NeT-Vent

University of Queensland Engineering Design Hackathon, Oct 2020

End-to-End Open-Source, Low-Cost & Easy to Manufacture Ventilator Design with Automatic Reduction of Pulmonary Barotrauma (VILI) & IoT enabling to drastically reduce PPE-Kit Requirement & exposure of medical staff to COVID-19.

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Prior Art (Literature Review)

In this project, the problem of pulmonary barotrauma is addressed based on experimental results published in different articles.

1. McGuinness, G., Zhan, C., Rosenberg, N., Azour, L., Wickstrom, M., Mason, D. M., ... & Moore, W. H. (2020). High incidence of barotrauma in patients with COVID-19 infection on invasive mechanical ventilation. *Radiology*, 202352.
2. Udi, J., Lang, C. N., Zotzmann, V., Krueger, K., Fluegle, A., Bamberg, F., ... & Staudacher, D. L. (2020). Incidence of Barotrauma in Patients With COVID-19 Pneumonia During Prolonged Invasive Mechanical Ventilation–A Case-Control Study. *Journal of intensive care medicine*, 0885066620954364.
3. Pattupara, A., Modi, V., Goldberg, J., Ho, K. S., Bhatia, K., Herrera, Y., & Ghassibi, J. (2020). PULMONARY BAROTRAUMA DURING NONINVASIVE VENTILATION IN PATIENTS WITH COVID-19. *Chest*, *158*(4), A337.
4. Glas, G. J., Horn, J., van der Hoeven, S. M., Hollmann, M. W., Cleffken, B., Colpaert, K., ... & Malbrain, M. (2020). Changes in ventilator settings and ventilation–induced lung injury in burn patients—A systematic review. *Burns*, *46*(4), 762-770.
5. Katira, B. H. (2019). Ventilator-induced lung injury: classic and novel concepts. *Respiratory care*, *64*(6), 629-637.
6. Oeckler, R. A., & Hubmayr, R. D. (2007). Ventilator-associated lung injury: a search for better therapeutic targets. *European respiratory journal*, *30*(6), 1216-1226.

Literature Review suggests that Pulmonary Barotrauma (Ventilator Induced Lung Injury) is a major problem during ventilation of patients with COVID-19 & other diseases which is life-threatening, can lead to multi-organ failure & leads to increased mortality.

Pulmonary Barotrauma (VILI)

- Pulmonary barotrauma, a form of Ventilator induced lung injury (VILI), occurs due to elevated transalveolar pressure causing alveolar rupture while patient is on Ventilator.
- Results in increased mortality, can lead to multi-organ failure & is life-threatening. Moreover, excess alveolar air could result in complications such as pneumothorax.
- The natural mechanism of breathing in humans depends on -ve intrathoracic pressures, whereas patients on mechanical ventilation ventilate with +ve pressures. Since +ve pressure ventilation is not physiological, it may lead to barotrauma.
- Adjacent CT Scan shows clinical course of an cerebral air embolism likely due to ruptured pulmonary bullae.

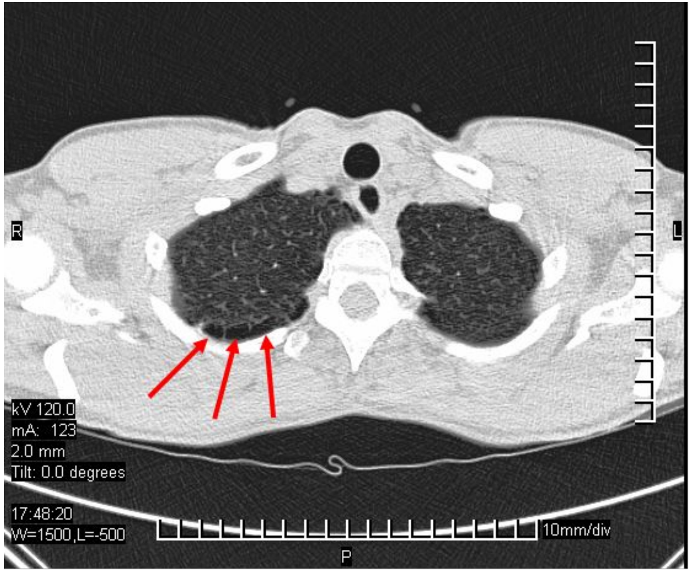


Fig 1. Ventilator Induced Lung Injury (Pulmonary Barotrauma) (CT Scan with *Bullae in Lung*) *(Courtesy: AquaMed) [1]*

Prevention of Pulmonary Barotrauma

Various approaches used to minimize pulmonary damage in patients with ARDS include [2]-

- Delivering low V_T (to Minimize shear forces via smaller-volume inflation of aerated alveoli adjacent to flooded/atelectatic alveoli) & while maintaining a low plateau pressure to prevent overdistention. This is often referred to as “lung protective ventilation”
- High PEEP to reduce cyclical atelectasis (Decrease blood flow to attenuate capillary stress failure)
- Prone Positioning
- Airway pressure release ventilation (APRV)
- High-frequency oscillatory ventilation (HFOV) & Limit Inspiratory & Plateau Pressure

