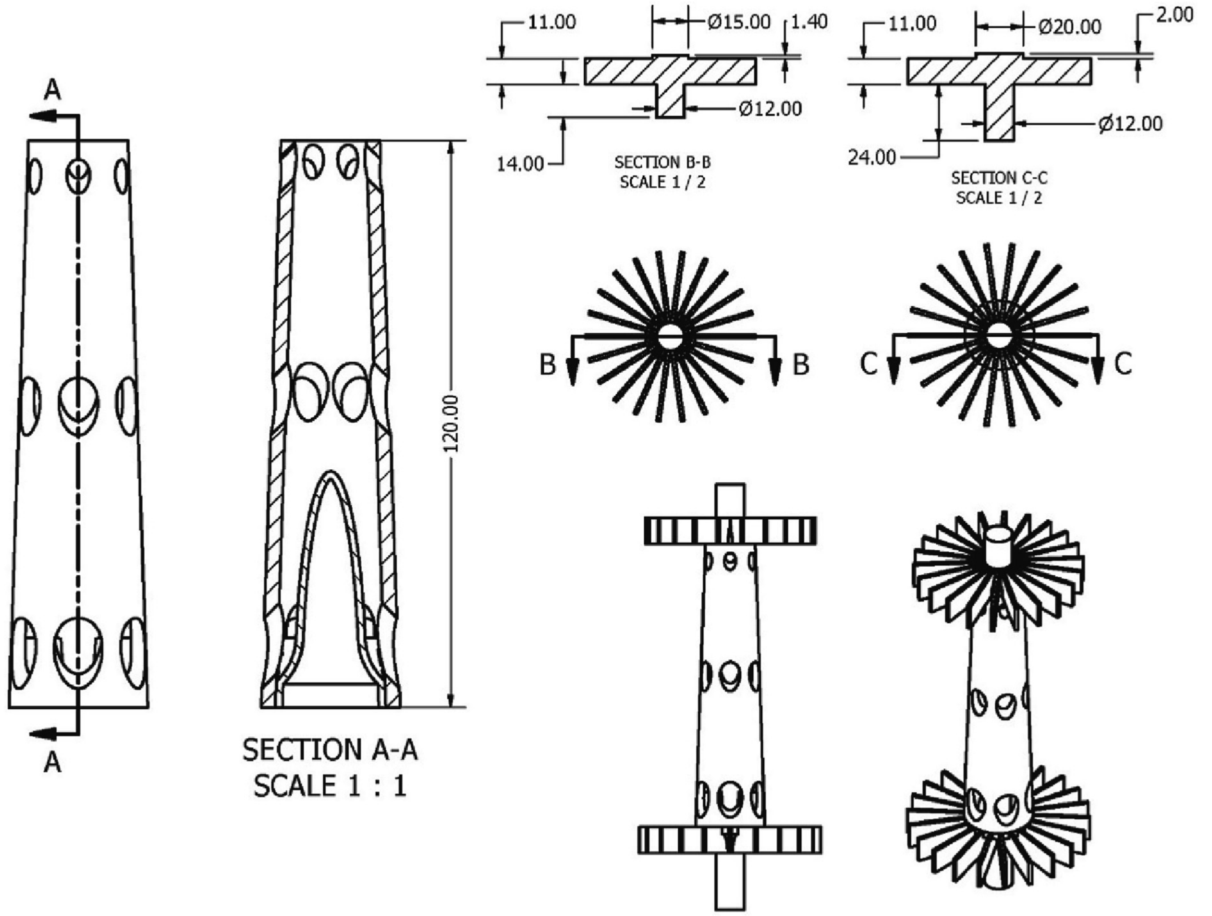

Fig. 7. The technical drawings of the oxygenator mandrel together with the sacrificial fiber holder fins provided at both ends. For this prototype design version, the fiber holders have 22 pins on both sides. Dimensions are in millimeters.

Fiber_Winding_Machine: Video showing the operation of the fiber winding machine.
Matlab_Winding: This zipped file contains the Matlab functions for calculating the turn-around and winding angles.
Matlab_Guide: Video showing the procedure of running the Matlab functions.
Matlab_Explanation: A pdf file containing information regarding the winding process and the possible angle index.

4. Bill of materials summary

.

