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Research Article

Design of powered air purifying respirator used for healthcare workers in isolation room

Vo Ta An Thanh[1], Le Thanh Long[1,2,3], Tran Ngoc Dang[4], Pham Le An[4], Nguyen Tan Tien[1,2,3,*]

ABSTRACT

From December 2019, the COVID-19 outbreak has rapidly spread throughout the whole world and become a devastating infectious diseases, with the risk of cross infection quickly and no drug treatment is available. Some countries have been facing shortage of medical equipment, which leads to millions of deaths and may put healthcare workers at risk of infection when they caring for patients sicked with COVID-19 in isolation room, so need to ensure their occupational health and safety. In order to solve this problem, the paper presents a design of Powered Air Purifying Respirator (PAPR) to prevent cross-contamination COVID-19 infection in isolation room, protect for occupational health and safety of healthcare workers. That is specialized equipment for medical industry using ambient air as energy source to operate, the device removes contaminated air through the filters and UVC germicidal light bulbs, then provides clean air to the user's face through blower. It creates continuous positive pressure, and this positive pressure prevents outside contaminated air to a face, but it must be com ply with the safety standards of NIOSH. Especially, this design can be used in case of an emergency, lack of medical supplies and equipment because it can be connected to commercially available masks through a hose connector and a respiratory hose. In case the device does not work or out of battery, a mask accompanied by a hose connector can be connected to the breathing tubes placed in isolation room, all these breathing tubes use clean air from heating, ventilating, and air conditioning (HVAC) of isolation room. Simulations and experiments are attached below to compare the difference between ideal parameters and actual results. From which to draw conclusions and development directions of the research.

Key words: Personal Protection Equipment, Clean Air, Dual Filter For Respirator, COVID-19 Prevention

[1]*National Key Laboratory of Digital Control and System Engineering (DCSELab), Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam.*

[2]*Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam.*

[3]*Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam.*

[4]*GIC, University of Medicine and Pharmacy at Hochiminh City*

Correspondence

Nguyen Tan Tien, National Key Laboratory of Digital Control and System Engineering (DCSELab), Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam.

Faculty of Mechanical Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam.

Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam.

Email: nttien@hcmut.edu.vn

INTRODUCTION

From December 2019, the COVID 19 outbreak has rapidly spread throughout all over the world and become a devastating infectious diseases, with a high case fatality rate and no drug treatment is available for COVID-19. The burgeoning need for respiratory personal protection equipment (PPE) precipitated major challenges of suppliers and strategic reserves. Some nations have been dealing with the lack of medical equipment which leads to millions of deaths and probably the collapse of a whole medical system. In the United States, shortages triggered contingency and crisis standards of practice which deviated from conventional and accepted best practices. In order to solve the given challenging problem, the authors introduce PAPR used for healthcare workers in case of preventing COVID-19 infection in isolation room.

The isolation room is the combination of two connected containers designed to have negative pressure value to keep the airflow one way in and out through special ventilating system keeping all bacteria and pathogens from which the infected patients isolated inside the room for curing the infected and preventing the pandemic from spreading into the community. All areas must be airtight to each other and to the outside atmosphere. On the other hand, the following room is used in tough conditions of the front line of the epidemic so it needs to endure continuous weather condition change and the restricted of replacing materials. Five areas are called anteroom for medical staff handling sanitary issues, hall area for inserting patients, sickroom for curing the infected, disinfection room for sanitizing all inside equipment and finally the WC respectively. Anteroom has the highest pressure in the whole module to prevent the airflow from moving into the room itself. Next, the sickroom would have lower pressure value than the above areas (except the WC) keeping the airflow circulate inside it and then pumped outside through special filters. Lastly, the WC is where all bacteria would be trapped in and eliminated by UV light system. The air is filtered by HVAC system placed above two connected containers. The overall design of isolation room module is shown in Figure 1.

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Separating between five areas of the isolation room are the combination of panel walls and automatic doors for temporary isolating the walking way inside the module, both of which are specially designed for medical purposes. Besides, breathing tubes use clean air from HVAC system to protect for occupational health and safety of healthcare workers are also placed inside the isolation room module as shown in Figure 2.

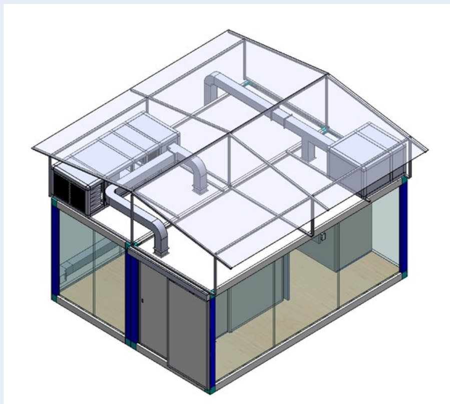

Figure 1: Isolation room module

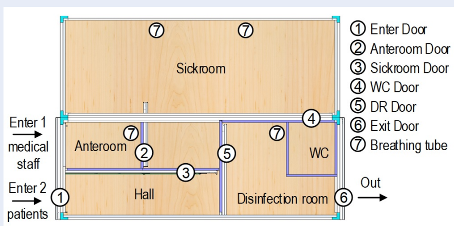

Figure 2: Layout of areas

Caring for patients sick with COVID-19 may put healthcare workers at risk of infection. Therefore, healthcare workers are required to a suite of protection to ensure occupational health and safety during work. This can be accomplished by a PAPR [1]. PAPR provide users with a continuous flow of clean air, usually through a mask or helmet. This type of air purifying respirator is specialized for medical sector, it removes particles (dust, smoke, mist, virus) and toxic chemical in the atmosphere by using particle filters and then use a battery powered blower to supply air to a mask. This positive pressure prevents entry of polluted air and protects the healthcare workers from inhaling virus particles such as COVID-19 [2].