VILI Prevention can attenuate multiorgan failure & improve survival. In Literature, “No well defined Ideal Strategy for prevention of VILI & no clinical data to suggest efficacy as rescue therapy.” [2]

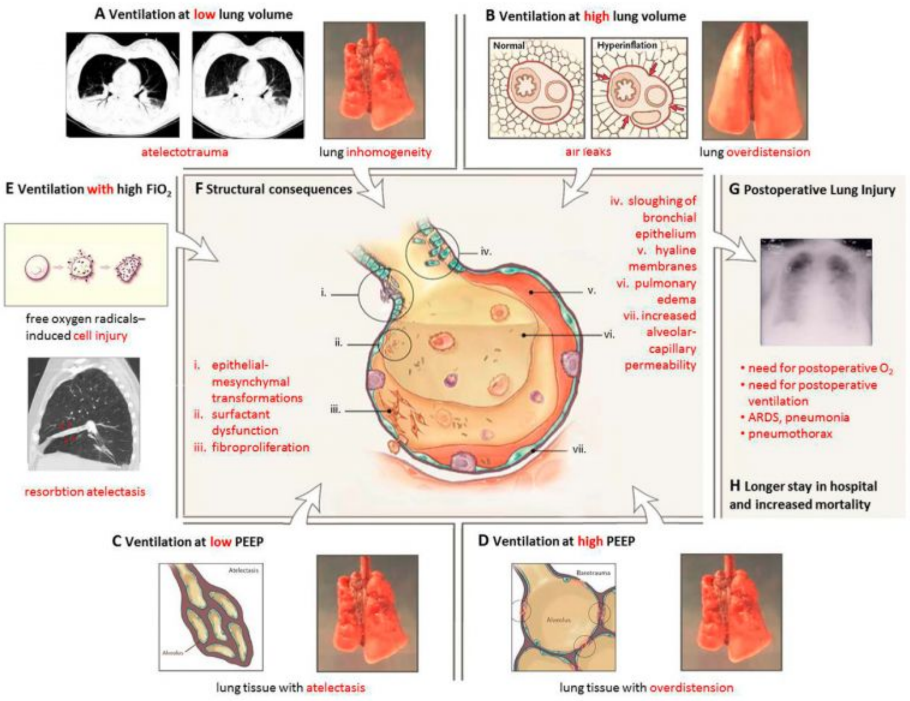


Fig 2. Postoperative pulmonary complications caused by forces generated by ventilation at low and high lung volumes, low and high PEEP and high FiO2 *(Courtesy: Swiss Medical Weekly) [3]*

Our Research Problem (Scope)

1. Designing an Open-Source, Low-Cost, Easy-to-manufacture & use Ventilator system
2. The Ventilator will control factors which induce pulmonary barotrauma in patients under ventilation system for long durations using novel and cheap methodology available at our disposal.
3. To develop a system to drastically reduce PPE-Kit Requirement in COVID-19 Ward
4. To prevent nearly complete contact of medical staff with COVID-19 Patients.

Assumptions pertaining to Research problem

The assumptions necessary to understand how the design concept solves the identified need

1. High pressure approach has been used.
2. Uninterrupted Power Supply & Easy access to compressed oxygen in great supply
3. Availability of trained medical staff
4. Sufficient cooling for the ventilator system
5. Normal breathing condition data used for validation
6. Monitoring pressure & volume flow will be sufficient to generation correction signal
7. Feedback in the control system is efficient to trigger solenoid valves
8. Other factors (non-mechanical) influencing VILI is negligible

