Design of a simple drive train and control system for an oxygen blend valve for use with premature infants

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By

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

Design of a simple drive train and control system for an oxygen blend valve for use with premature infants

presented by Erik Pierce,

a candidate for the degree of Master of Science

and hereby certify that, in their opinion, it is worthy of acceptance.

Professor Roger Fales

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Professor Steven Borgelt

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Abstract

Automating the regulation of the fraction of inspired oxygen (FiO_2) in neonatal mechanical ventilation shows great promise of providing better patient outcomes. Historically, controlling the FiO_2 valve has required manual adjustment of a control knob, allowing 21%-100% oxygen to flow to the patient. The current approach requires intense vigilance on the medical staff to ensure that the patients arterial oxygen saturation levels (SpO_2) are above the minimum threshold while simultaneously not high enough to risk retrolental fibroplasia (RLF). Retrolental fibroplasia is an abnormal proliferation of fibrous tissue behind the eye lens that can lead to blindness. Retrolental fibroplasia is caused by the administration of excessive oxygen to premature babies.

Previous work has included the design and physical construction of an automated FiO_2 control valve prototype as well as explored advanced modeling techniques of the prototype and the patient as a complete control system. From this work a second-generation design and six working units were desired with the goal of providing enhanced automated control of the FiO_2 valve and the development of a manufacturable design.

A design for the mechanical interface was created with the following general requirements: utilizing as much of the existing FiO_2 valve design as possible, maintaining the same look and feel to the end user, a desired response time for valve position of one second and allowing for a modular, repeatable manufacturing cycle.

After the new mechanical design became functional, open-loop experiments were conducted to provide data for a basic control model. The model was then refined into a closed-loop system with the objective of minimal position error within an acceptable response time based on previous work. This model was then incorporated into the design of the digital controller.

1 Introduction

1.1 Background

An infant born before full term gestational period of 40 weeks, known as premature, can face many challenges with the final stages of development. This underdevelopment coupled with a lack of surfactant production leads to respiratory distress syndrome (RDS).[1] An infant's lungs are not fully developed until 38-42 weeks old. If an infant is born before this period, some form of supplemental oxygen therapy is necessary to allow the proper oxygen saturation that would normally be provided to the infant via the umbilical cord from the mother.

An abnormal proliferation of fibrous tissue behind the eye lens known as Retrolental Fibroplasia (RLF) was recognized in the United States about 1936, however ideas around the disease did not crystallize until 1942.[2,3] Researchers reported infants with bilateral retrolental fibrous masses appearing during the first six months of life. At the time, this disease was seen as a hazard of prematurity which resulted in blindness in 20% of infants whose birth weight was below 3lb rather than a correlation of treating the patient to higher concentrations of FiO_2 .

Unfortunately, understanding the correct percentage of FiO_2 to provide for the patient to obtain the optimum outcome and regulating the FiO_2 percentage has been a work in progress dating back to the 1940's.[2] Incubators in the late 1940's allowed for high concentrations of FiO_2 for extended periods of time.

Further investigation into the epidemic of RLF in the early 1950's led to adopting a 40% FiO_2 upper limit for the neonatal patient.[1,3] The treatment protocol was revised again in the 1960's allowing for increased oxygen delivery.[1] A second RLF epidemic in the 1980's led to studies that concluded low birth weight and gestational age as the single most important predictors for the development and severity of retinopathy of prematurity (ROP)[1] an alternative name for RLF.

Wright et al have studied the physiologic reduced oxygen protocol (PROP), maintaining a patient's SpO_2 level between 83% to 93% as measured with pulse oximetry. Bounding the SpO_2 to this level has led to a decrease in incidence and treatment for threshold ROP.[1]

To regulate the patients SpO_2 levels, medical staff currently utilize manual control of the blend valve for FiO_2 as well as, heart rate monitoring (HR) and the patient's respiratory rate (RR). This treatment model requires vigilance by the medical staff, if the patient experiences too much FiO_2 there is risk of ROP. Too little FiO_2, and the patient is at risk of hypoxia. The response time to changes of FiO_2 also vary across the population of patients. From previous work a neonatal patient requires between 31.8 and 122.1 seconds to respond to the blend valve position change stimuli.[4]

Literature suggests that the complicated interplay between system variables can be managed with adaptive and robust control techniques. For these techniques to be maximally effective, the mechanical device actuating the FiO_2 blend valve needs to provide consistent and reliable positioning results.[4,5,6,7]

1.2 Literature review

1.2.1 Prior modeling of PMSM

PMSM motors have been studied in detail in full step, hybrid, and micro-stepping configurations.[8] Typical industrial application of stepper motors utilizes full step, open-loop control and relies on the step size to provide positional control without requiring positional feedback. Utilizing full step, open-loop control can unfortunately lead to torque ripples and spontaneous speed reversals. Bodson recommends the utilization of micro-steping with feedback control to achieve the best positional control of the stepper motor.[9] Micro-stepping of the PMSM utilizes additional current setpoints which are a fraction of the maximum current allowing for smaller step angles. As the step angle is decreased the vibration and other dynamic phenomena are reduced.[9]

Additionally, sensorless position control of PMSM has been studied using control techniques such as extended Kalman filtering to estimate mechanical variables of the motor at steady state conditions.[10] However, for low and zero speed, back electromagnetic field detection cannot be used as a sensorless positional control technique.[11] Open-loop control of PMSM provide positional accuracy that is adequate in most applications, but the lack of feedback is a risk for critical applications. Therefore, feedback control is the most appropriate strategy for this work.

1.2.2 Prior work at the University of Missouri

For over a decade, the University of Missouri-Columbia (UMC) has been researching the ability to better control and maintain the oxygen saturation levels in neonatal intensive care unit (NICU) patients. The first-generation automated blend valve controller was created to execute positional changes and aide in the development of more accurate models of the overall system consisting of the patient and blend valve.

The proof-of-concept prototype unit is shown below in Fig 1-1, this system utilized a brushless DC motor which transmitted power with the use of a (geared) belt.

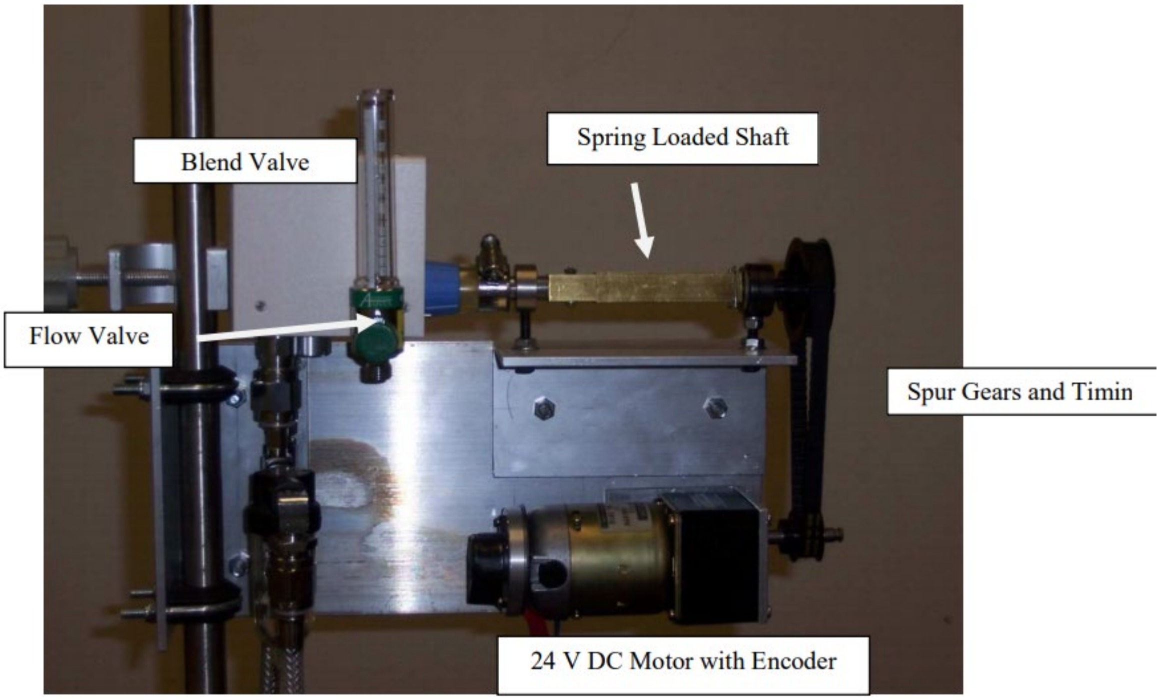

Figure 1-1 Proof of concept prototype mechanical drive train for automated valve control

Ultimately this design was not utilized, and the first-generation automated blend valve controller was proposed and built by Quigley.[12] Figure 1-2 shows Quigley's design that utilizes a brushless DC motor fixed at ninety degrees to the blend valve shaft. Mechanical energy was transferred with the use of two gears and a drive shaft and flexible coupling.