PAPR includes a mask, an air flow control, filters for air handling, the battery pack power supply, a hose connector, a respiratory hose and a belt. Inside air flow controller is a centrifugal blower, an air flow sensor, two UVC germicidal light bulbs comes with two ballasts, a microcontroller and other electronic components. In addition, healthcare workers need to prepare medical protective suit to ensure safety. Based on previous research about PAPR [3–6] and commercially available PAPR such as 3M Versaflo PAPR, FELIX100 PAPR or MSA Safety PAPR, This PAPR is similarly designed and retrofitted UVC germicidal light bulbs to handle air flow effectively before healthcare workers inhale.

This device can connect with SUBEA Easybreath snorkeling face mask by a 3D printed hose connector, use in case of emergency, lack of medical supplies and equipment. However, there must be a backup measure to protect for occupational health and safety of healthcare workers in case the device does not work or out of battery in isolation room. In order to solve this problem, a mask accompanied by a 3D printed hose connector must be connected to breathing tubes placed inside the isolation room module, the air flow of each breathing tube is adjusted and monitored through an adjustable panel type flowmeter is presented in the mechanical design section. The design of system in both cases is shown in Figure 3.

Key specificaions:

- According to minimum air flow rate standard [7], A tight-fitting PAPR must provide a constant airflow of 115 liters per minute.
- Dual filtration system and UVC germicidal light.
- Approximate operational life of 4-6 hours depending on the installed air flow mode.

RESEARCH METHODS

A tight-fitting PAPR help healthcare workers safety because it prevents bacterial penetration during respiration, it also saves more battery life than loose-fitting PAPR. So must be comply with the safety standards of NIOSH for tight-fitting PAPR about filter, airflow, bactericidal intensity, tightness, operating time, etc. Parts of the research include mechanical design shows the operating principle and the structure of the device, control system design shows mathematical model and system control algorithm, electrical design shows block diagram, algorithm flowchart and choose electrical equipment to control device, then results and discussion are given and finally conclusion for the whole system.

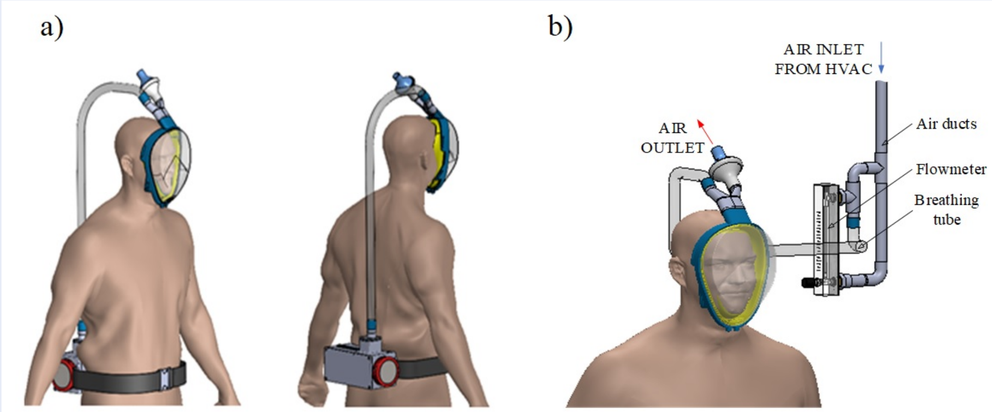

Figure 3: System design overview, a). Design of PAPR, b). Design of backup measure