NeT-Vent Design Model

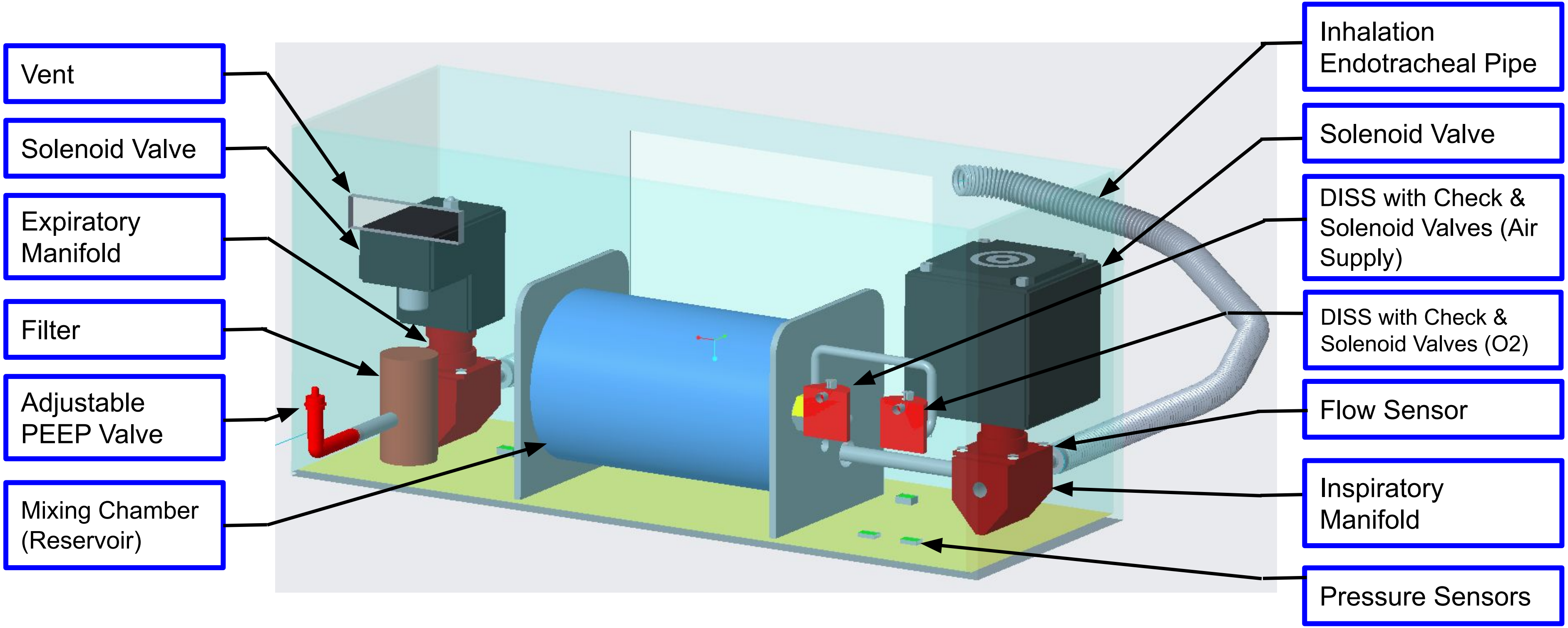
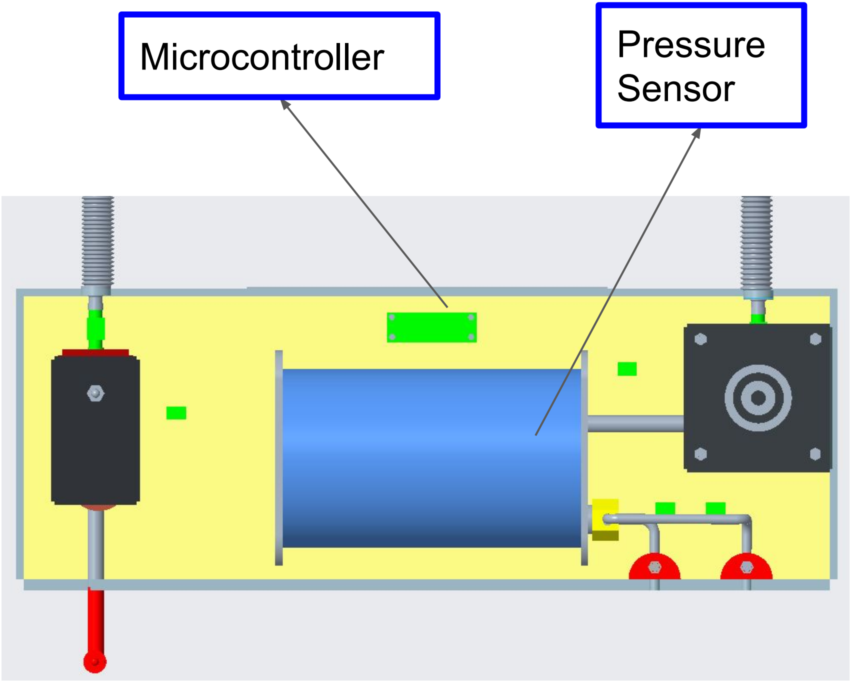