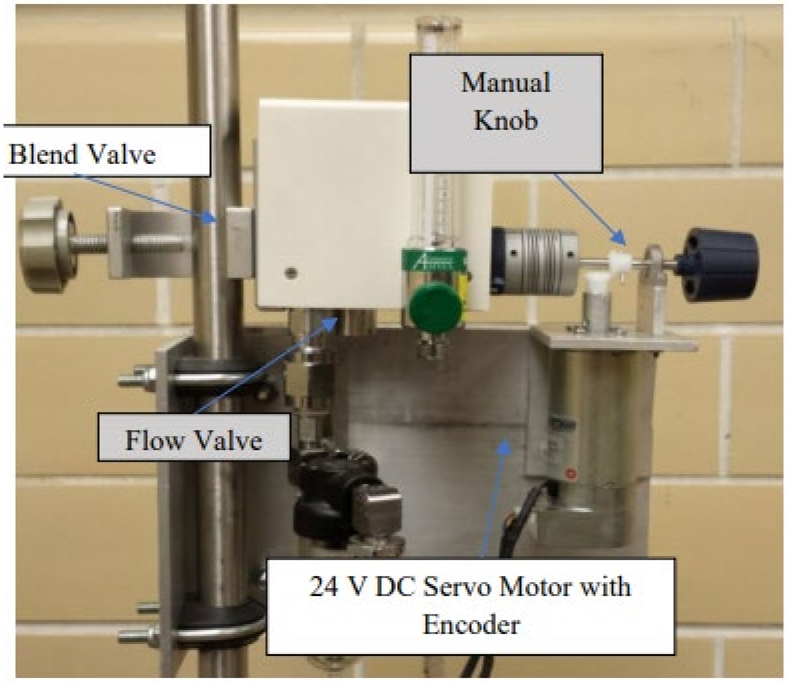

Figure 1-2 First generation prototype mechanical drive train for automated valve control

An important design feature of the first-generation automated blend control valve is the mechanical swiper that is attached to the flexible coupling joining the driveshaft to the BIO-MED DEVICES NEO$_2$ BLEND valve.[12] Shown in Fig. 1-3 this swiper aids in shaft alignment with the BIO-MED DEVICES NEO$_2$ BLEND valve and prevents the operator or control system from exceeding the allowable rotational travel of the blend valve.

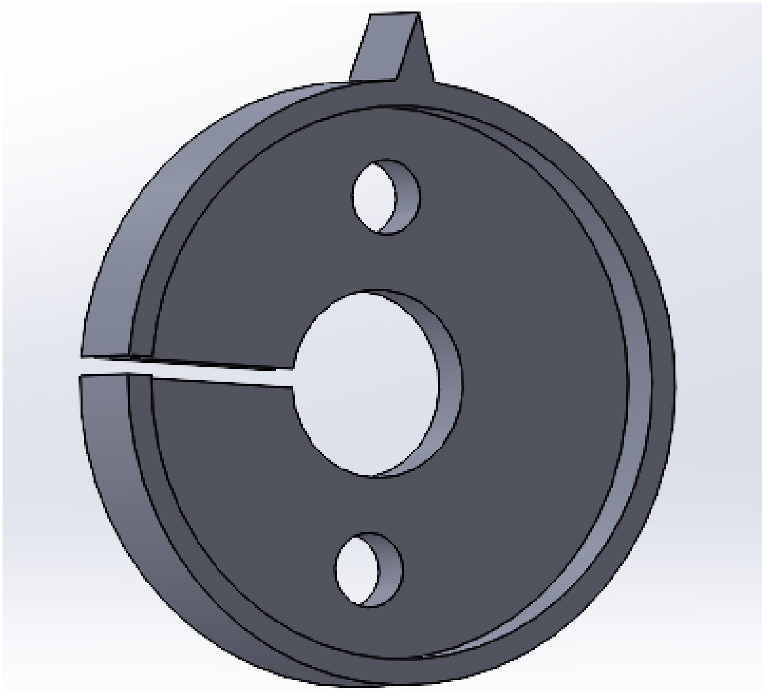

Figure 1-3 First-generation mechanical swiper

Upon obtaining successful results from a first-generation prototype automated blend valve controller design, further refinement was desired. Though previous work indicates that when given a step response of FiO_2, the patient's corresponding SpO_2 has relatively long response time.[4] Kiem's research found that these response times could vary from 31.8138 to 122.1249 seconds, meaning that the patient or system reacts slowly when compared to the capability of most control algorithms.

1.3 Design requirements and research objectives

1.3.1 Design requirements

Several end user needs were considered for the mechanical design as well as the desired approach to the physical actuation of the FiO_2 blend valve position. As the FiO_2 blend valve is calibrated care must be taken when physically interfacing with the actual blend valve. The base FiO_2 blend valve assembly has physical stops that keep the end user from overturning the valve. This feature is integral as it protects the systems calibration.

An additional need and requirement included the end user's ability to overpower the PMSM. The torque of the motor should not exceed the torque produced by the end user.

Finally, the overall experience by the end user needs to be as close as possible to the existing technology. By maintaining the same user experience, less training will be required and there will be easier integration into the medical community. The control knob feel and texture needed to be as close as possible to the original design including a dial indicator.

The end user needs, and requirements are included below.

Table 1.3 End user requirements

End User Need	**End User Requirement**		**Units**
Appearance			
Size should be as compact as possible (width)		3	inches
Size should be as compact as possible (height)		5	inches
Size should be as compact as possible (length)		9	inches
Knob shaft should allow for new knob design	standard shaft, round 5		mm
User-Experience			
Installation should not require recalibration			
Torque of motor should less than avg human grip		15	in-lb
Motor operation should be audible		40	db
Operation			
Accurate positional control	reach 98% of set point in one (1) second		second
Repeatable positional control	2% commanded positional error less		% error
Electro- Mechanical design			
Positional control should be accurate	Utilize an encoder 12 bit or greater resolution		counts
	Utilize a motor driver: 0.9 accuracy or greater 0.5 accuracy or greater		Degree/ %FiO2
Utilize standard voltage supply	Components use 5V, 12V or 24V DC power		VDC

1.3.2 Research objectives

With an understanding of the customer requirements the research objectives were defined. The objective of this research was to develop a second-generation automated blend valve controller capable of meeting the customer requirements, while simultaneously operating for prolonged periods unattended and to produce a design capable of rate manufacturing. Literature reviews of PMSM applications yielded no results of an existing system integration capable of meeting these requirements.

In addition to the creation of necessary engineering documentation to arrive at a working second-generation mechanical prototype, an overall mathematical model would be created that describes the dynamics and interactions of the PMSM and the corresponding drive train. The desired model would be able to be incorporated into a larger control system model that would include the patient's dynamics and previous control strategies to regulate SpO2 for the patient.

PMSM's offer a general positional accuracy of approximately 1.8^{o} degrees when operating in an open-loop controller design. A research objective was to design an open-loop control system that when combined with a micro-stepping controller would allow the second-generation mechanical prototype to maintain positional accuracy greater than 1.8^{o} degrees. Upon realization of the open-loop model, a closed-loop model incorporating positional feedback from an encoder would be developed. A goal of positional accuracy of the 0.5^{o} degrees closed-loop model was desired.

1.4 Thesis overview

Chapter 2 discusses the design of the mechatronic automated valve control and the eventual manufacturing of six working second-generation automated blend valve controllers. Discussion encapsulates the design process from the first-generation design, through the second-generation physical device assembling to the BIO-MED DEVICES NEO_2 BLEND valve. In addition to the physical components, development of the mathematical model for the second-generation automated control system valve is also detailed. The open-loop response of the automated control valve is modeled and then a closed-loop block diagram is created for the model. Equations describing the relationship between the output of the system, the controller and PMSM control gains are explored.

Chapter 3 is broken into four sections. The first section reviews the second-generation mechanical device design results while the second section provides a discussion of the physical design. The third section provides the results for the open-loop and then closed-loop mathematical model. Finally, the fourth section of chapter 3 discusses the results and the implication of the model results.

Chapter 4 summarizes and provides conclusions for the mechanical drive train design and then closed-loop controller. Future work is also discussed including the next steps of the research project.