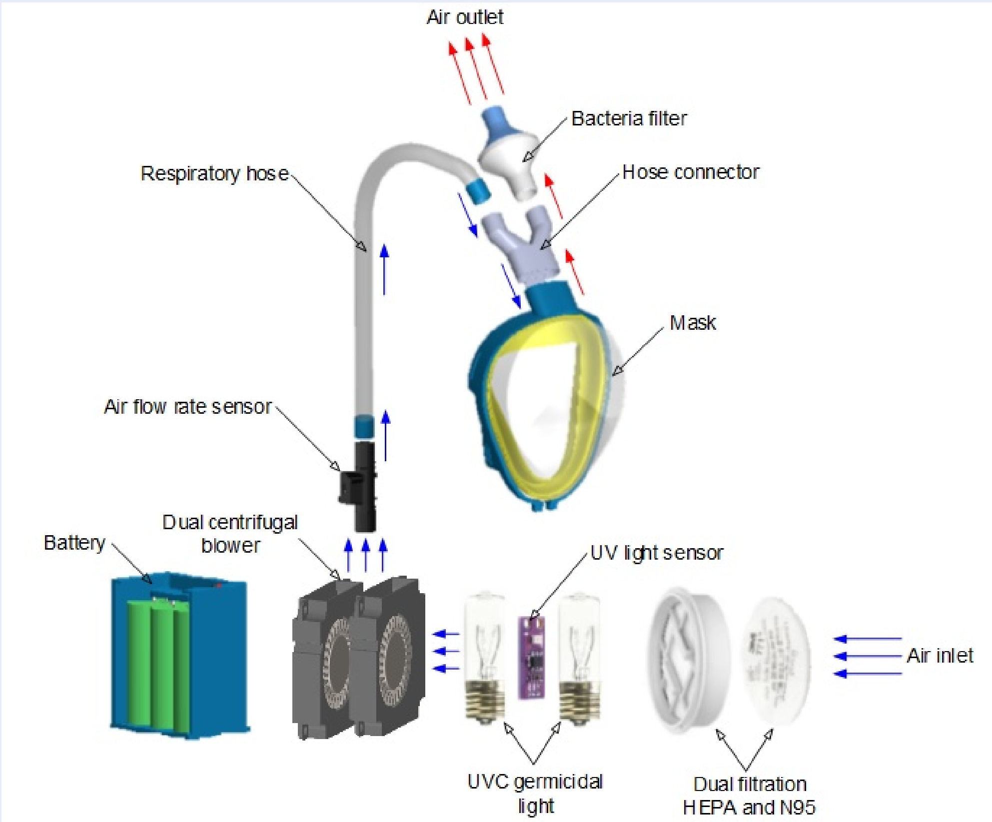

Figure 4: Principle diagram of the system

MECHANICAL DESIGN

Principle diagram

The mask used for this design is a SUBEA Easybreath snorkeling mask, which ensures a snug fit but does not cause discomfort to the user because of the rubber pads to protect the face. Principle diagram of the system shown in Figure 4.

Design a mechanical of PAPR

For air flow

In order to achieve the required air flow, blower must provide more than 115 liters per minute with a tight-fitting PAPR. During use, there are many factors that cause an air flow is reduced such as the performance of the filter will be reduced after a period of use, or due to the difference in air pressure. Therefore, should use centrifugal blower with max air flow more than about twice the standard of tight-fitting for this system. Two DC blowers model BFB04512HHA-DB52 is chosen to provide air flow as requested above, with each blower up to a maximum of 102 liters per minute.

For dual filtration system

A 3M Particulate Filter according to N95 standards [8] is installed at the air inlet and a HEPA Filter according to HEPA standards [9] is installed immediately behind it, these particle filters are used to arrest very fine particles effectively, but they do not filter out gasses and odor molecules. Hence must be additional UVC germicidal light to clean air, based on the UV dose in needed to inactivate virus Corona [10], the UV power can be calculated to choose the suitable UVC germicidal light. The formula is as follows [11].

$$UV\ Dose = E \times t = \frac{P}{A} \times t \tag{1}$$

where, E: UV intensity, mW/cm^2
t: UV exposure time, s
P: UV power, mW
A: contact area, cm^2
From the calculation as above, two UVC germicidal light bulbs model GTL3 can achieve the desired UV dose inactivate virus Corona up to 99%.

For backup measure

A mask accompanied by a 3D printed hose connector will not connect to respiratory hose lead to the air flow control of PAPR. At the air outlet is still connected to the bacteria filter, but the air inlet is replaced by breathing tubes placed inside the isolation room module. These breathing tubes are placed in sickroom, anteroom and disinfection room as shown in Figure 2, it take clean air from HVAC through air ducts to deliver air flow to a mask.
However, this air flow must be adjusted to achieve the desired air flow. This required can be done thanks to adjustable panel type flowmeter LZM-15T, with air low measure range from 27 to 270 liters per minute and black adjustable knob on the front. In order to, this air flow to pass through the tube it must first raise a float held within the tube. The float moves in the most part due to the velocity head of the air flow, then the float can be compared to a scale printed onto the tube itself help users adjust and monitor air flow.

CONTROL SYSTEM DESIGN

Mathematical model

In control systems, sliding mode control (SMC) is an efficient nonlinear control method that forces the system to slide along the sliding surface, SMC has been widely used because it is insensitive to parameter variations, modeling errors, and external noise.
Consider the following n-order SISO nonlinear system

$$x^{(n)} = f(x,t) + bu(t) + d(t) \tag{2}$$

In this system, dual centrifugal blower is controlled through driver and airflow sensor to obtain the desired value. Where $b > 0$ is known control gain and $f(x,t)$ is known nonlinear function, based on control input u (PWM), the desired airflow output $x\,(l/min)$, the relationship between u and x is nonlinear. In addition, there are factors called disturbance $d\,(l/min)$ such as the filter is dusty by the time or air resistance, so using SMC is a common approach used in controlling this nonlinear systems.
In the sliding mode controller, the control law usually consists of the equivalent control u_{eq} and the switching control u_{sw}. The equivalent control keeps the state of system on the sliding surface, while the switching control forces the system sliding on the sliding surface. To describe the mathematical model, block diagram of SMC system shown in Figure 5.