Designator	Component	No.	Cost per unit (Euro)	Total cost (Euro)	Source of materials
stepperMotorNema23	Nema 23//2N. m//6A//1000 Line Encoder Integrated Easy Servo Stepper Motor	2	350 117	700 234	https://www.segaotomasyon.com/ https://www.automationtechnologiesinc.com/products-page/nema23-closed-loop-stepper-motor-system-hybrid-servo-kit/kl-5056h
spiderCouplingMandrel	Spider Coupling	1	15	15	https://www.doguskalip.com.tr/
30x60x400sigma	30x60 Sigma Profiles	9	5.2	46.8	https://www.doguskalip.com.tr/
axialSpiderCouplingBallScrew	Spider Coupling	1	15	15	https://www.doguskalip.com.tr/
165t3BallScrew	Hiwin 15-5T3 Ball Screw	1	40	40	https://www.segaotomasyon.com/
165t3BallScrewShaftWinding	Hiwin 15-5T3 Screw Thread	1	35	35	https://www.segaotomasyon.com/
lineerRailCar	Hiwin HGW15CC Car	1	35	35	https://www.segaotomasyon.com/
lineerRailWinding	Hiwin HGW15CC Rail	1	35	35	https://www.segaotomasyon.com/
30x60x850sigma	30 × 60 Sigma Profiles	1	11	11	https://www.doguskalip.com.tr/
axialFixture_1	Fixture	1	100	100	MACHINED
axialFixture_2	Fixture	1	100	100	MACHINED
BS 290 SKF- with two low-friction seals SKF 6201-2RZ	Deep Groove Ball Bearing	4	5	20	https://www.klasrulman.com.tr/
bearingPlateReversed	Fixture	4	70	280	MACHINED
motorPlate	Fixture	2	5	10	MACHINED
mandrelShaft	Shaft	1	100	100	MACHINED
30x60x310sigma	30x60 Sigma Profiles	1	4	4	https://www.doguskalip.com.tr/
30x60x340sigma	30x60 Sigma Profiles	3	4	12	https://www.doguskalip.com.tr/
30x60x480sigma	30x60 Sigma Profiles	1	5	5	https://www.doguskalip.com.tr/
20x20x52sigma	20x20 Sigma Profiles	1	2	2	https://www.doguskalip.com.tr/
20x20x60sigma	20x20 Sigma Profiles	2	2	4	https://www.doguskalip.com.tr/
axialGuideRollerHorizontal	Pipe	2	15	30	MACHINED
guideRollerVertical	Pipe	2	15	30	MACHINED
ISO 15 7 27–6 × 10 × 3	Deep Groove Ball Bearing	8	2	16	https://www.klasrulman.com.tr/
Spacer	Shaft	2	30	60	MACHINED
Washer	Washer	2	1	2	FDM PRINTED
rollerFixture_1	Fixture	2	2	4	FDM PRINTED
rollerFixture_2	Fixture	2	2	4	FDM PRINTED
ceramicHolder	Fixture	1	2	2	FDM PRINTED

(*continued on next page*)

a (*continued*)

Designator	Component	No.	Cost per unit (Euro)	Total cost (Euro)	Source of materials
ceramic	Ceramic Guide	1	2	2	https://www.erginer.com.tr
165t3BallScrew	Hiwin 15-5T3 Ball Screw	1	40	40	https://www.segaotomasyon.com/
lineerRailCar	Hiwin HGW15CC Car	1	35	35	https://www.segaotomasyon.com/
lineerRailAccumulator	Hiwin HGW15CC Rail	1	35	35	https://www.segaotomasyon.com/
accumulatorFixture_1	Fixture	1	100	100	MACHINED
accumulatorFixture_2	Fixture	1	100	100	MACHINED
sheaveShaftCar	Shaft	1	35	35	https://www.segaotomasyon.com/
stepperMotorNema23	Nema 23//2N.m//6A//1000 Line Encoder Integrated Easy Servo Stepper Motor	1	350	350	https://www.segaotomasyon.com/
165t3ballScrewShaftAccumulator	Hiwin 15-5T3 Screw Thread	1	40	40	https://www.segaotomasyon.com/
30x60x950sigma	30x60 Sigma Profiles	3	13	39	https://www.doguskalip.com.tr/
tensionSensor	[2.0 + -0.1 mV/V] // 2 kg // Nonlinearity 0.1 % F.S. //Repeatibility 0.1 %F.S Tension Sensor	1	167.41	167.41	https://tr.aliexpress.com/item/1005002305667757.html
BS 290 SKF- with two low-friction seals SKF 6201-2RZ	Deep Groove Ball Bearing	2	5	10	https://www.klasrulman.com.tr/
bearingPlate	Fixture	1	70	70	MACHINED
bearingPlateReversed	Fixture	1	70	70	MACHINED
motorPlate	Fixture	1	70	70	MACHINED
30x60x370sigma	30x60 Sigma Profiles	2	4	8	https://www.doguskalip.com.tr/
30x60x600sigma	30x60 Sigma Profiles	2	6	12	https://www.doguskalip.com.tr/
sheaveShaftFixed	Shaft	1	70	70	MACHINED
fixedShaftFixture	Fixture	1	70	70	MACHINED
Rolling Bearing JB/T 8721-1998 Type E E16	Deep Groove Ball Bearing	5	15	75	https://www.klasrulman.com.tr/
Sheave	Sheave	5	150	750	MACHINED
ballScrewSpiderCouplingAccumulator	Spider Coupling	1	15	15	https://www.doguskalip.com.tr/
sensorFixture	Fixture	1	10	10	LASER CUT-BENDED
ISO 15 7 27–6 × 10 × 3	Deep Groove Ball Bearing	12	3	36	https://www.klasrulman.com.tr/
accumulatorGuideRollerHorizontal	Pipe	4	10	40	MACHINED
guideRollerVertical	Pipe	4	10	40	MACHINED
guideRollerShaftVertical	Shaft	4	10	40	MACHINED
guideRollerShaftHorizontal	Shaft	2	10	20	MACHINED
accumulatorGuideRollerFixture	Fixture	4	10	30	LASER CUT
30x60x288sigma	30x60 Sigma Profiles	2	4	8	https://www.doguskalip.com.tr/

a (*continued*)

