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PROGRAMMING TECHNIQUES IN CONTROL
Term Project

Definition of the control problem:

Mechanical ventilators (MV) are one of the most crucial medical devices in intensive care units (ICU) to provide life support for critically ill patients with respiratory failure. This machine helps patients to breathe when they are not able to breathe enough on their own.

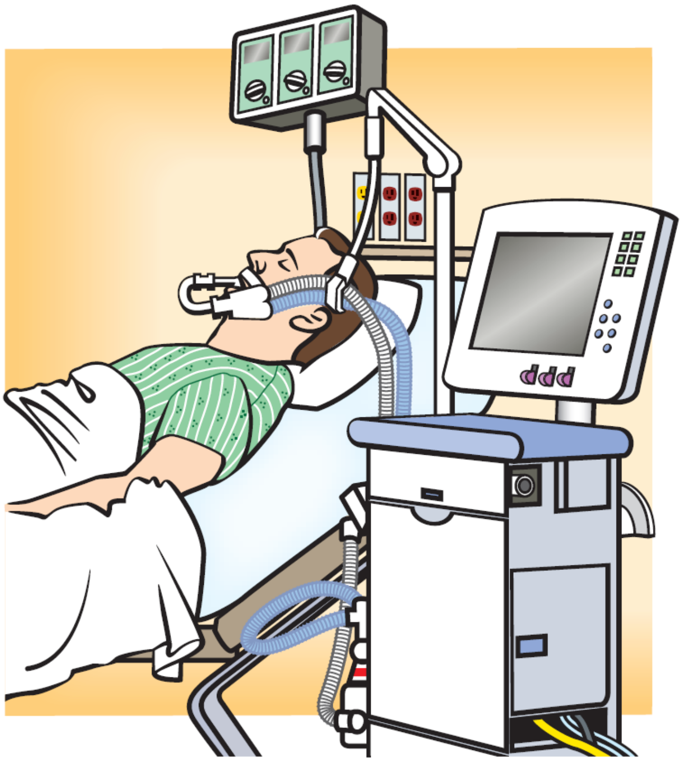

Figure 1: Mechanical ventilation schema [1].

In such cases, MV device is connected to the patient through a tube placed into the mouth or nose. The ventilator blows air (with oxygen as needed) into the lungs of patient; thus, it helps patient by doing all of the breathing work or by just assisting the patient breathes.

In this project, it is aimed to design a mechanical ventilator device and to test it on a human respiratory system model via MATLAB/Simulink.

Steps to be followed:

1) *Modelling of the Lungs:* The electrical analogous for the human lung mechanics model is depicted in the following figure.

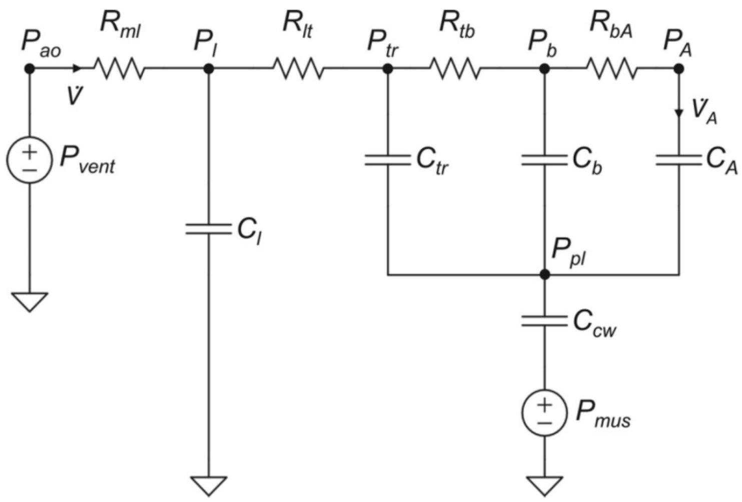

Figure 2: The lung mechanics model [2].