Calculate the control system

Ignoring external disturbance and uncertainty, the plant can be described as

$$x^{(n)} = f(x,t) + bu(t) \tag{3}$$

$$x = \begin{bmatrix} x & \dot{x} & \ldots & x^{(n-1)} \end{bmatrix}^T \tag{4}$$

where, x: an n-dimensional state vector
From the initial starting point x, the state trajectory reaches the sliding surface, then it will slide along the

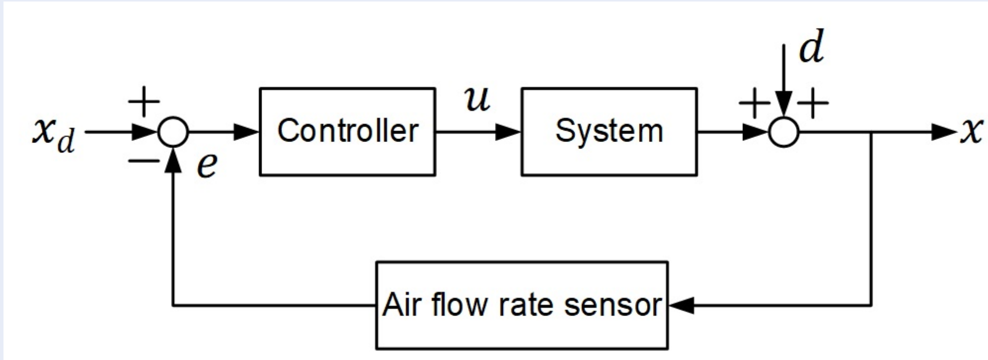

Figure 5: Block diagram of SMC system

sliding surface and direct to desired trajectory x_d, the tracking error vector as

$$e = x - x_d = \begin{bmatrix} e & \dot{e} & \dots & e^{(n-1)} \end{bmatrix}^T \tag{5}$$

Sliding variable is selected as

$$s(x,t) = Ce = c_1 e + c_2\dot{e} + \dots + e^{(n-1)} \tag{6}$$

where, C: a $1 \times n$ vector, $C = \begin{bmatrix} C_1 & C_2 & \dots & C_{n-1} & 1 \end{bmatrix}$
Choose $\dot{s} = 0$

$$\begin{aligned} \dot{s}(x,t) &= c_1\dot{e} + c_2\ddot{e} + \dots + e^{(n)} = c_1\dot{e} + \\ & c_2\ddot{e} + \dots + e^{(n)} + c_{n-1}e^{n-1} + x_d^{(n)} - x^{(n)} \\ &= \sum_{i=1}^{n-1} c_i e^{(i)} + x_d^{(n)} - f(x,t) - bu(t) \end{aligned} \tag{7}$$

The control law is designed as

$$u_{eq} = \frac{1}{b}\left[\sum_{i=1}^{n=-1} c_i e^{(i)} + x_d^{(n)} - f(x,t)\right] \tag{8}$$

In order to satisfy reaching conditions of sliding mode control $s(x,t) \times \dot{s}(x,t) \leq -\eta\,|s|$, $\eta > 0$, we must choose switching control whose control law is

$$u_{sw} = \frac{1}{b} K sgn(s) \tag{9}$$

where, $K = D + \eta$
D: maximum external disturbance and uncertainty
The sliding mode controller include the equivalent control and switching control

$$u = u_{eq} + u_{sw} \tag{10}$$

The control system will be determined from measured data and given in the Results and Discussion section of this paper.

ELECTRICAL DESIGN

After supplying power to PAPR, the system will be controlled for 3 mode: 120/140/160 liters per minute by pressing a button. Besides, two UVC germicidal light bulbs can be turned on or turned off by holding a button for 3 seconds depending on the purpose of use. Control mode and necessary parameters such as battery capacity, airflow, UV lamp status will be displayed on the LCD screen make it easy for users to follow and use. Block diagram of electrical system shown in Figure 6 and algorithm flowchart of the system shown in Figure 7.

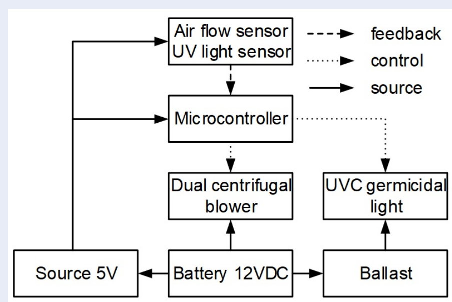

Figure 6: Block diagram of electrical system

Air flow sensor

PAPR detects output air flow with the help of SFM3020 Sensirion flow sensor then sensor feedbacks the signal to microcontroller. Then according to the output given by sensors microcontroller drives the motors. The air flow sensor works through a thin film mounted on the sensor head, the air will pass through the film to create vibrations and then this sensor generates the corresponding signal through the jump. Therefore, the sensor is used to identify the air