Designator	Component	No.	Cost per unit (Euro)	Total cost (Euro)	Source of materials
stepperMotorNema23	Nema 23//2N.m//6A//1000 Line Encoder Integrated Easy Servo Stepper Motor	1	350	350	https://www.segaotomasyon.com/
motorPlate	Fixture	1	70	70	MACHINED
ballScrewSpiderCouplingAccumulator	Spider Coupling	1	15	15	https://www.doguskalip.com.tr/
BS 290 SKF 61800	Deep Groove Ball Bearing	2	5	10	https://www.klasrulman.com.tr/
unwindingShaft	Shaft	1	15	15	MACHINED
unwindingBearingPlate	Fixture	1	4	4	FDM PRINTED
mandrel	Mandrel Part	1	8	8	SLA PRINTED
mandrel_2	Mandrel Part	1	5	5	SLA PRINTED
finTop	Fins	1	7	7	SLA PRINTED
finBottom	Fins	1	7	7	SLA PRINTED
–	180 MHz Arm Cortex M-4 32 bit Teensy 3.6	1	50	50	https://www.direnc.net/teensy-3-6-gelistirme-karti
–	ANAKS Extension Board	1	28.20	28.20	https://www.pcbway.com/project/shareproject/Teensy_3_6_Extension_Board_3_3V_to_5V_RS485_2222957d.html
–	24-bit Sigma-Delta// 50–100 Hz// Input: mV/V Output: 4–20 mA Tension Load Cell	1	60	60	https://www.esit.com.tr/tr/indikatorler_ve_kontrol_cihazlari/tr_3_yuk_hucresi_analog_sinyal_transmitter/urun/62
–	4–20 mA to Analog 5v Isolated Signal Converter	1	80	80	https://www.klemsan.com.tr/product/Index/tr-TR/6341/
–	3D Printer Resin	0.5 Liter	150	75	https://www.formlabs.com/store/materials/
–	3D Printer Filament	1 kg	39	39	https://3dfilaprint.com/product/fillamentum-petg-essential-natural-1-75mm-3d-printer-filament/
–	DC 24 V Power Supply	2	160	320	https://www.trendyol.com/mervesan/mt-305-d-ii-0-60-0-30-volt-5-10-amper-ayarli-guc-kaynagi-p-81848595?boutiqueId=61&merchantId=142967
*C6, C7	47 nF	2	–	500	https://www.direnc.net/
C1, C2, C3, C4, C5, C8, C9, C10, C11, C12, C16, C17, C18, C19, C20, C21, C22, C25	100 nF	18			
C15	10 uF	1			
C13, C14, C23, C24	2.2 uF	4			
D1, D2	AQ05-02HTG	2			

(*continued on next page*)

a (*continued*)

Designator	Component	No.	Cost per unit (Euro)	Total cost (Euro)	Source of materials
*U1	SN65HVD1477D	1			
U3	MCP120T-485I/TT	1			
U2, U4, U5	SN74HCT245PWR	3			
*R1, R2	0R	2			
R12	1 k	1			
R7, R8, R9, R10, R11, R15, R18, R21, R24, R27, R32, R41, R42, R43, R44, R45, R51, R52, R53, R54, R55, R56	15 k	22			
R16, R19, R22, R25, R28, R29, R30, R31, R33, R34, R35, R36, R37, R38, R39, R40, R57, R58	22.1R	18			
R13, R14, R17, R20, R23, R26, R46, R47, R48, R49, R50	30.1 k	11			
R3, R4, R5, R6	60.4R	4			

R, C, and U indicate resistor, capacitor, and IC, respectively.

5. Build instructions

5.1. Mandrel design instructions

The sample mandrel design (assemblyMandrel.stl) provided in this article is targeted for blood experiments and will be assembled in a research oxygenator. Because this is a test prototype manufacturing system, the mandrel shape can vary a lot depending on the application and we used parametrized 3D-printing approach as suggested in [33]. If the application involves blood, the 3D-printed parts should be made of a biocompatible material or heparin coated. In our application, all the parts are made of biocompatible gray color resin printed with Formslab 2 SLA 3D-printer and heparin-coated. Fig. 7 shows the parts used in the mandrel design. A medical grade epoxy (EA M-31CL Henkel's LOCTITE Inc.) is also used in the final assembly.

The Formslab 2 SLA 3D-printer uses a stereolithography (SLA) process. In this process, liquid resin is cured layer by layer using a UV laser to create solid objects. A gray resin was utilized to print mandrels and sacrificial fiber holding fins for oxygenator manufacturing. The layer thickness was set at 0.165 mm, and the support density was set to one, with a touchpoint size of 0.5 mm. The total time taken for one set was around 5 h, with a total volume of 30 ml of the resin used. These parameters were chosen based on specific requirements for printability, structural integrity, and ease of removal of the sacrificial material.