Fig 3. The CAD Model of Net-Vent designed in PTC Creo

Other Design Views



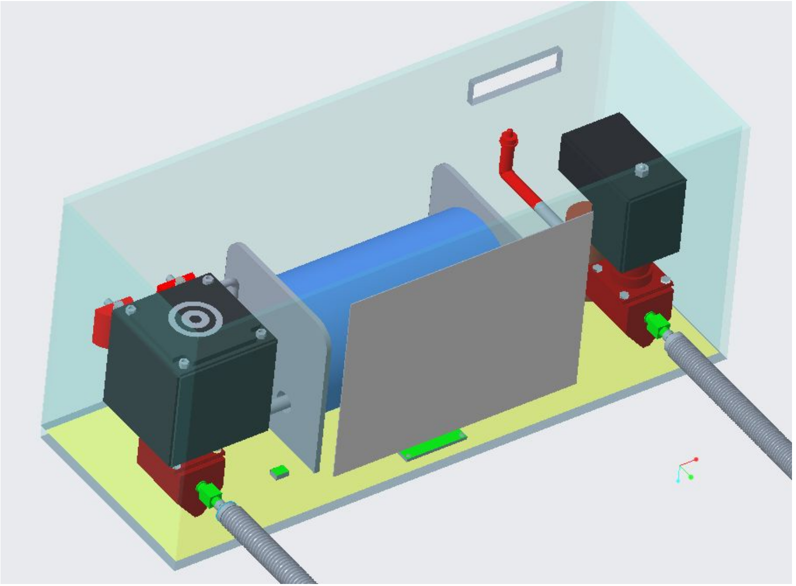
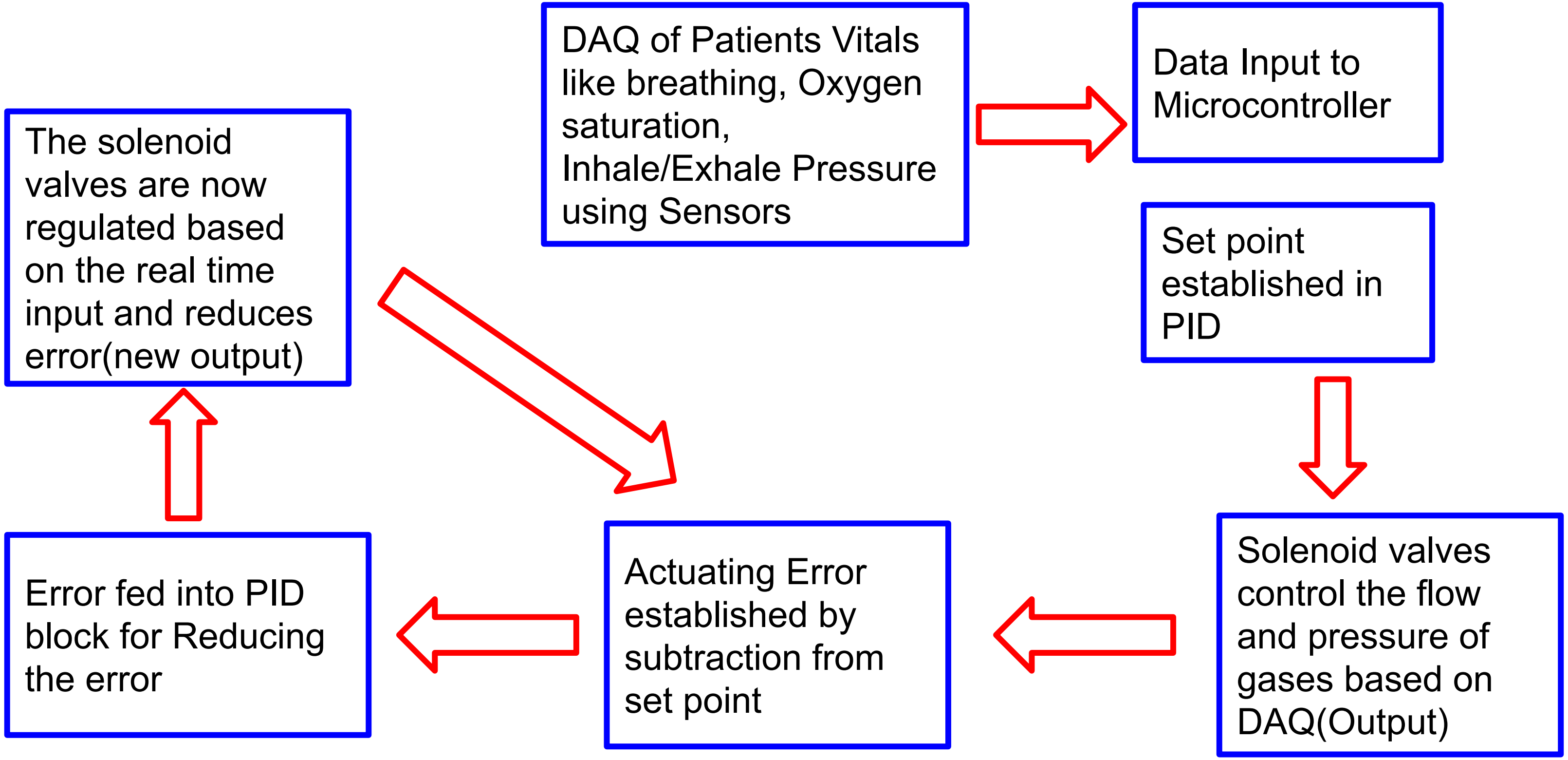


Fig 4. The Top & Isometric view of the CAD Model of Net-Vent designed in PTC Creo