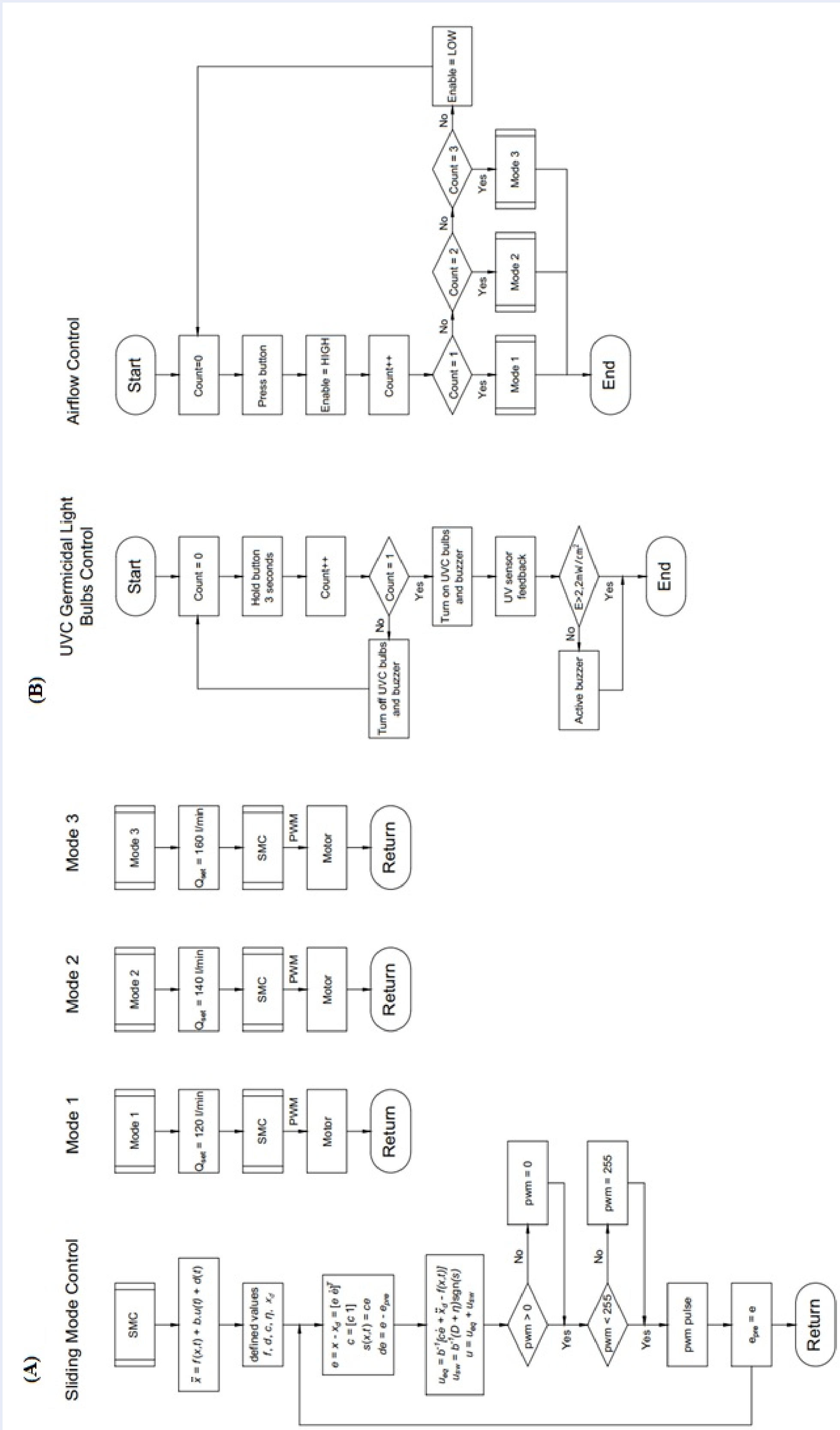

Figure 7: Algorithm flowchart of system, a). Sliding mode control, b). UVC germicidal light bulbs and airflow control

flow mode, keep to systems always provide the desired constant air flow. According to the manufacturer's datasheet, equation for converting from analog signal to air flow of SFM3020 Sensirion as shown below.

$$Q = 212.5 \times \left(\frac{A_{out}}{V_{DD}} - 0.1\right) - 10 \tag{3}$$

where, Q: air flow, l/min
A_{out}: linear analog voltage output, V
V_{DD}: voltage supply, V

UV light sensor

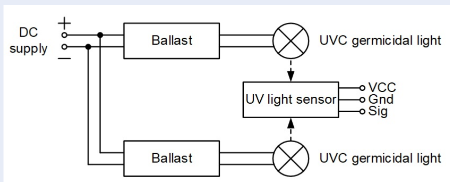

Figure 8: Measurement diagram of UV light sensor

UV light sensor GUVA-S12SD is sensitive to light from $240nm \div 370nm$, helps to monitor and measure UV-C light intensity[12]. UV intensity measurement diagram of sensor is shown in Figure 8, place sensor 2cm away from UVC germicidal lamp, then convert output voltage to UV intensity using the following formulas

$$I_D = \frac{V_{out}}{G \times R_G} \tag{12}$$

where, I_D: current from diode, A
V_{out}: output voltage, V
G: voltage gain
R_G: transimpedance gain, Ω
Convert the current from diode to total power on diode

$$P_D = \frac{I_D}{Re} \tag{13}$$

where, P_D: total power on diode, W
Re: responsivity at $254nm$, A/W
Divide the total power by the excitable active area of the diode to get UV intensity E

$$E = \frac{10^3 \times P_D}{S_a} \tag{14}$$

where, S_a: active area, cm^2
Compare UV intensity through above calculation and UV intensity is inferred as in Eq. (1). When UV intensity drops below the specified level, the buzzer will be active, let users know they need to maintain the system.

RESULTS AND DISCUSSION

Block diagram of experiment system is shown in Figure 9. From the measured data with $n = 2$, A 2-order SISO nonlinear system of the simulation is given by

$$\ddot{x} = -3.133\dot{x} - 7.769x + 24.73u + d$$

and the controller

$$u = u_{eq} + u_{sw}$$
$$= \frac{1}{24.73}\left[1.7e + 3.133\dot{x} + 7.769x + 432sgn(s)\right]$$

Simulation of sliding mode control

To ensure the system control calculation, simulation using MATLab tools is conducted. The response of the controller shown in Figure 10. Where desired airflow $x_d = 120\ (l/min)$, Other desired airflows such as 140 and 160 liters per minute are simulated similarly, initial state $= 0\ (l/min)$, controller parameters $c = 1.7$, $\eta = 420$, maximum external disturbance and uncertainty $D = 12\ (l/min)$,

Simulation of air movement direction

Use Solidworks Flow Simulation tool to simulate the direction of air flow, get the result as shown in Figure 11.