For 3D printing the parts, changes were made to the touchpoint size and orientation of the parts, while keeping the default settings for other parameters. These changes in touchpoint size and orientation were made to optimize printability, reduce the risk of part distortion or failure, and improve overall print quality. Other parameters, such as layer thickness and support density were kept at default settings as recommended by the printer software. After printing the mandrels and sacrificial fiber holding fins, the parts were cleaned in isopropyl alcohol to remove excess resin and ensure proper curing. Next, the supports were removed, taking care not to damage the delicate printed parts. Finally, the parts were cured using UV light to fully solidify and harden the resin, resulting in the final mandrels and sacrificial fiber holding fins for the oxygenator manufacturing process.

An example technical drawing of the mandrel is presented in Fig. 7. The mandrel design has three components, which consist of the mandrel cone and the two sacrificial fiber-holder fins located in both ends. The fiber holders on both sides of the mandrel have 22 pins each. These pins are used for holding the fibers during the winding process and turned flash during the oxygenator assembly. Cyanoacrylate-contained adhesives or medical grade epoxy can be used to bond printed structures depending on the application.

The sacrificial fiber holding fins are designed to securely hold the hollow fibers in place during the manufacturing process. These fins are typically made of the same material that can be easily machined after the fibers are wound around the mandrel and bonded, leaving behind the desired shape and arrangement of the hollow fibers. The primary purpose of the sacrificial fiber holding fins is to provide stability and support to the hollow fibers, preventing them from shifting or moving during the winding process. This helps to ensure that the fibers are evenly spaced and maintain their intended orientation, which is crucial for a working oxygenator function. Additionally, the sacrificial fins also aid in maintaining the shape and structure of the oxygenator during subsequent manufacturing steps, such as bonding or curing processes, by holding the hollow fibers in place until they are securely fixed in position. Once the manufacturing process is complete, the sacrificial fiber holding fins are removed, leaving the hollow fibers in their final configuration within the oxygenator. This allows the oxygenator to function effectively in delivering oxygen and removing carbon dioxide during its intended use in medical or respiratory applications.

In our application the mandrel and the winded fibers were used as a unit. But in other composite applications mandrel can be removed from the fibers. After winding the hollow fibers around the mandrel and securing them in place with the sacrificial fiber holding fins, a potting process was used to embed the fibers in an epoxy resin. The resin was then cured to create a solid, durable structure that encapsulated the fibers. Subsequently, both ends of the mandrel, including the part with the sacrificial fiber holding fins, were cut, leaving only the ends of the fibers embedded in the cured resin. This remaining mandrel and the fibers were used in the oxygenator, where the mandrel provided a uniform flow of blood as well as structural support to maintain the shape of the oxygenator, while the embedded fibers facilitated gas exchange between the blood and the surrounding environment.

5.2. Machine design instructions

The schematic overview of the extension board (see the Gerber_Files.zip) and the electrical connections of the entire system are presented in Fig. 8. Note that the first step in designing this system was the preparation of the extension board. At first, we used a much simpler extension board compared to the latest version. Once we were sure about the functionality of the system, we developed the latest version of the board, which can operate all four motors successfully and communicate with the tension sensor at high speeds.

The motor selection and type are very important to run the system. Motors are controlled via a step and direction interface. Thus, the user can either use a stepper motor with an external driver or a driver-integrated servo motor with step and direction interfaces. In this system, we tested both options in different sections.

As a first step, the winding unit, please see assemblyAll.stp, can be designed, manufactured, and operated since it does not require the tension control mechanism. The operation of the stepper motors is based on a looped periodic algorithm central