2 Design, methods, and modeling of system

2.1 Design of mechatronic automated valve control

2.1.1 Mechanical Design

Starting with the first-generation automated blend valve controller prototype, the valve housing was removed as shown in Fig. 2-1. The design was benchmarked against the existing technology to determine areas that met the customer requirements and identified gaps for consideration for the second-generation design.

Four screws anchored the existing housing to the BIO-MED DEVICES NEO$_2$ BLEND valve, these anchor points were reused in the new housing and drive system as part of the design requirements discussed in section 1.3.1. Fig. 2-2 shows the front view of the base FiO$_2$ blend valve assembly with the housing, control knob and first-generation blend valve mechatronic assembly removed.

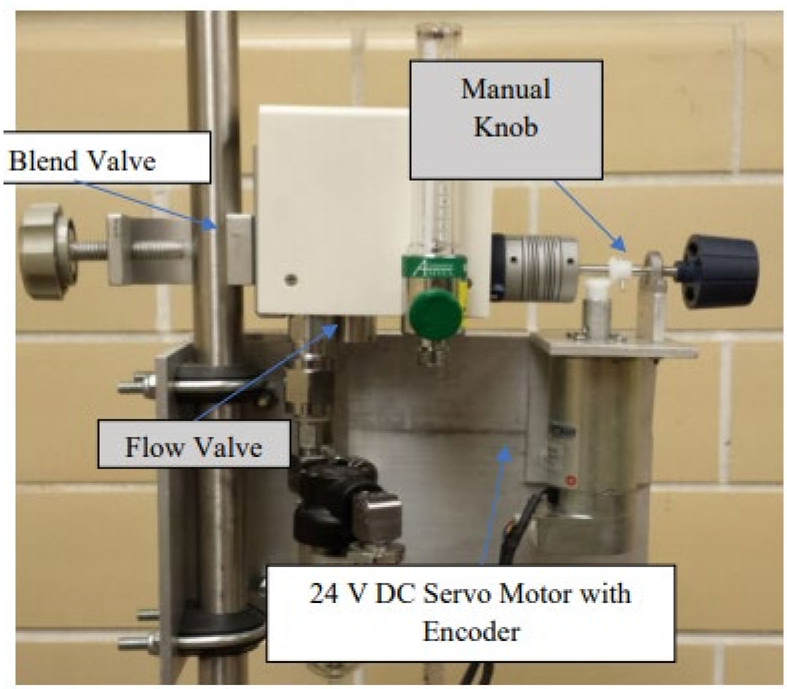

Figure 2-1 Mechanical drive train for first-generation automated valve control

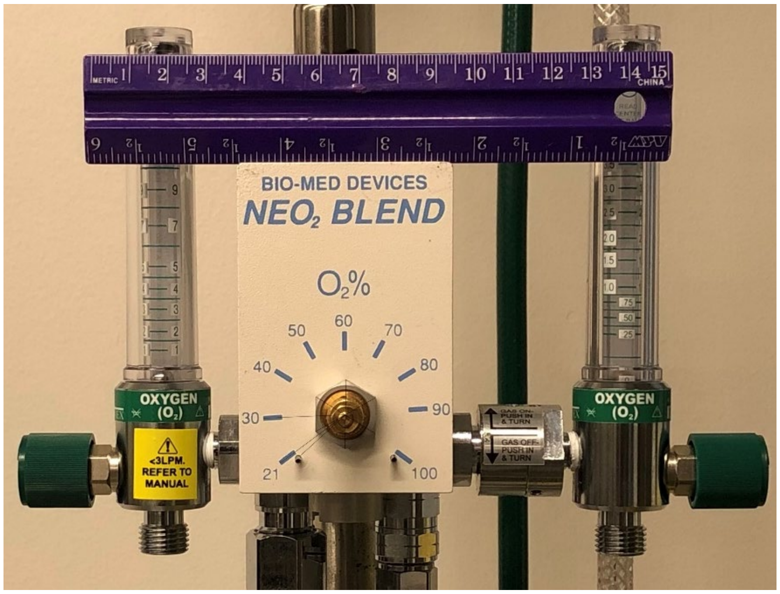

Figure 2-2 Front view of BIO-MED DEVICES NEO$_2$ BLEND valve

The manual knob annotated in Fig. 2-1 is constructed with 3-dimensional printing filament and has a series of slight grooves to improve grip between an operator and the drive shaft. The manual knob is attached to the drive shaft and is supported by a pillow block bearing. A set of nylon gears are used to transfer torque from the DC motor to a drive shaft. A mechanical flex coupling joins the BIO-MED DEVICES NEO$_2$ BLEND valve to the drive shaft. Finally, the mechanical swiper is directly mounted to the flexible coupler. The additional mechatronic components are supported by two mechanical plates that have been attached to the IV pole with use of two-hole u clamps.

While this first-generation prototype has allowed for field testing and other development of controller work within the University of Missouri-Columbia, a more robust design that would meet customer requirements and allow for mass production was desired. A basic failure modes and effects analysis (FMEA) was performed to evaluate areas of concern on first-generation design. The key result from the FMEA was the need for a drive train that minimalized any slippage/positional error. The drive train needed to minimize any parametric uncertainty allowing for simplification of a control system design. From this paradigm, a refined automated blend valve controller conceptual design was proposed that would utilize a permanent magnet stepper motor. The PMSM when paired with a micro stepping controller will improve the positional control accuracy and repeatability of drive shaft movements. Stepper motors have been used for positional control in other applications such as computer numerical control (CNC) machining equipment and are regarded for their durability, simplicity, and high torque to inertia ratio.[5] In addition to the PMSM, an absolute encoder would be added to provide constant feedback of the shaft position.

Starting with the base BIO-MED DEVICES NEO$_2$ BLEND valve, and the selection of an appropriate PMSM, a second-generation mechanical design was proposed. A mechanical design was desired that minimized the amount of misalignment therefore minimizing any torque losses or positional error. By incorporating flexible shaft couplings and ball bearing reaction points, any slight misalignment could be minimized allowing smooth rotational movement.

In addition to the need for minimal misalignment in an operational environment, special consideration needed to be given to aligning the mechanical components during assembly. Alignment tooling was developed to aid in repeatable assembly and locating the centerline of any drive train assemblies.

2.1.1.1 Permanent Magnet Stepper Motor

A basic dual shaft PMSM was selected with a step angle of 1.8° equating to 200 steps per 1 revolution. Like most basic stepper motors, the unit selected is two phase. The phases are created by the excitation of the two coils that make up the PMSM. While one coil is excited with a Sine wave the other is excited with a Cosine waveform. The PMSM will be controlled by a motor driver capable of micro-stepping up the signal into 1/32 of the standard step size of 1.8°.[13,14] The torque of the selected PMSM was below the requirement of 15 in-lb, allowing the user to easily overpower the PMSM in the event of a catastrophic system failure.

2.1.1.2 Encoder

From the end user requirements, an absolute encoder was selected that offered 12-bit resolution. Using RS-485 serial communication protocol, the encoder and cable were mounted to a custom aluminum standoff. RS-485 is an industry standard communication protocol that is considered robust and allows for 'polling' or verification that the communication path is still active.

2.1.1.3 Overall design of mechanical drive train

The 3-dimensional model of the overall design is shown in Fig. 2-3. To meet the design requirements, the mechanical drive train consisting of the following: dual shaft PMSM, absolute encoder, shaft couplings and alignment bearings set shown in the basic mounting fixture.

This mounting fixture is then mounted to a cradling bracket that mates with the overall housing. The cradled assembly can rest in the overall housing until the it is fastened to the BIO-MED DEVICES NEO$_2$ BLEND valve with the use of the four mounting screws. Once in position the four cradle screws also shown in Fig. 2-3 can be adjusted to allow the mounting fixture to slide toward the BIO-MED DEVICES NEO$_2$ BLEND valve. The flexible shaft coupling can then be attached to the BIO-MED DEVICES NEO$_2$ BLEND valve.