Control Flow Chart



Control System Schematic

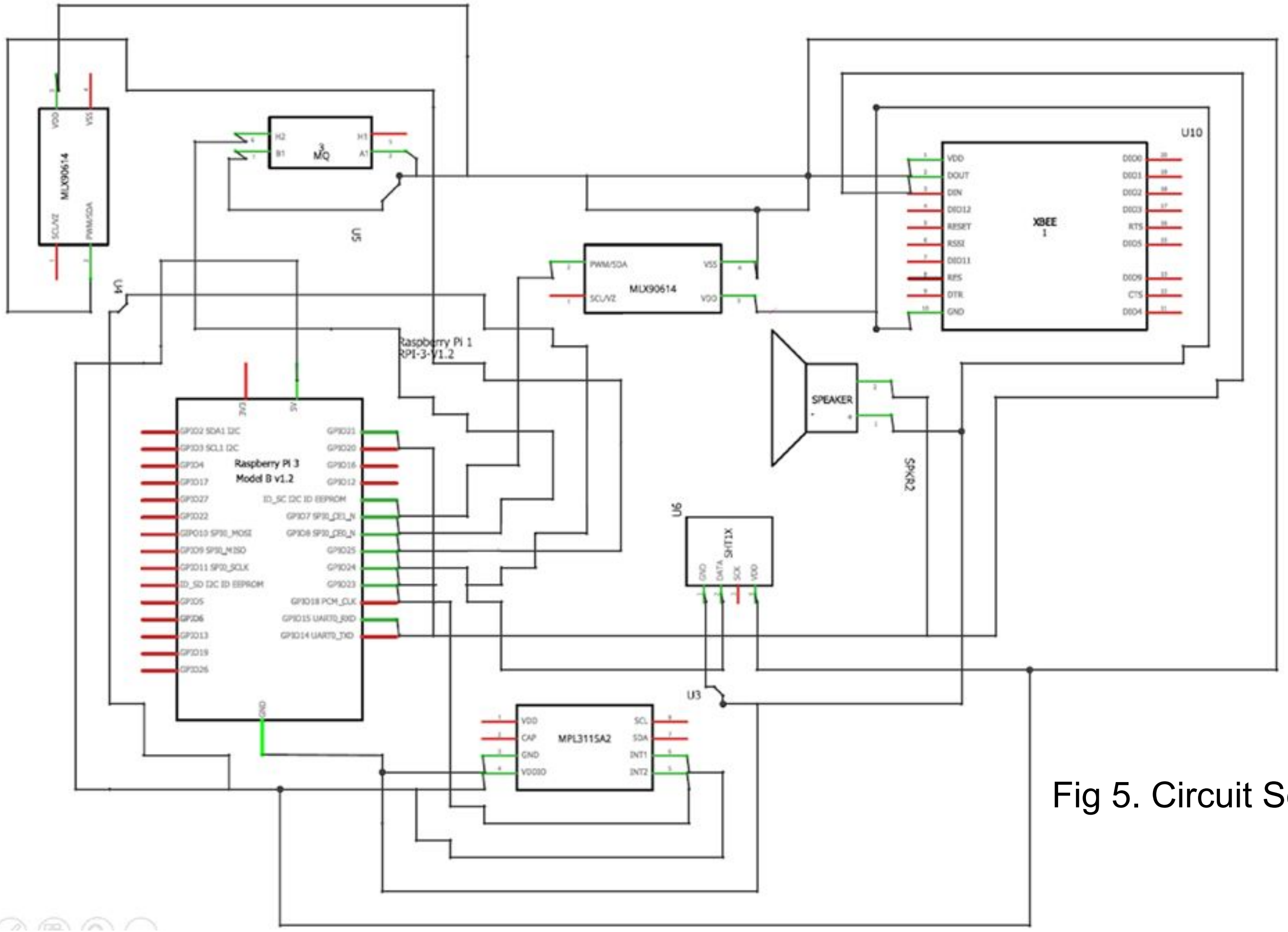


Fig 5. Circuit Schematic of NeT-Vent

IoT Enabling

By introduction of Internet of Things (IoT), doctors and medical staff will be able to monitor the state of patients remotely using an app/web-based interface & need not visit the COVID-19 ward in frequently.

This will indirectly reduced COVID-19 virus transmission from patients to the medical staff & is estimated to reduce the use of PPE Kits to a great extent.

ZigBee/ XBee Module

Bee modules are based on the IEEE 802.15. 4-2003 standard designed for point-to-point and star communications.

They will allow different Net-Vents to communicate with each other and allow data sharing. Important data could be shared with each other, as they get connected on a low-Wifi based network over the cloud.