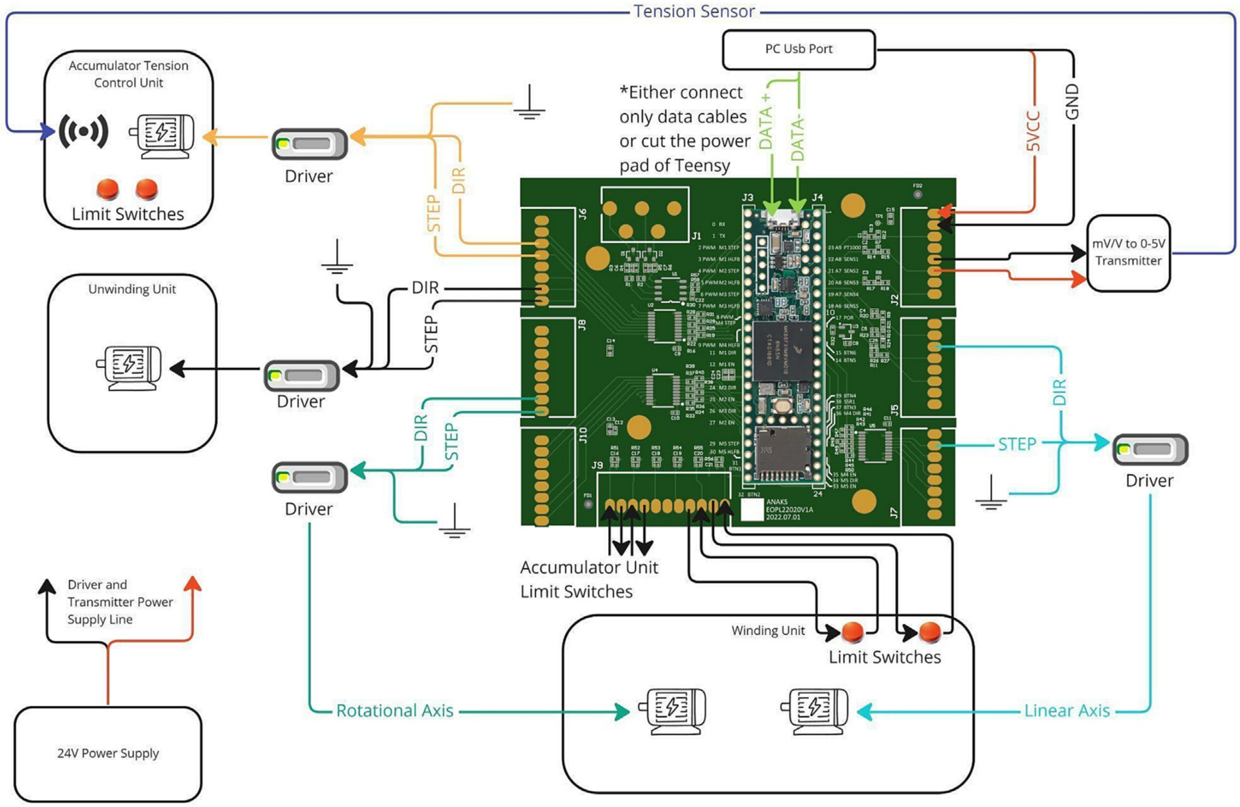

Fig. 8. The schematic overview of the extension board and electrical components of the entire control hardware and circuit. The figure is modified from www.pirc.com.

to the entire system operation due to the requirement of very precise movements without losing any motor steps. On the other hand, the accumulator unit, provided in assemblyAll.stp, serves as the main tension control component, which can be designed without considering the details of the cascaded PID controller. We initially operated this unit with a PID controller and tested its operation at various conditions and design parameters. One of the most important problems in controller design is the ability of the controller to avoid disturbances. Durability is another important aspect of a system integrated with the controller. Hence, we tested the accumulator unit for extended periods by applying irregular disturbances. During the test period, we identified operational problems and updated the mechanical and controller design files accordingly. These minor problems were solved by redesigning some parts and tuning the control parameters.

Once this system is working robustly, the unwinding unit can be introduced to provide the input fibers for the accumulator unit. For this task, a cascaded PID controller software, as in Arduino_final.ino file is developed. This software operated all units together. While the winding unit was laying the fibers on the mandrel, we observed and tested the operation of the tension control mechanism. Similarly, this unit is also tested for multiple hour of operation. During our tests, we applied multiple irregular disturbances and tuned the controller's parameters. In these verification tests, the winding speed was selected to be very low so that we could focus on the basic functions of the system and avoid possible malfunctions that would damage the setup. Further tests gradually increased the winding speed, and we repeated the long duration operation tests. In general, the user can only change the time required for traveling a period. The speed of winding is related to this variable. It is recommended to use 4 s for a period, and it is not recommended to go beyond this value too much. Obviously, increasing the speed of winding can disturb the PID controllers and the parameters of the PID controller should be readjusted.

6. Operation instructions

We tried our best to design a device that is easy to use. The first step is to switch on the DC power supply and wait a few seconds so that the electrical power reaches their nominal values. Then, the user can connect the controlling board to the PC. A simple and low-cost PC is enough to operate the system. For safety, the system is controlled through the serial communication port between the PC and the controller board; allowing the flexibility to start or stop the device at any time. Four commands are valid: "b", "m", "s", and "e", which mean "begin", "move", "stop", and "emergency stop", respectively. Before every operation, the motors need homing. Hence, by sending the command "b", the accumulator unit's motor travel upward and the translational motor of the winding unit travel to the left-hand side of the lead screw until they press and activate the micro switches. Then, the accumulator unit's motor travels a pre-defined distance to position itself in the middle of the lead screw and the translational motor of the winding unit position itself in front of the mandrel's fin as depicted in Fig. 9. The user can now send "m" as the message to start the operation and use "s" to stop the winding process. In case of emergency, the command "e" can be used to halt all the motors quickly without allowing any motor deceleration.