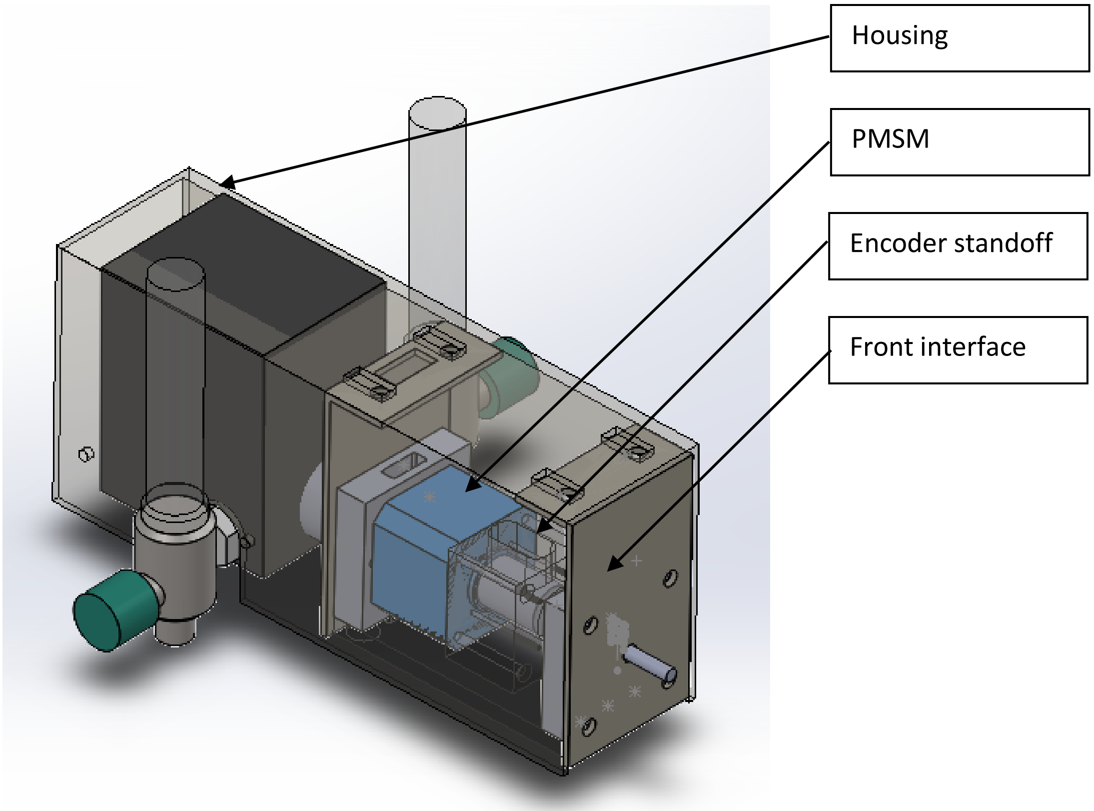

Figure 2-3 3-D representation of automated blend valve controller mechanical assembly

2.1.2 Electrical Design

The approach for the electrical design of the mechatronic assembly was to control the phase signals to the dual shaft, two phase, PMSM through use of a motor driver by commanding the frequency response of the motor. Starting with the NI controller, an output of commanded pulses and desired motor direction will be sent to the motor driver as illustrated in Fig. 2-4. The motor driver will then output DC voltages at a specific frequency on each PMSM phase. The combination of controlling the frequency to each coil or phase of the PMSM allows the achievement of a micro-stepped response. [9,13]

The selected motor driver is capable of micro-stepping the commanded response up to thirty-two segments. For this work a micro-stepping value of two was selected. This value was chosen as it would effectively double the resolution of the PMSM to 400 counts per revolution. This arrangement allows for 0.9^{o} of travel per PMSM step of movement.

Noting that the BIO-MED DEVICES NEO_2 BLEND valve can travel approximately 259^{o} representing a range of FiO_2 of 21-100%. This scenario results in approximately 3.6 steps per percentage change of FiO_2.

Starting with an open-loop response evaluation, closed-loop control would be explored and incorporated with the use of an absolute encoder. Fig. 2-4 shows the overall mechatronic schematic [4].

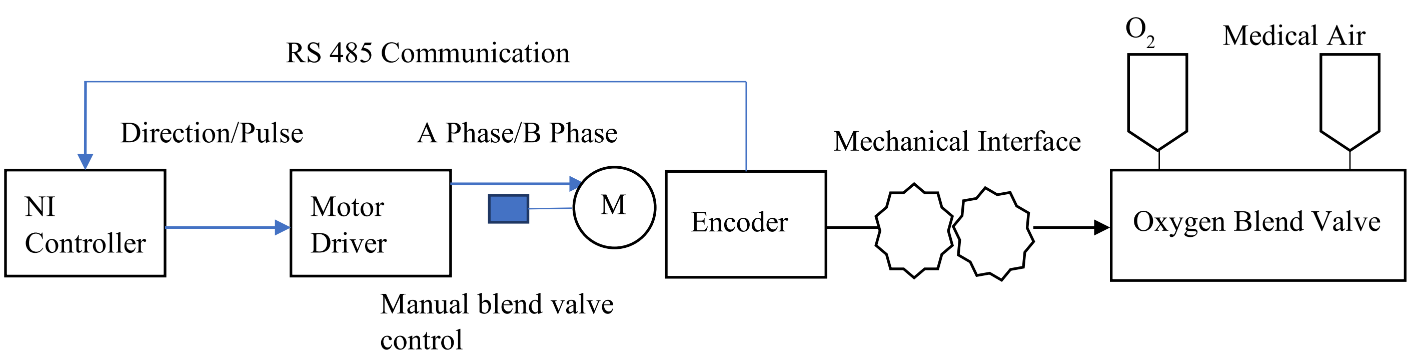

Figure 2-4 Design model of FiO_2 blend valve mechatronic system

2.1.2.1 Open-loop model

Starting with the mechanical assembly positioned on a bench top as shown in Fig. 2-5 several open-loop tests were conducted to characterize the dynamics of the second-generation automated blend valve controller.

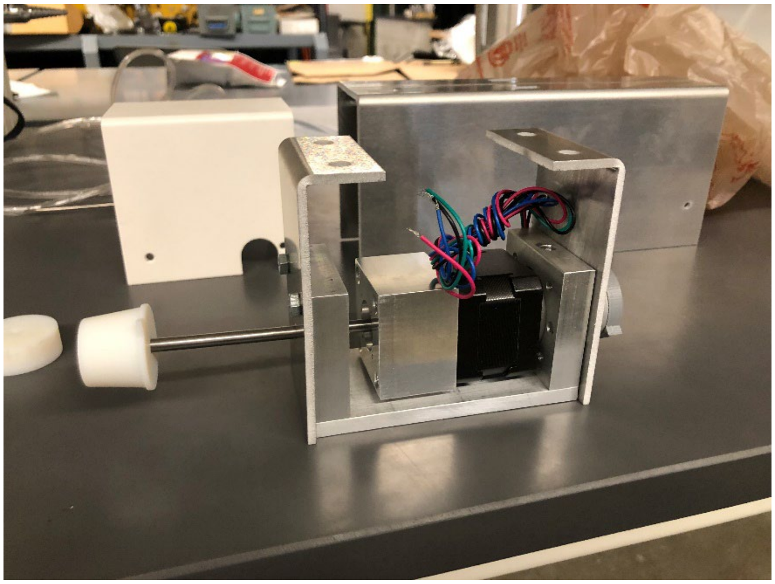

Figure 2-5 Basic mechanical assembly used to facilitate open-loop experiments

The NI controller broadcast a direct current (DC) voltage at a user-controlled frequency to create a square wave signal. A NI LabVIEW user interface allowed for changes of direction, and control of the square wave frequency. This square wave frequency was then micro-stepped and sent to the PMSM to achieve a change in position. Figure 2-6 shows the open-loop mechatronic schematic.

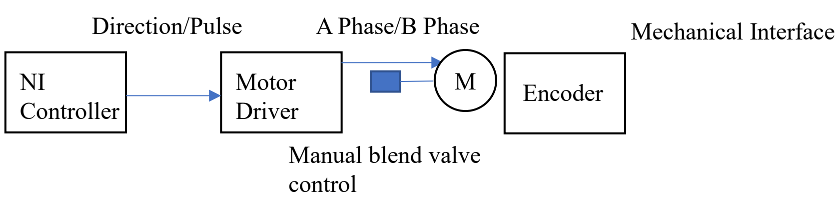

Figure 2-6 Basic mechatronic for open-loop experiments

The open-loop model was evaluated over a constant frequency of $4x10^6$ periods/tick. The motor shaft position in encoder counts was plotted against time. Given a constant frequency of pulses to the PMSM, it can be expected that the positional response is approximately linear or described by a first order polynomial over a given time which is consistent with integration of a constant signal over time, $y(t) = K_1 \int f(t)\, dt$, where K_1 is proportional PMSM gain, $f(t)$ is the frequency response provided to the PMSM and $y(t)$ is the PMSM position. This type of system is known as a type I system and can be easily mathematically modeled with the use of an integrator.[15] The plant, $G(s)$, is described as,

$$G(s) = \frac{Y(s)}{F(s)} = \frac{K_1}{s}. \qquad (2.1)$$

Utilizing Simulink, a very basic model was created to represent the open-loop system shown in Fig. 2-7.