Experimental air flow

Conduct air flow experiment to compare between desired air flow and measured air flow, experimental results for the controller is shown in Figure 12.
Figure 12 show that the experimental results for the controller almost like to the simulation results. However, the stability is still not optimal.

Experimental UV intensity

Feedback signal of UV light sensor must be ensured that UV intensity achieve the desired inactivate virus Corona at maximum air flow. The measured value when starting to activate the UVC germicidal lamp is shown in Figure 13.
From the datasheet of sensor, we have $G = 4.3$, $R_G = 10^7\Omega$, $Re = 0.04\ A/W$, and $S_a = 0.00076\ cm^2$
Figure 12 shows measured UV intensity of UV light sensor increasing over time and higher than required UV intensity, experiment results are surveyed at a distance of 2cm from UVC germicidal light.

CONCLUSION

Based on the experiment, the controller shows the results obtained almost like simulation. The device can meet the required air flow efficiently by using sliding mode control for centrifugal blowe, and meet the

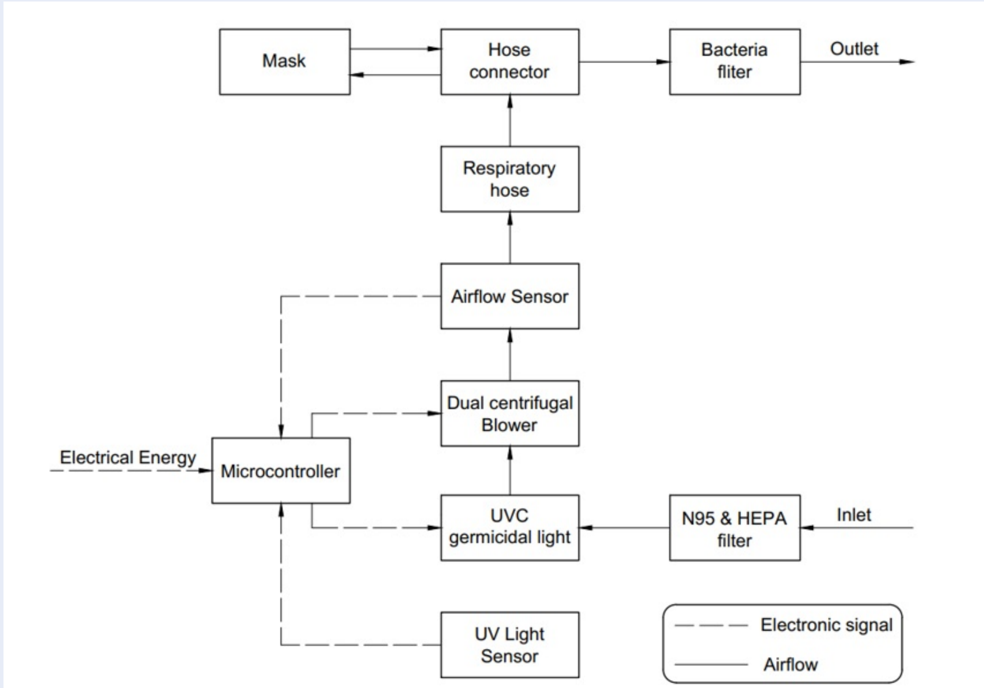

Figure 9: Block diagram of experiment system

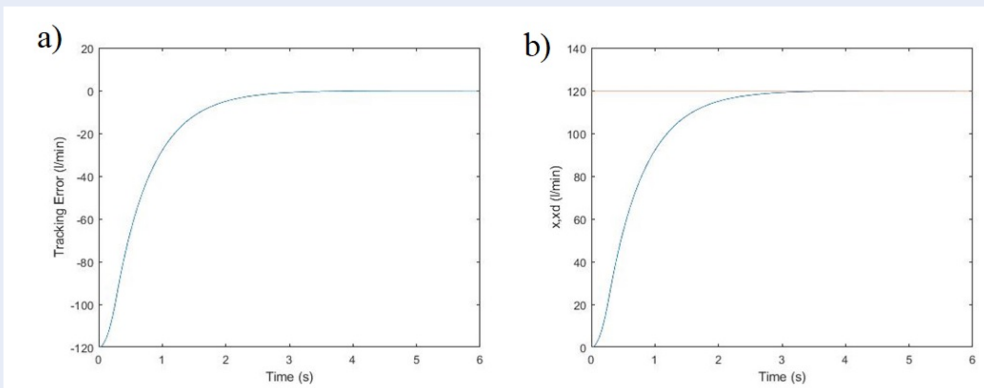

Figure 10: Simulation of the controller, a). Tracking error, b). Airflow —tracking.