In addition, a safe travel distance is defined in the software for all motors. If any motor reaches these limits, either traveling forward or backward, the system will shut down quickly. As an example, during the winding process, if the fiber breaks,

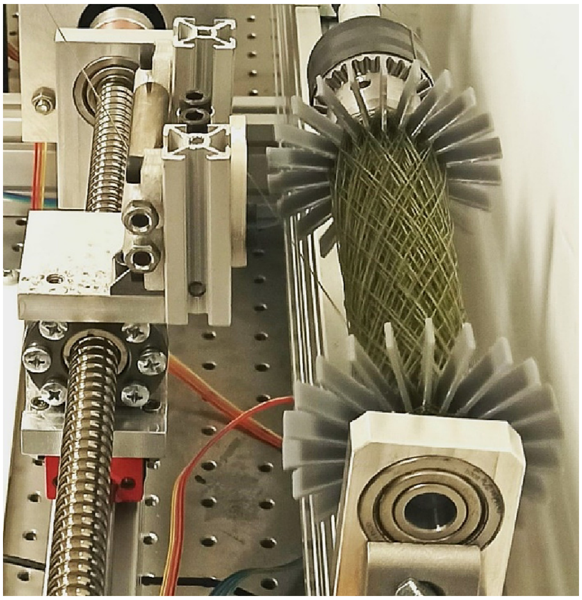

Fig. 9. Homing position of the winding unit's wagon is provided. The wagon automatically stops in this location after the user sends the command "b" through the serial communication port to the board.

Fig. 10. A tapered mandrel wound with 135 m of fiber and 117 m of length between the two supports. The winding process last 5 h, which can be significantly reduced by increasing the velocity of motors.

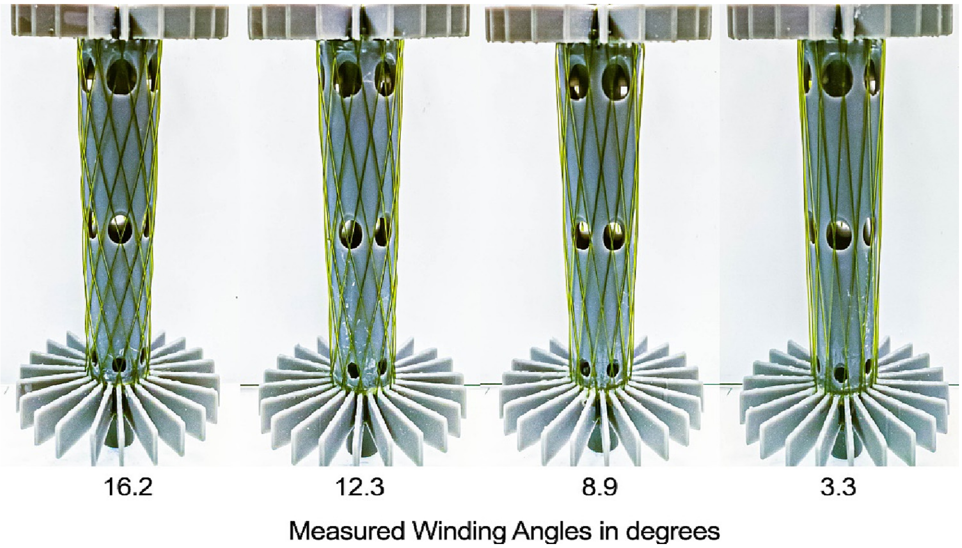

Fig. 11. Examples snapshots of mandrels wound with different winding angles are provided. Proposed system can wind fiber lines on a mandrel with 3.3, 8.9, 12.3, and 16.2 degrees.

the tension sensor will read low values and the accumulator motor will work in one direction constantly. This will cause the accumulator wagon to reach to the end of the lead screw and accidentally break the whole system, as the motors are very powerful. In such conditions, once the motors pass the limits, the whole system halts.

While the system is not posed a major hazard and does not require a skilled operator, general laboratory safety rules and critical engineering judgment needs to be employed during its operation. For example, the user is strongly recommended to:

- not wear loose clothes and protect long hairs
- never touch the lead screws for problems related to long-term oxidization
- not touch the moving parts during the operation
- not disturb the tension sensor while the controller is working
- avoid touching cables without switching off the power supplies

Validation and characterization

We wound 135 m of nylon on the mandrel to test the system at different tension levels. The length of the winded nylon between the two supports is 117 m. The winding process typically lasted five hours, and the machine successfully maintained the desired tension value during the entire process. The image of the winded mandrel is presented in Fig. 10.

We also wound fiber lines with different winding angles. The winding angles of 3.3, 8.9, 12.3, and 16.2 were achieved. Fig. 11 presents the mandrel wound with different winding angles. Similarly, it is possible to adjust the design and modify the code to wind with different winding angles. These results, together with the results of the cascaded PID controller (shown in Fig. 6), indicate that the proposed system is capable of winding at any desired angle while maintaining the tension on the fibers around a constant value during the winding process. The proposed device in this paper is a novel low-cost system. The professional systems intended for mass production are very expensive reaching close to 1 M USD, while a versatile commercial prototype system like the one presented here can cost 100 k USD. To the best of the authors knowledge, the technical details of commercial manufacturing systems are not available in the literature.