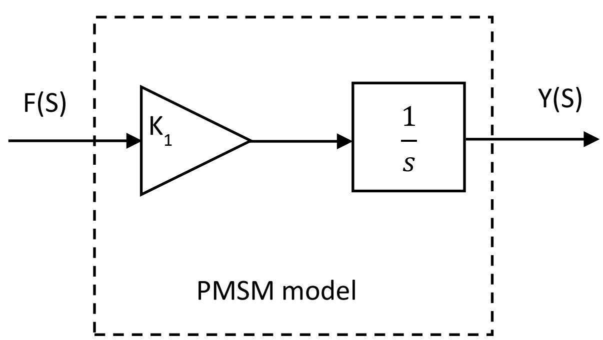

Figure 2-7 Type 1 system open-loop model

The modeled motor shaft position in units of counts was plotted along with the data from an experiment using a second-generation mechanical assembly and shown in Fig. 2-8. When subjected to a step response, the system was indeed first order or a ramp function confirming the validity of a type I system approach.

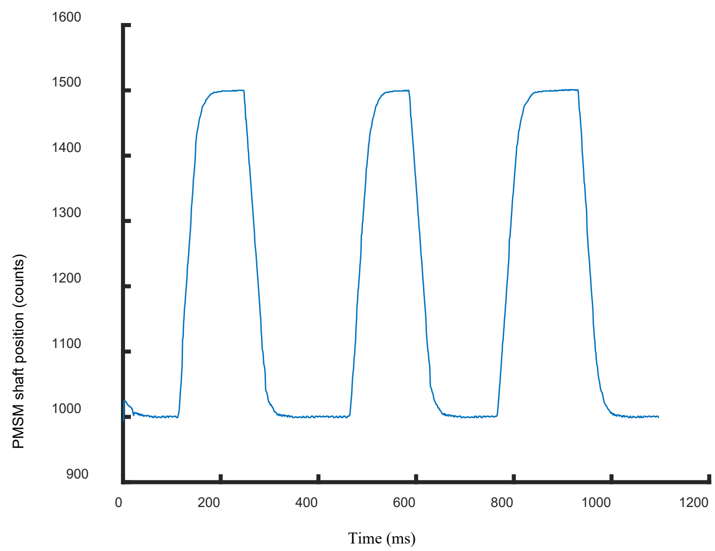

Figure 2-8 PMSM shaft position during open-loop step response experiment.

To match the model and test results, the slope of the positional response was calculated. Using this slope and the constant frequency, K_1 was determined.

2.1.2.2 Closed-loop system design

The selected PMSM when coupled with the micro-stepping controller is capable of positional error of approximately 0.9^{o} while operating in an open-loop configuration. While this may have been adequate to meet the customer requirements of positional error for this application, an open-loop control scheme is not appropriate for a medical application. The addition of an absolute encoder allows for the mitigation of several failure modes identified in the FMEA. By providing the NI controller an absolute position, calibration algorithms, and error handling can be added to the overall system architecture.

Determining the desired positional accuracy for a closed-loop controller, it was noted that the BIO-MED DEVICES NEO_2 BLEND valve has an Oxygen % accuracy of +/- 3% [16], or approximately 112 encoder counts. The PMSM can maintain an accuracy of approximately 21 encoder counts with open-loop and no micro stepping of frequency pulses. As such, a design goal of 6 encoder counts of positional error was selected for a closed-loop control.

The critical variable to the patient is the control of SpO_2. From previous work the settling time for a patient is over seventy seconds long [4]. A one second settling time for the position of the FiO_2 valve was selected as a design constraint to allow the system respond quickly while unintended dynamics such as torque rippling can be eliminated.

The closed model was proposed and is illustrated in Fig. 2-9. Since this system can be modeled as a single integrator (and is a type I system), a simple proportional control is proposed and evaluated for this project. A zero-order hold block also shown in Fig. 2-9 was added to act as a sample and hold associated with the digital to analog conversion for the mathematical model. This conversion block allows the model to represent real dynamic interactions more accurately. To determine the value of K_2, a set of equations for the closed-loop system were derived from the block diagram.

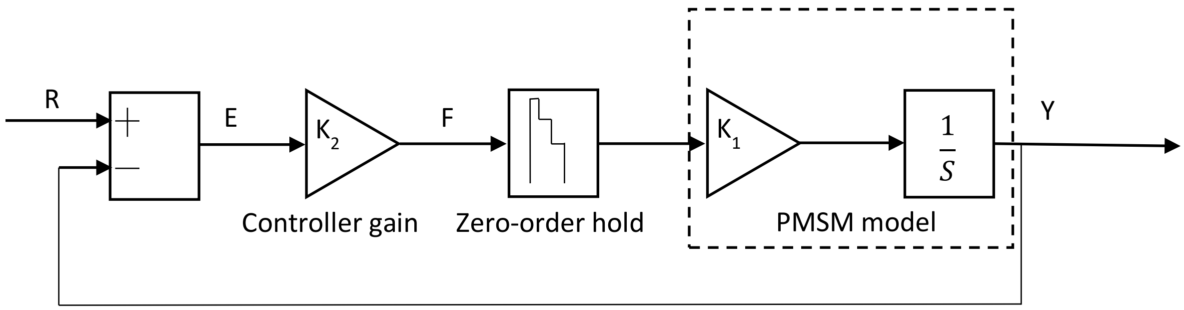

Figure 2-9 Closed-loop model of second-generation automated blend valve

The frequency $F(s)$ and the system error $E(s)$ are,

$$F(s) = E(s)K_2, \text{ and} \tag{2.2}$$

$$E(s) = R(s) - Y(s), \tag{2.3}$$

where K_2 is the proportional gain for the system. The system error is the reference commanded position subtracting the current position. Relating the system error to the proportional gain (2.4) relates the system error to the proportional gain K_2 as shown below

$$E(s) = \frac{Y(s)}{G(s)K_2} \ . \tag{2.4}$$

Substituting $E(s)$ from (2.4) into (2.3), (2.5) can be established as,

$$Y(s)(1 + G(s)K_2) = G(s)K_2R(s) \tag{2.5}$$

further simplification of (2.5) results in

$$\frac{Y(s)}{R(s)} = \frac{G(s)K_2}{1 + G(s)K_2} = \frac{1}{1 + \frac{1}{G(s)K_2}}. \tag{2.6}$$

Finally, substituting (2.1) back into (2.6),

$$\frac{Y(s)}{R(s)} = \frac{G(s)K_2}{1 + G(s)K_2} = \frac{1}{1 + \frac{s}{K_1K_2}} \tag{2.7}$$

creates (2.7).

Using Ogata's correlation between the system response to a step input [17] and (2.7) a relationship between the time constant T_c, the PMSM gain, and proportional controller gain is realized.

This relationship is shown below in (2.8) and (2.9)

$$T_c = \frac{1}{K_1K_2}, \text{and solving for } K_2, \tag{2.8}$$

$$K_2 = \frac{1}{K_1T_c}. \tag{2.9}$$

Since this is a first order system, when provided a step response it can be expected that the system will be at approximately 98.2% of commanded position at four time constants T_c. [12]

A T_c of 0.25 seconds was chosen as one second is still substantially faster than the response of the neonatel patient.[4]

3 Results and discussion

In this chapter the results and discussion will be presented for the mechanical design, the open-loop controller and closed-loop controller for the second-generation automated blend valve controller.

3.1 Second-generation automated blend valve mechanical design results

Starting the selected components detailed in Chapter 2, a first article was created for the encoder standoff shown below in Fig. 3-1 and Fig. 3-4. For the material, a basic aluminum was chosen due to ease of availability and machining characteristics.

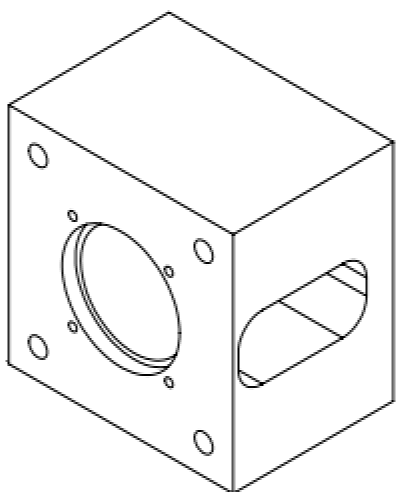

Figure 3-1 Encoder standoff allowing encoder integration to dual shaft PMSM

The encoder standoff is unique in that it allows for an additional flexible shaft coupling to be installed in the drive train. An offset slot was milled into the side to allow for adjustment of the flexible shaft coupling.