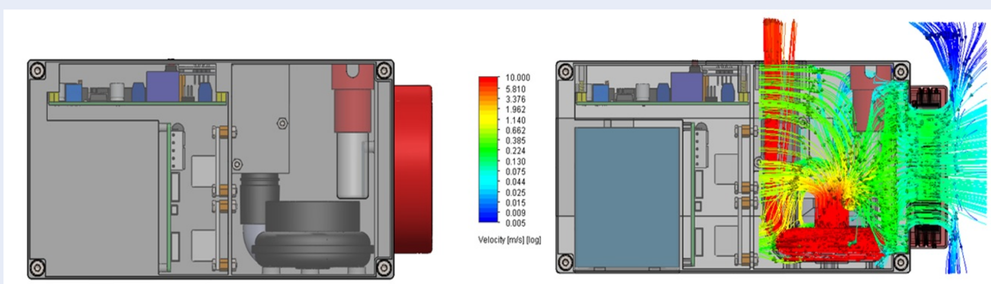

Figure 11: Simulation of air movement direction

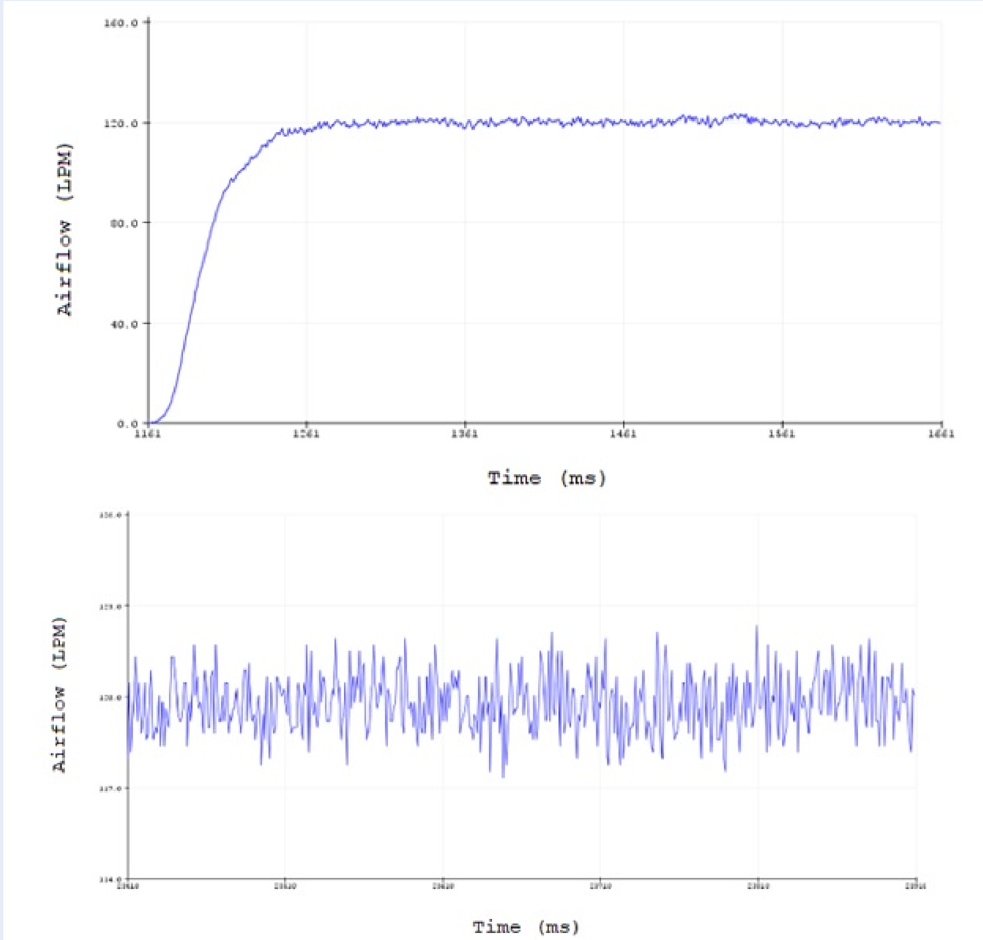

Figure 12: Experiment of the controller

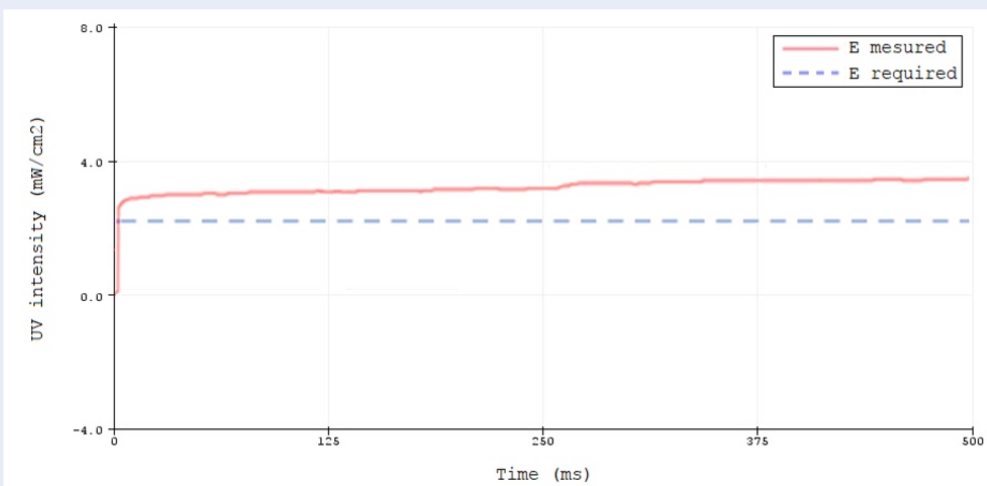

Figure 13: Response of sensor to the UV intensity

required UV dose to inactivate virus Corona. With a compact, lightweight and low-noise design, PAPR can be worn behind the user's hip, comfortable during work. Feedback signals from sensors and LCD screen will help users monitor and control the system effectively. However, using PAPR for a long time may make users feel uncomfortable, and they must be careful when equipping PAPR to avoid accidentally infecting users or other healthcare workers because the device may be contaminated by droplets. Backup measure in isolation room can deliver alternative air flow, but it won't be stable and continuous compared to PAPR. Furthermore, this research has not yet examined viral inactivation, more intensive research can test inside device and increase UV dose inactivate virus Corona than 99%, or help the device save more battery to increase operational life.