Discussion and conclusion

In recent years, fiber winding technology on circular mandrels has gained attention due to its potential for producing high-performance and lightweight components. However, the cost of commercial fiber winding machines is prohibitively expensive. Particularly for small-scale research applications where different configurations need to be tested experimentally, versatile and low-cost systems are desired. The fiber winding machine presented in this study found to be adequate for winding the hollow fibers of blood oxygenator prototypes where a variety of fiber configurations are successfully produced. The machine is capable of winding fibers at the specified angle while controlling the fiber tension at the desired value using a cascaded PID controller. The machine can operate in any environment, with or without skilled personnel, making it suitable for a wide range of applications.

As a future improvement, the system can be expanded to wind multiple fibers at a time by incorporating additional feeds and sensors. This will improve its winding speed and allow new winding patterns. As such, the machine is not designed for winding fibers on large size mandrels but the proposed concept can easily be scaled-up if needed. This low-cost fiber winding machine has potential for broader composite manufacturing applications, particularly in research environments and small-scale prototype production facilities.

CRediT authorship contribution statement

Easa AliAbbasi: Conceptualization, Methodology, Software, Validation, Visualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Anil Akseki:** Conceptualization, Methodology, Software, Validation, Visualization, Formal analysis, Investigation. **Azmat Ullah:** Methodology, Visualization, Validation, Writing – original draft. **Kerem Pekkan:** Conceptualization, Methodology, Supervision, Resources, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Funding was provided by research grants from the European Research Council (ERC) Proof of Concept BloodTurbine, TUBITAK 118S108 and BİDEB – 2247A – 120C139 (PI: Kerem Pekkan).

References

[1] T. Kolobow, R.L. Bowman, Construction and evaluation of an alveolar membrane artificial heart-lung, ASAIO J. 9 (1) (1963) 238–243.
[2] Drinker, P.A. Progress in membrane oxygenator design. In The Journal of the American Society of Anesthesiologists. 1972. The American Society of Anesthesiologists.
[3] Clark, R., et al., Experimental and clinical use of an automated perfusion system and a membrane oxygenator. Circulation, 1974. 50(2 Suppl): p. II213-II218.
[4] K.H. Fraser, M.E. Taskin, B.P. Griffith, Z.J. Wu, The use of computational fluid dynamics in the development of ventricular assist devices, Med. Eng. Phys. 33 (3) (2011) 263–280.
[5] J. Zhang, T.D.C. Nolan, T. Zhang, B.P. Griffith, Z.J. Wu, Characterization of membrane blood oxygenation devices using computational fluid dynamics, J. Membr. Sci. 288 (1-2) (2007) 268–279.
[6] Y. Li et al, Design and experiment on light weight hydraulic cylinder made of carbon fiber reinforced polymer, Compos. Struct. 291 (2022) 115564.
[7] L. Sorrentino, E. Anamateros, C. Bellini, L. Carrino, G. Corcione, A. Leone, G. Paris, Robotic filament winding: An innovative technology to manufacture complex shape structural parts, Compos. Struct. 220 (2019) 699–707.