A front and rear mounting bracket and a base plate were created to complete the basic drive train of the assembly. The front mounting bracket is shown in Fig. 3-2 additional mounting holes were added to facilitate future end user interface designs. Extra holes are included to allow the adjustment or replacement of the encoder without complete disassembly of system.

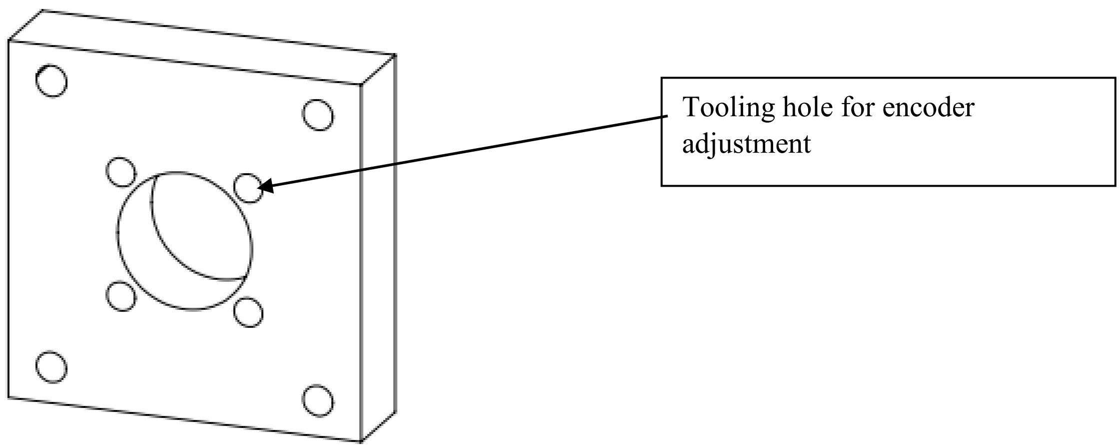

Figure 3-2 Front mounting bracket

Figure 3-3 illustrates the back drive train bracket. Additional slots in the top and the bottom of the bracket allow for adjustment to the flexible shaft coupling that attaches to the BIO-MED DEVICES NEO_2 BLEND valve.

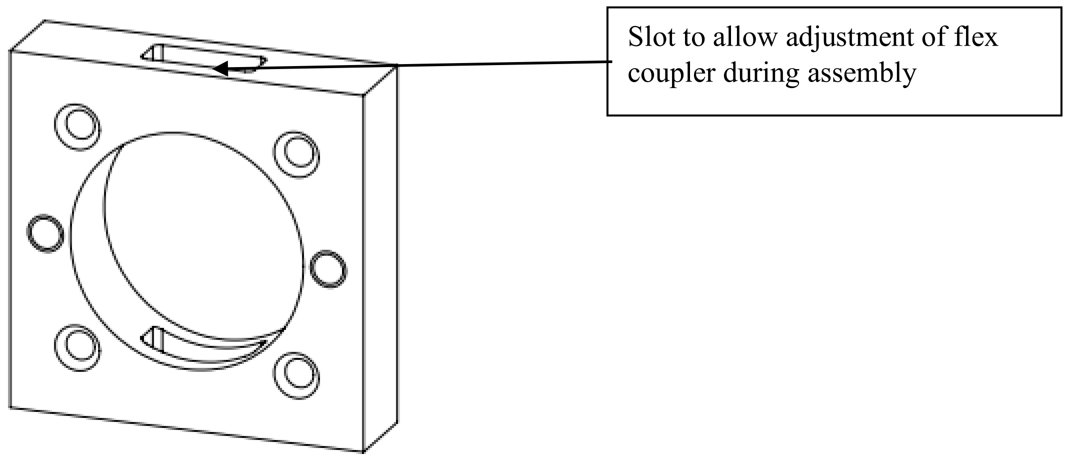

Figure 3-3 Back mounting bracket

After the mechanical drive train was established, a basic first article was created for the housing and cradle brackets that allow the drive train to mechanically integrate with the BIO-MED DEVICES NEO_2 BLEND. An actual drive train assembly with attached cradle brackets are shown in Fig. 3-4. The housing is shown in the Fig. 3-5.

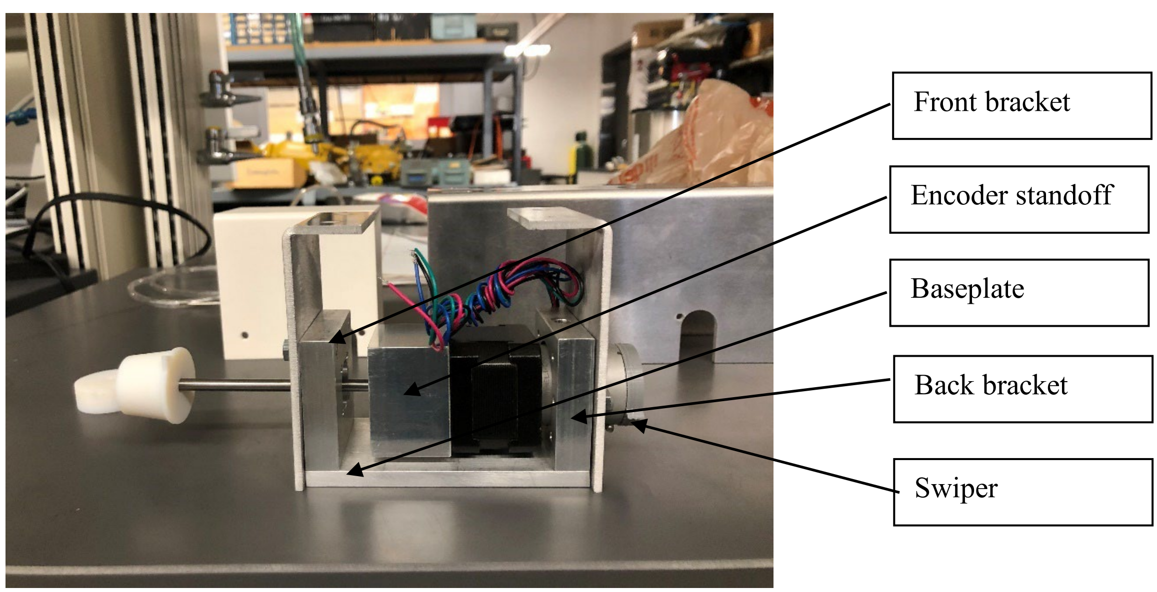

Figure 3-4 Mechanical assembly for second-generation automated blend valve controller

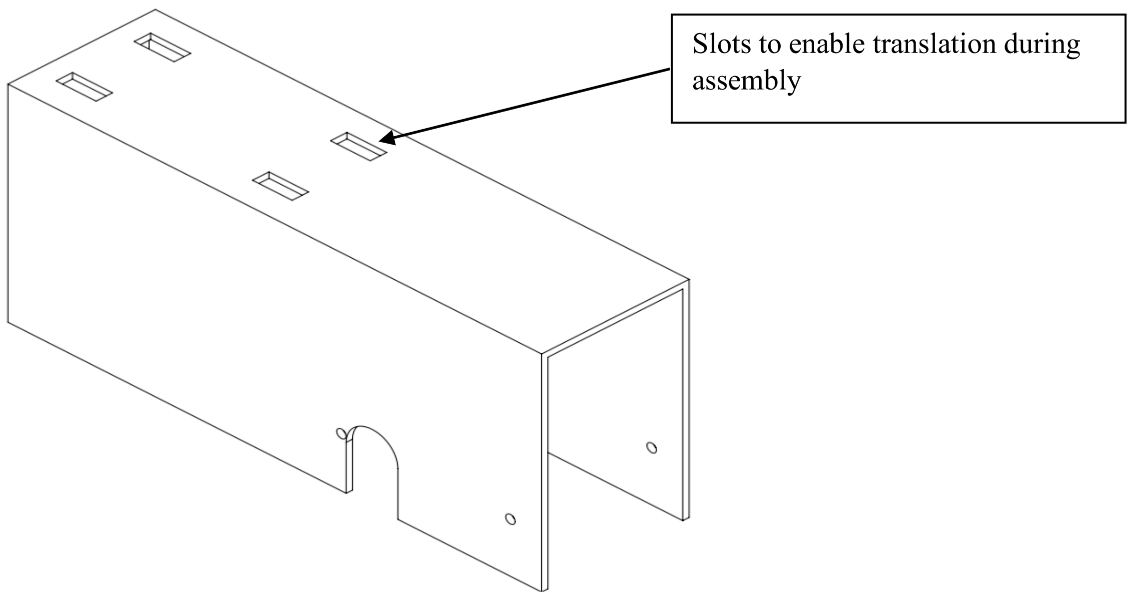

Figure 3-5 Overall housing for second-generation automated blend valve assembly

After the first article fit up had been completed, drawings were updated, and a bill of materials (BOM) created. Figure 3-6 shows the entire finished assembly mounted on the IV support pole.