CONFLICT OF INTEREST

There is no conflict of interst.

AUTHORS CONTRIBUTION

Thanh VTA contributes in device design, simulation and experiments the system.

Tien NT contributes in design ideas, supervision, references, data checking, proofreading and editing of the manuscript.

Long TL, Dang TN, An PL contributes in ideas for product improvement, formal analysis, visualization, references.

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Bài nghiên cứu

Mặt nạ thở lọc khí chạy bằng pin dùng cho nhân viên y tế trong phòng cách ly áp lực âm

Võ Tá An Thanh[1], Lê Thanh Long[1,2,3], Trần Ngọc Đăng[4], Phạm Lê An[4], Nguyễn Tấn Tiến[1,2,3,*]

TÓM TẮT

Từ tháng 12 năm 2019, đợt bùng phát COVID 19 đã nhanh chóng lan rộng trên toàn thế giới và trở thành một căn bệnh truyền nhiễm nguy hiểm với nguy cơ lây nhiễm chéo nhanh chóng và hiện vẫn chưa có thuốc điều trị. Một số quốc gia đang phải đối mặt với tình trạng thiếu hụt trang thiết bị y tế dẫn đến hàng triệu người tử vong và có nguy cơ khiến cho các nhân viên y tế bị lây nhiễm chéo khi họ chăm sóc các bệnh nhân nhiễm COVID-19 trong phòng cách ly áp lực âm, vì vậy cần phải đảm bảo an toàn và sức khỏe nghề nghiệp cho các nhân viên y tế. Để giải quyết vấn đề này, bài báo trình bày thiết kế mặt nạ thở lọc khí chạy bằng pin (PAPR) để ngăn ngừa sự lây nhiễm chéo COVID-19 trong phòng cách ly, bảo vệ sức khỏe nghề nghiệp và sự an toàn của nhân viên y tế. Đó là thiết bị chuyên dụng cho ngành y tế sử dụng không khí xung quanh làm nguyên liệu để hoạt động, thiết bị loại bỏ không khí ô nhiễm này qua màng lọc và bóng đèn diệt khuẩn UVC, sau đó cung cấp không khí sạch đến mặt của người dùng thông qua quạt gió. Thiết bị tạo ra áp suất dương liên tục, và áp suất dương này ngăn không khí ô nhiễm từ bên ngoài vào trong mặt nạ, nhưng nó cần phải tuân thủ các tiêu chuẩn an toàn sức khỏe của NIOSH. Đặc biệt thiết kế này có thể sử dụng trong trường hợp khẩn cấp, thiếu vật tư, thiết bị y tế vì có thể kết nối với mặt nạ có sẵn trên thị trường thông qua đầu nối và ống hô hấp. Trong trường hợp thiết bị không hoạt động, mặt nạ có gắn đầu nối có thể được kết nối với các ống thở được đặt trong phòng cách ly, tất cả các ống thở này sử dụng không khí sạch từ hệ thống sưởi, thông gió và điều hòa không khí (HVAC) của phòng cách ly. Mô phỏng và thực nghiệm được trình bày bên dưới để so sánh sự khác biệt giữa các thông số lý tưởng và kết quả thực tế. Từ đó rút ra kết luận và hướng phát triển của nghiên cứu.

Từ khoá: Thiết bị bảo vệ cá nhân, Không khí sạch, Bộ lọc kép cho mặt nạ thở, Phòng ngừa COVID-19

[1]*Phòng Thí nghiệm Trọng điểm Điều khiển Số và Kỹ thuật Hệ thống (DCSELab), Trường Đại học Bách khoa (HCMUT), 268 Lý Thường Kiệt, Quận 10, Tp. Hồ Chí Minh, Việt nam.*

[2]*Khoa Cơ khí, Trường Đại học Bách khoa (HCMUT), 268 Lý Thường Kiệt, Quận 10, Tp. Hồ Chí Minh, Việt nam.*

[3]*Đại học Quốc gia Tp. Hồ Chí Minh, Phường Linh Trung, Quận Thủ đức, Tp. Hồ Chí Minh, Việt Nam.*

[4]*Trung tâm Hỗ trợ Dự án và Đổi mới Sáng tạo, Đại học Y dược, Tp. Hồ Chí Minh, Việt nam.*

Liên hệ

Nguyễn Tấn Tiến, Phòng Thí nghiệm Trọng điểm Điều khiển Số và Kỹ thuật Hệ thống (DCSELab), Trường Đại học Bách khoa (HCMUT), 268 Lý Thường Kiệt, Quận 10, Tp. Hồ Chí Minh, Việt nam.

Khoa Cơ khí, Trường Đại học Bách khoa (HCMUT), 268 Lý Thường Kiệt, Quận 10, Tp. Hồ Chí Minh, Việt nam.

Đại học Quốc gia Tp. Hồ Chí Minh, Phường Linh Trung, Quận Thủ đức, Tp. Hồ Chí Minh, Việt Nam.

Email: nttien@hcmut.edu.vn

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