[8] B. Ellul, D. Camilleri, J. Grech, M. Muscat, Filament wound composite pressure vessels and pipes subject to an internal pressure: an experimental and material characterization study, J. Press. Vessel. Technol. 138 (6) (2016).
[9] Baldwin, D., Development of high pressure hydrogen storage tank for storage and gaseous truck delivery. 2017, Hexagon Lincoln LLC, Lincoln, NE (United States).
[10] J. Mlýnek, M. Petrů, T. Martinec, S.S. Rahimian Koloor, Fabrication of high-quality polymer composite frame by a new method of fiber winding process, Polymers 12 (5) (2020) 1037.
[11] M.a. Quanjin, M.R.M. Rejab, M.S. Idris, B. Bachtiar, J.P. Siregar, M.N. Harith, Design and optimize of 3-axis filament winding machine, IOP Conf. Ser.: Mater. Sci. Eng. 257 (2017) 012039.
[12] N.N. Kadir, Design and development of small scale 2-axis filament winding machine, Mech. Syst. Des. 25 (2016).
[13] S. Srivastava, S. Hoda, A brief theory on latest trend of filament winding machine, Int. J. Adv. Eng. Res. Sci. 3 (4) (2016) 258859.
[14] J.T. Evans, A.G. Gibson, Composite angle ply laminates and netting analysis, Proc. R. Soc. Lond. A 458 (2028) (2002) 3079–3088.
[15] D.K. Roylance, Netting analysis for filament-wound pressure vessels, Army Mater. Mech. Res. Center Technical Note (AMMRC TN) 76 (3) (1976).
[16] M. Rosenow, Wind angle effects in glass fibre-reinforced polyester filament wound pipes, Composites 15 (2) (1984) 144–152.
[17] S. Bhavya et al, Failure analysis of a composite cylinder, IOSR J. Mech. Civil Eng. 3 (3) (2012) 01–07.
[18] L. Parnas, N. Katırcı, Design of fiber-reinforced composite pressure vessels under various loading conditions, Compos. Struct. 58 (1) (2002) 83–95.
[19] F.H. Abdalla, S.A. Mutasher, Y.A. Khalid, S.M. Sapuan, A.M.S. Hamouda, B.B. Sahari, M.M. Hamdan, Design and fabrication of low cost filament winding machine, Mater. Des. 28 (1) (2007) 234–239.
[20] M. Azeem et al, Application of filament winding technology in composite pressure vessels and challenges: a review, J. Storage Mater. 49 (2022) 103468.
[21] S.T. Peters (Ed.), Composite Filament Winding, ASM International, 2011.
[22] J. Frketic, T. Dickens, S. Ramakrishnan, Automated manufacturing and processing of fiber-reinforced polymer (FRP) composites: An additive review of contemporary and modern techniques for advanced materials manufacturing, Addit. Manuf. 14 (2017) 69–86.
[23] J.A. Ateba, G. Verchery, S. Aivazzadeh, A 5-axes filament winder with software control, Sci. Eng. Compos. Mater. 11 (4) (2004) 259–266.
[24] D. Tabuchi et al, Development of a filament-winding machine based on internal heating by a high-temperature fluid for composite vessels, Sensors Mater. 23 (6) (2011) 347–358.
[25] N. Shotton-Gale, D. Harris, S.D. Pandita, M.A. Paget, J.A. Allen, G.F. Fernando, Clean and environmentally friendly wet-filament winding, in: Management, Recycling and Reuse of Waste Composites, Elsevier, 2010, pp. 331–368.
[26] S.D. Pandita, M.S. Irfan, V.R. Machavaram, N. Shotton-Gale, R.S. Mahendran, C.F. Wait, M.A. Paget, D. Harris, C. Leek, G.F. Fernando, Clean wet-filament winding–Part 1: design concept and simulations, J. Compos. Mater. 47 (3) (2013) 379–390.
[27] S. Lye, F. Boey, Development of a low-cost prototype filament-winding system for composite components, J. Mater. Process. Technol. 52 (2–4) (1995) 570–584.
[28] T. Krishnamurthy, M. Idkan, Fabrication of low cost filament winding machine, Int. J. Recent Trends Electr. Electron. Eng 4 (2014) 30–39.
[29] J. Bassler, Colorado State University Rocket team builds newly designed rocket fuselage with filament winding equipment provided by Prodigm, Lattice Composites resins, and Composites One carbon fibers, Reinf. Plast. 64 (2) (2020) 92–96.
[30] P.R. Pagilla, I. Singh, R.V. Dwivedula, *A study on control of accumulators in web processing lines*, J. Dyn. Sys Meas. Control 126 (3) (2004) 453–461.
[31] A.K. Zimmermann, N. Weber, H. Aebert, G. Ziemer, H.P. Wendel, Effect of biopassive and bioactive surface-coatings on the hemocompatibility of membrane oxygenators, J. Biomed. Mater. Res. Part B 80B (2) (2007) 433–439.
[32] A. Andrianov, E.K. Tomita, C.A.G. Veras, B. Telles, A low-cost filament winding technology for university laboratories and startups, Polymers 14 (5) (2022) 1066.
[33] K. Kukko, J.S. Akmal, A. Kangas, M. Salmi, R. Björkstrand, A.-K. Viitanen, J. Partanen, J.M. Pearce, Additively manufactured parametric universal clip-system: An open source approach for aiding personal exposure measurement in the breathing zone, Appl. Sci. 10 (19) (2020) 6671.

Easa AliAbbasi is a Ph.D. candidate at the computational sciences and engineering department of Koc University. He is a member of the Robotics and Mechatronics Laboratory (RML) and currently, his research focuses on surface haptics. Easa attended Oslo University for a period of 2 months as a visiting researcher and learned the basics of electrical impedance and bioimpedance measurements. He completed his master's studies at University of Tabriz with a mechatronics engineering degree. His research interests include haptics, mechatronics, and mathematical modeling.

Dr. Kerem Pekkan is a researcher specialized in cardiovascular engineering, focusing congenital heart defects, cardiovascular mechanics and biological fluid mechanics. He worked as a faculty member at Georgia Institute of Technology, Carnegie Mellon University and Koc University. He published over 120 peer-reviewed manuscripts including 5 international patents on novel pediatric cardiovascular devices. His research team developed computational tools that allow modeling the growth mechanics of blood vessels and used them to improve the surgical operations of pediatric heart diseases.

Anil Akseki's is a undergraduate student at the mechanical engineering department of Koc University. I am a member of Biofluids and Cardiovascular Mechanics laboratory (BCM), and my research focus is on oxygenators and hollow fiber membrane production. Anil founded a research and development start-up company, which is currently working on a project named OriginZero, which aims to develop industrial logic controller devices and low code automation software tools. His research interests include mechatronics, programming, and mechanical design.

Azmat Ullah is pursuing his research as a Ph.D. student in Biomedical Sciences and Engineering Department at Koc University. His research mainly focuses on bio-microfluidics, bioelectronics, MEMS, biosensors, and physics-informed neural networks. He is currently working on developing novel biosensors for extracorporeal membrane oxygenation (ECMO) devices.