Using the lessons learned from the first article build, five more second-generation automated blend valve controllers were created and assembled. From the first to second-generation automated blend valve a 7.36% reduction in height was realized. The overall length increased by 18.73% for the housing itself however, the auxiliary mounting plate was able to be removed from the IV pole shown in Fig. 3-6, Fig. 3-7 and an overall comparison between the first-generation and second-generation automated blend valve controllers is shown in Fig. 3-8.

Figure 3-6 Second-generation automated blend valve controller with housing and auxiliary mounting plate

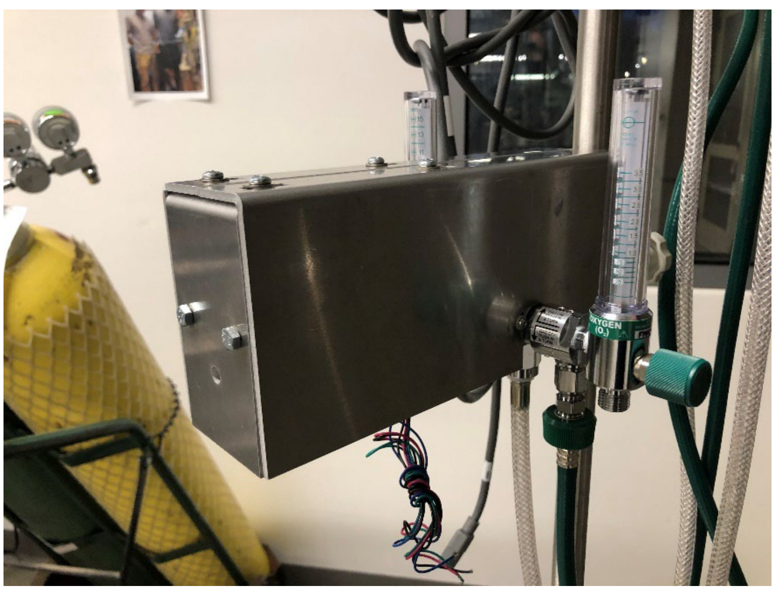

Figure 3-7 Second-generation automated blend valve controller with housing

Figure 3-8 First-generation (left) and second-generation (right) automated blend valve controller

Consideration was given for the calibration of the BIO-MED DEVICES NEO_2 BLEND valve . The new design allows for mating of the shaft coupler to the original valve while the new mechanical assembly is supported by the outer housing.

The mechanical portion of the second-generation automated blend valve controller can be assembled in approximately twenty minutes and can be kitted for rapid deployment to end users. Four screws allow the mechanical drive assembly to slide forward or backward while mating the flexible coupler to the BIO-MED DEVICES NEO_2 BLEND valve.

3.2 Second-generation automated blend valve mechanical design discussion

The mechanical design was successful in meeting the design requirements, as well as improvements to the mounting of the controller to the IV, the overall alignment of the drive train, and upgrading the motor to a PMSM. An auxiliary mounting plate is no longer needed and the second-generation automated blend valve controller can mount to and IV pole using the existing hardware from the BIO-MED DEVICES NEO_2 BLEND valve. The new drive train is mechanically robust and tooling allows for alignment of the PMSM driveshaft during assembly. The selected PMSM is audible when in operation and can be overpowered by an operator in an emergency. The PMSM can maintain accurate positional control and with the use of the mechanical swiper from the first-generation design, recalibration of the valve can be avoided during assembly.

Several design improvements such as additional slots to aide assembly, were made during the first article part and are included in the latest red lined drawings and subsequent part releases.

A takeaway from previous work, zeroing out the mechanical swiper (shown in Fig. 1-3) in relationship to the 21% FiO_2 on the blend valve was integral to this design effort as well. Maintaining calibration throughout the reinstallation of the automated drive train will be paramount for success of field upgrades.

3.3 Second-generation control system results

3.3.1 Open-loop response results

The slope of the response from the open-loop system experiment is shown in Fig 3-9 and was calculated to be 1.0296×10^4 counts/second.

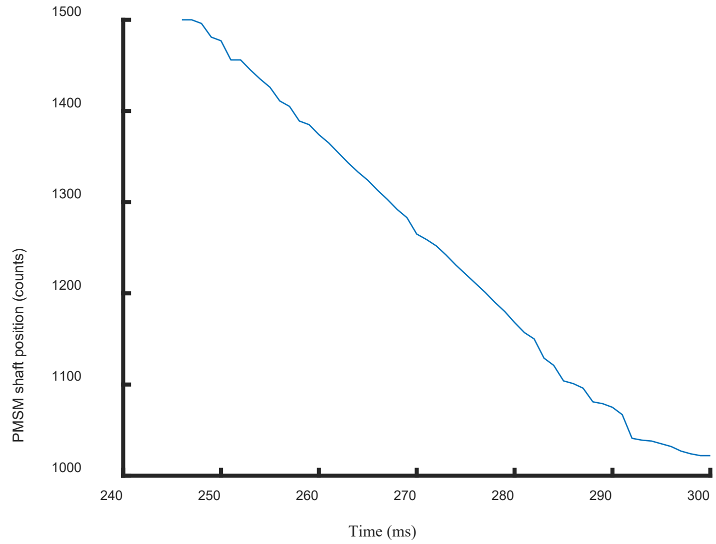

Figure 3-9 PMSM shaft position over time for an open-loop experimental case vs a first order PMSM model

Since the experiment was performed at a constant frequency of 4×10^6 periods/tick, K_1 was determined to be 2.571×10^9 periods/second.

3.3.2 Closed-loop response to a step input results

After mathematically determining the motor gain and the subsequent proportional controller gain K_2 was calculated as 1.502×10^{-8} using the equations shown in Chapter 2.1.2.2. The automated blend valve controller was able to obtain a position that was within 3 encoder counts of the commanded position when supplied a step response. An input of a step response of 1000 counts was supplied to the closed-loop system. Figure 3-10 and Fig. 3-11 show both the model and actual response to the step input. The error of the closed-loop response is illustrated in Fig. 3-12.

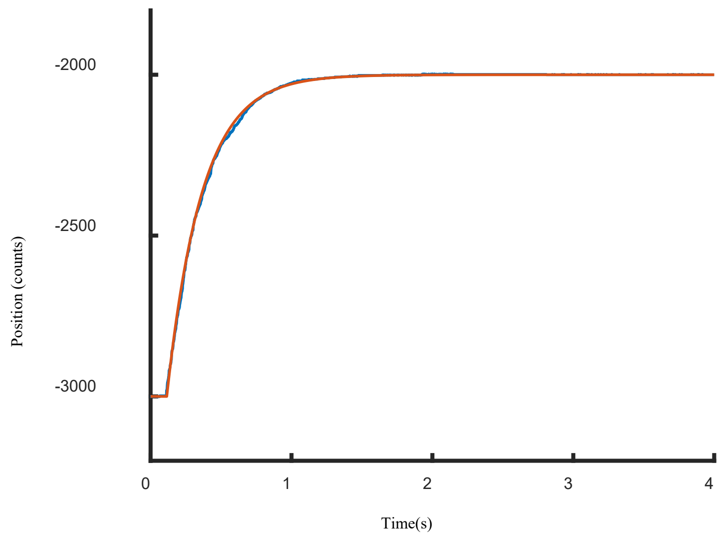

Figure 3-10 Step response of closed-loop model versus second-generation automated blend valve response

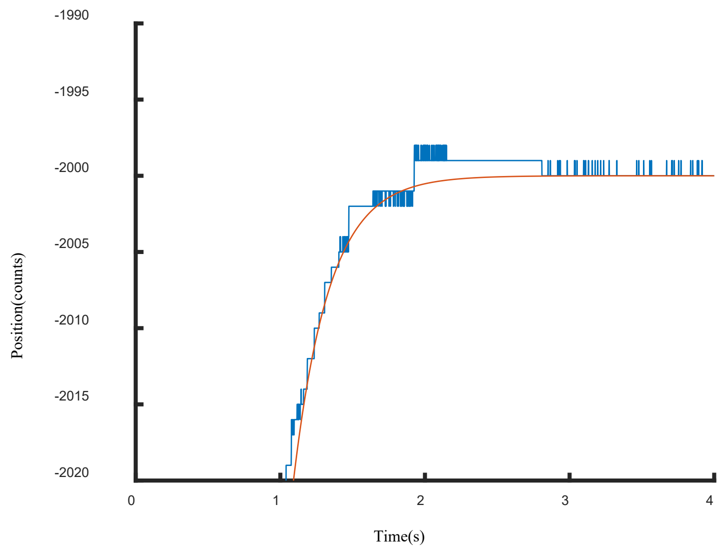

Figure 3-11 Commanded position of second-generation automated blend valve with closed-loop control versus reference step input.