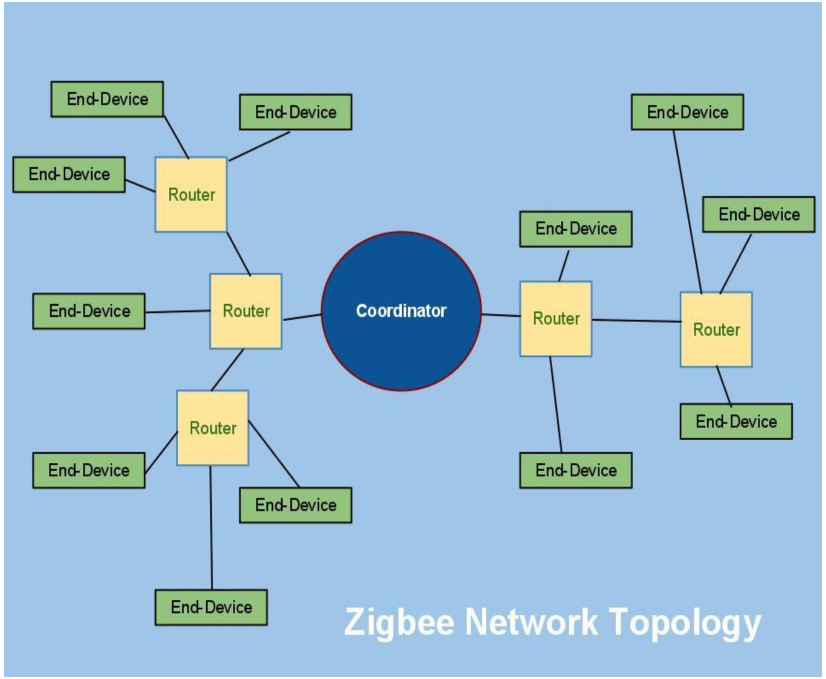
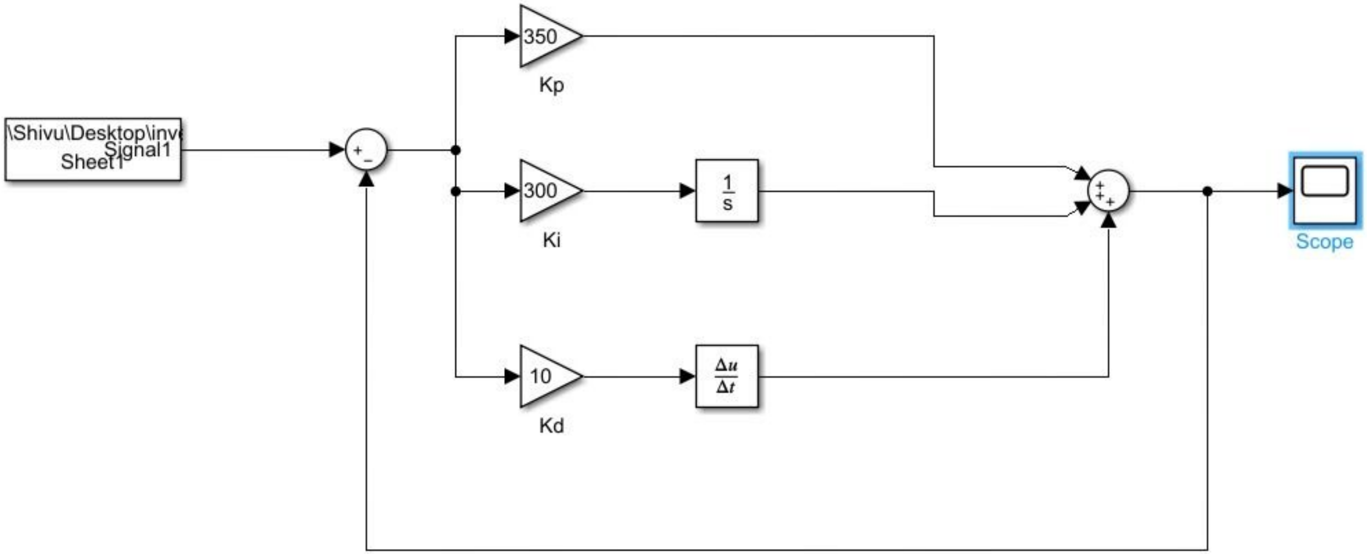


Fig 6. The Zigbee Network Topology

Control System Block Diagram in Simulink



Kp = 350, Ki = 300, Kd = 10

Fig 7. Design of the PID Controller (on which our control system is based) in Simulink

Australian Requirements (Satisfied)

Table 1: Compliance of Net-Vent with the Australian Govt. Ventilator Requirements [4]

Australian Design Requirements	Australian Requirement Range	NeT-Vent's Range (Design & Simulation Based)
Positive end expiratory pressure (PEEP)	5 to 25 cm H2O adjustable	6 to 8 cm of H2O
Respiratory rate	5 to 30 breaths per minute	5- 10 breaths per minute
Tidal volume (Vt)	200 mL to 800 mL, adjustable	-
Airway pressure safety	Have an operator-adjustable limit up to 50 cm H2O	Present
Inspired oxygen proportion (FiO2)	The ventilator must present 22 mm outside diameter (OD)	present
Oxygen supply to ventilator	All gas connectors and hoses must use standard non-interchangeable connectors and be colour coded according to AS 2902-2005	DISS with check valve present
Air supply to ventilator	All gas connectors and hoses must use standard non-interchangeable connectors	DISS with check valve present