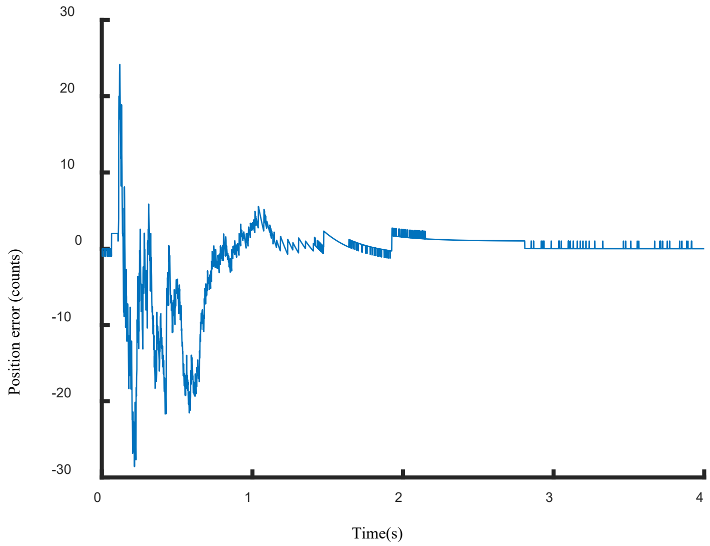

Figure 3-12 Positional error for closed-loop control of second-generation automated blend valve

The combination of the PMSM, micro-stepping motor driver and closed-loop proportional control produced a system capable of repeating positional accuracy of 0.26º rather than 1.8º for a standard PMSM.

3.4 Second-generation automated blend valve control design discussion

3.4.1 Open-loop response to a step input discussion

The modeling of the open-loop response of the selected PMSM as a type I system was successful when considering the results. This was to be expected as PMSM are used in many applications currently, with open-loop control and have a relatively low percentage of error. Though further exploration of the model is possible with consideration to higher or ultra-high frequency responses, the necessary customer requirements don't call for this type of rapid response. The open-loop model provides an appropriate approximation for the second-generation automated controller for the BIO-MED DEVICES NEO_2 BLEND valve.

The positional error was slightly lower for the lower frequency experiments which aligns with previous research and expectations. Based on these results, a frequency limit for system operation would be appropriate to ensure consistent positional error responses.

3.4.2 Closed-loop response to a step function discussion

Building off the open-loop model, the closed-loop proportional control was deemed an appropriate starting point for investigation. Proportional control though a basic approach when compared to other controller strategies, provides an acceptable positional tracking when responding to a step response for this application. Further refinement to the positional tracking may be possible with the addition of control strategies such as proportional integrator control, however with the very low positional error with respect to customer requirements it was not deemed necessary at this time.

Closed-loop control for a PMSM has been explored in previous research [11,14] and the accuracy of the positional tracking is reasonable when compared to other efforts combining PMSM with micro-stepping of phases.

4 Summaries, Conclusions and Future Work

4.1 Automated blend valve controller summary

A working second-generation automated blend valve controller was designed, manufactured, and assembled incorporating customer requirements based off the initial efforts to automatically control the BIO-MED DEVICES NEO_2 BLEND valve. A bill of materials, step (.stp) mechanical model files and drawings were created to facilitate a repeatable manufacturing process that would be ready for manufacturing optimization. The design consists of a motor encoder standoff, drive train assembly and cradle and housing that allow for the mechanical connection to the BIO-MED DEVICES NEO_2 BLEND valve. The design allowed for the integration of an absolute encoder to be joined to the dual shaft PMSM with consideration given to the wiring of both the encoder and the PMSM. The incorporation of a dual shaft PMSM is unique when compared to previous literature in that it allows the use of an absolute encoder and serves as a manual override to the controller.

The design was refined during an initial first article build and then repeated to produce a total of six automated blend valve controllers that will be used for upcoming clinical trials for the overall system. The second-generation automated blend valve controller when combined with NI controller and micro-stepping motor driver produced repeatable positional accuracy greater than the design requirements. The second-generation automated blend valve controller also has a reduced overall footprint, the ability to be user overridden in emergency and has the ability to be produced on a large scale.

4.2 Closed-loop controller summary

The automated blend valve controller was designed using a simple proportional control algorithm based on laboratory experiments with open-loop control to determine the PMSM model. The control system, although basic, achieves positional control within 0.175% of the commanded position. Further refinement may be possible, however when considering the downstream system, it was decided that this controller is currently adequate for the design objectives.

4.3 Conclusions

Starting with the previous work of Kiem and Quigley, an analysis was performed to determine customer needs, customer requirements and eventually research objectives to further refine parts of this work. The research objectives included: development of a mechanical prototype and necessary documentation for rate production, researching and developing a control algorithm that would provide highly accurate positional control while maintaining an appropriate settling time, and meet the customer requirements.

The research objectives were met as the necessary mechanical manufacturing documentation was created, the control algorithm performs above the requirements and all customer needs are met except for a slightly longer overall footprint. The increase of the footprint is deemed acceptable as an auxiliary mounting plate can be removed and the second-generation automated blend valve controller can be left unattended for up to twelve hours.

4.4 Future work

The second-generation automated blend valve controller can now be integrated into the large system as shown in Fig. 4-3 and Fig. 4-4. Refinement will continue the user interface with ergonomic improvements.

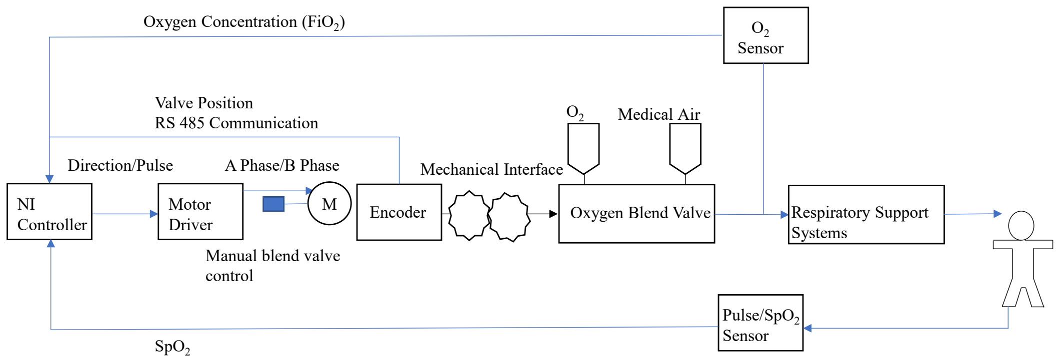

Figure 4-3 Overall system for neonatal patient control of %SpO_2.

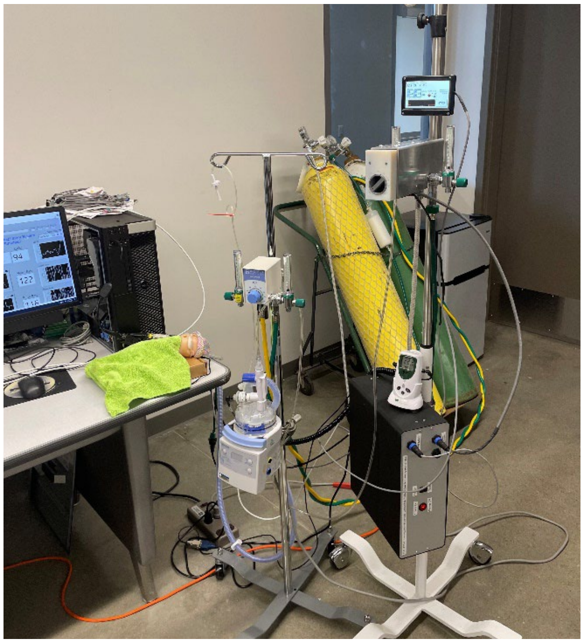

Figure 4-4 Second-generation automated blend valve controller with prototype user interface and human machine interface (HMI).

Automation of the O_2 valve is also under consideration. The system is about to undergo clinical trials and will be left unattended for up to twelve hours providing critical performance data drive further refinements.

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