Simulation Results: Pressure vs Time Curve

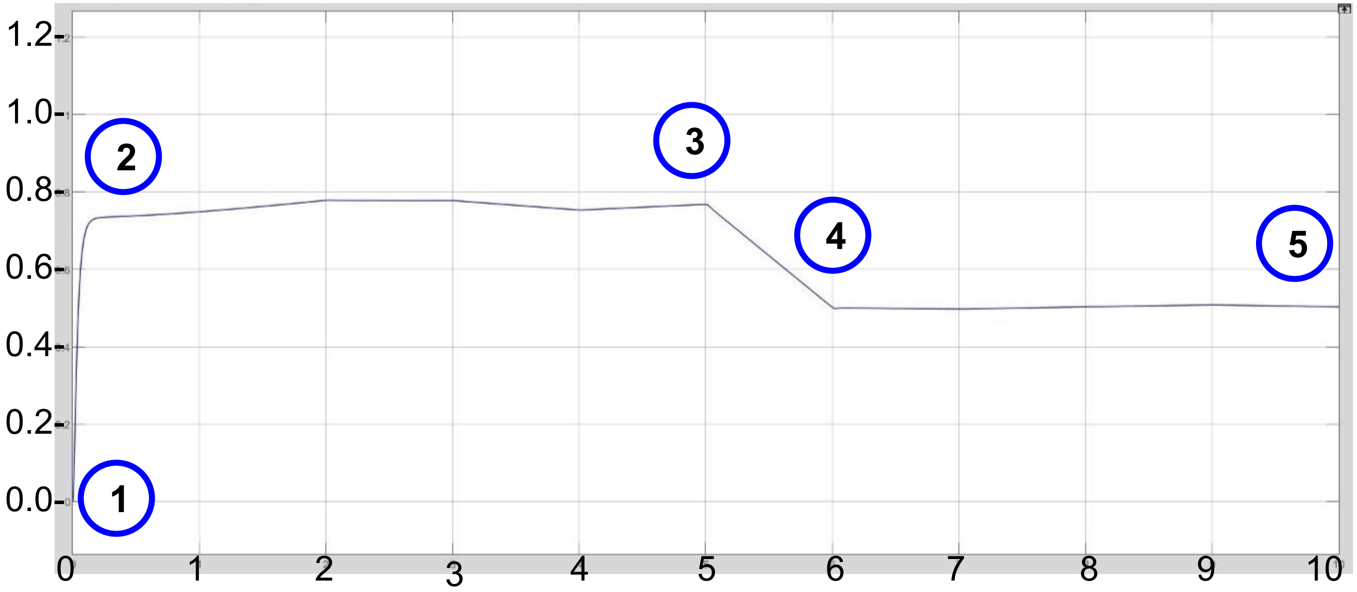
1-2 is Plateau Pressure (Maintaining Low Plateau Pressure)

At pt., 2 termination of pressure support occurs

4. Baseline PEEP (High PEEP to Decrease blood flow to attenuate the capillary stress failure)

Fig 8: Pressure vs Time Curve obtained from our Control System. Measured Input data taken from [5]

Simulation Results: Flow Rate vs Time Curve



1-5 Demonstrates the Curve obtained for the Flow Rate vs Time through our Simulink Simulink

Delivering low V_T (to Minimize shear forces via smaller-volume inflation of aerated alveoli adjacent to flooded alveoli)

Fig 9: Flow Rate vs Time Curve obtained from our Control System. Measured Input data taken from [5]

Table 2: Bill of Materials with their Cost & Source

Part	Quantity	Cost in ASD	Source
Base	1	9.5 - 10	-
Inhale Manifold	1	10	https://www.industrybuying.com/plug-socket-techno-PN.CO.PL.1585091/?utm_source=Google&utm_medium=PLA&utm_campaign=PLA_New_Pneumatics&gclid=Cj0KCQjw8rT8BRCbARIsALWiOvRIV2cj3WC8tCes5xXZALwfJVZfFItAUMhAfCJQbhlxgeXKk44kxLwaAhOYEALw_wcB
Exhale Manifold	1	10	https://www.industrybuying.com/plug-socket-techno-PN.CO.PL.1585091/?utm_source=Google&utm_medium=PLA&utm_campaign=PLA_New_Pneumatics&gclid=Cj0KCQjw8rT8BRCbARIsALWiOvRIV2cj3WC8tCes5xXZALwfJVZfFItAUMhAfCJQbhlxgeXKk44kxLwaAhOYEALw_wcB
PEEP Valve	1	25	https://www.indiamart.com/proddetail/adjustable-peep-valve-6595750730.html
Solenoid Valves	4	12	https://www.industrybuying.com/22-solenoid-valve-techno-PN.CO.DI.363142/?utm_source=Google&utm_medium=PLA&utm_campaign=PLA_New_Pneumatics&gclid=Cj0KCQjw8rT8BRCbARIsALWiOvQWURiE3AoWUfm7vLWV7fZlbmA-NrHkNk98QrUsGvwuz15eTBiS3CAaApTUEALw_wcB
Pipes	5	10	https://www.hospitalsstore.com/disposable-ventilator-circuit-en/
Filter	1	10	https://www.redcross.org/store/hepa-filter-for-cpr-masks/760103.html
Microcontroller	1	51	https://www.electronicscomp.com/raspberry-pi-4-model-b-with-2-gb-ram-india?gclid=Cj0KCQjw8rT8BRCbARIsALWiOvRa65iX6vEvdogt0fQ3wa9n5ShjvDo-20iwuPCRTbqVNvKAbrXInlgaAqbREALw_wcB
Flow Sensor	2	13-14	https://www.electronicscomp.com/index.php?route=product/search&search=flow%20sensor
Pressure sensor	3	4	https://www.electronicscomp.com/bmp180-barometric-pressure-sensor-module-india?gclid=Cj0KCQjw8rT8BRCbARIsALWiOvSUvC3N-dXfbvvxg511NCcNye_h0OcV-FiXTXlIItqhX4Fg8P_GQIYaAv5oEALw_wcB
Humidity Sensor	1	3-4	https://www.arrow.com/en/products/shtc1-1000/sensirion-ag?gclid=Cj0KCQjw8rT8BRCbARIsALWiOvTmPIi68TeCLowSfDV8fE98x-EcFSooK3NwmAHRi9V77Rl0UyN13RUaAlFJEALw_wcB

NeT-Vent’s Ease of Manufacture

Table 3: Depiction of Ease of Manufacture of Net-Vent (in Australia)

Parts	Availability of Parts in Australia	Method of Acquirement
Base	Easily available	3D printing or conventional manufacturing
Inhale Exhale Manifolds	Easily available	3D printing or conventional market products
Solenoid Valves	Available	Manufacturers such as Burkert fluid control systems etc.
Flow, Pressure, Humidity Sensor	Available from vendors	Manufacturers like Manuflo,Mouser elec.
Filters	Available	Manufacturers like AES International etc.

NeT-Vent’s Ease of Use

Has IoT Smart System (unlike any other commercially available high-end ventilators)

Standard Power Requirements : 240V AC Mains Power Supply

Portability of Ventilator: Highly Portable

Part Malfunction: Highly reliable sensors but can be replaced easily on malfunction (includes Buzzer Alarm warning)

Early Warning by IoT : Warning system by IoT to the cell phone of medical staff, also zigbee module transfers data between each other.

Table 4: Comparison of Net-Vent with other existing Ventilator Models

Model	Proposed In	Major Challenges Addressed	Challenges Unaddressed	Manufacture Cost (ASD)
Medtronic PB560 [6]	Feb, 2010	Better Patient management	Easy to service parts in case of failure	14,000
GE Carescape R860	Jan, 2016			8,500
RespiraWorks	April 2020	Low cost patient monitoring	Use of less available & expensive microcontrollers	1000
SmithVent	June, 2020	Easy manufacturability and low cost components.	Airway pressure correction as per patient's needs, VILI unaddressed	-
Team Armadilla	April 2020	No specialised manufacturing dies or moulds required.	Patient breathing cycle, proper lung orientation, VILI Unaddressed	900
NeT-Vent (Our Model)	Oct, 2020	Correction of airway pressure & volume flow as per patient's requirement, Reduction in risk of Pulmonary Barotrauma (VILI), Reducing Medical Staff Exposure with COVID-19 Patients & Reduction in PPE kit requirements	Efficient Flow dynamics & patient orientation for effective ventilation	600-700

Novelty & Contribution

- Design based on low-cost (Approx. 500-600 ASD) & easily available parts (thus easily replaceable & serviceable)
- Accurate diagnosis of parameters & addressing the pressure and volume flow characteristic problems i.e., ventilation induced lung injuries (VILI) specifically Pulmonary Barotrauma to a great extent.
- IoT enabled, easy and remote monitoring of real time data on app/web based interface. IoT enabling to drastically reduce PPE-Kit Requirement & exposure of medical staff to COVID-19.
- Easy monitoring of data as per patient requirements.
- Complies with the regulatory design standards as per Australian Government.

Limitations & Future Study

- Fabrication with Medical Testing to get concrete results before actual use.
- Gyroscope, Accelerometer and Magnetometer sensors could also be used for proper mapping of the chest and diaphragm.
- A CFD Simulation analysis could also be useful in analysing various parameters.

References

[1] Auqamed, (2020). Pulmonary Barotrauma-A Case Study. *Aquamed Online*

[2] Beitler, J. R., Malhotra, A., & Thompson, B. T. (2016). Ventilator-induced lung injury. *Clinics in chest medicine*, *37*(4), 633-646.

[3] Slutsky, A. S., & Ranieri, V. M. (2013). Ventilator-induced lung injury. *New England Journal of Medicine*, *369*(22), 2126-2136. *Reprinted with permission in Swiss Medical Weekly*

[4] Australian government Ventilator Regulations (2020).

[5] Baxter Vent Input data (2020). *Co-Vent Challenge.*

[6] Medtronic PB 560. *Open Source Ventilator.*

[7] - Dr. Erich Schulz, A brief for engineers, by a doctor, on hacking a ventilator for surge capacity in Covid19 patients (2020) *(Vol. 1, 2, 3)*

Software Used: *PTC-Creo, MATLAB, Simulink, AutoDesk EAGLE*