$\boldsymbol{\dot{V}}$: Total airflow

$\boldsymbol{\dot{V}_A}$: Alveolar airflow

$\boldsymbol{P_{mus}}$: Pressure provided by the respiratory muscles (cmH_2O)

$\boldsymbol{P_{vent}}$: Pressure provided by the ventilator (cmH_2O)

$\boldsymbol{R_i}$: Resistances ($cmH_2O.s.L^{-1}$)

$\boldsymbol{C_i}$: Compliances (L/cmH_2O)

***Subscripts*:** ao (airway opening), ml (mouth to larynx), l (larynx), lt (larynx to trachea), tr (trachea), tb (trachea to bronchea), b (bronchea), bA (bronchea to alveoli), A (alveoli), cw (chest wall), pl (intrapleural).

$$(R_{ml} = 2.871,\ R_{lt} = 0.337,\ R_{tb} = 0.306,\ R_{bA} = 0.082)$$

$$(C_l = 0.00127,\ C_{tr} = 0.0024,\ C_b = 0.0131,\ C_A = 0.116,\ C_{cw} = 0.2)$$

a. Construct the circuit given in Figure 2 in Simulink with the help of the Simscape library (Here, set $P_{vent}(t)$ and $P_{mus}(t)$ as controlled voltage sources without any input for now).

b. Pressure equation provided by respiratory muscles (i.e. spontaneous breathing) is given as follows:

$$P_{mus}(t) = \begin{cases} \dfrac{-P_{mus,min}}{T_I\,T_E}t^2 + \dfrac{P_{mus,min}T}{T_I\,T_E}t & t \in [0,\ T_I] \\ \dfrac{P_{mus,min}}{1 - e^{-\frac{T_E}{\tau}}}\left(e^{-\frac{(t-T_I)}{\tau}} - e^{-\frac{T_E}{\tau}}\right) & t \in [T_I, T] \end{cases}$$

Here,

$\boldsymbol{T_I}$: Inspiratory Time (s)

$\boldsymbol{T_E}$: Expiratory Time (s)

$\boldsymbol{RR}$: Respiratory Rate (breaths/min)

$\boldsymbol{IE_{ratio}}$: Inspiration/Expiration Ratio

$$T_I + T_E = T = 60/RR$$

$$T_I = IE_{ratio} T_E$$

$$\tau = T_E/5$$

Create a subsystem in Simulink which has three inputs $\left(P_{mus,min}, RR, IE_{ratio}\right)$ and one output $\left(P_{mus}(t)\right)$ in order to produce the specified periodic signal. Simulate the Simulink file and plot the output of the subsystem for $RR = 10$, $P_{mus,min} = -5.0$ and $IE_{ratio} = 0.5$ during 60 seconds.

c. Connect the subsystem $P_{mus}(t)$ to the lung mechanics model constructed in Step 2a. By using a fixed step solver (with a proper sampling time), plot the airflow $\dot{V}(t)$ and tidal volume which is expressed as $V(t) = \int \dot{V}(t)$ (volume of the air blown into the lungs) in the same figure (as a *subplot*).

d. Find the open-loop transfer function between $P_{mus}(s)$ and $V(s)$ by assuming that $P_{vent} = 0$. In order to verify the obtained transfer function, apply the same input signal $P_{mus}(t)$ to the transfer function and compare the transient response of the system with the previous results.

e. Find the poles, zeros and gain of the transfer function $G_{spont}(s) = \frac{V(s)}{P_{mus}(s)}$ and show them on the s-plane.

f. Show that the lung mechanics model can actually be represented by a first order transfer function (*Hint*: Check the open-loop poles and zeros). After that calculate the values of the R and C parameters if the reduced-order transfer function is given as follows:

$$G_{lung}(s) = \frac{\frac{1}{R}}{s + \frac{1}{RC}}$$

g. Plot the airflow $\dot{V}(t)$ and tidal volume $V(t)$ for the first order transfer function representation of the lung mechanics model. Compare the results with the ones obtained in Step 2c and give your comments ($P_{vent} = 0$).

h. Plot the unit step responses of $G_{lung}(s)$ for $R \in [1.0, 9.0]$ and $C \in [0.05, 0.25]$ by taking at least 5 different values. Comment on the resulting plot.

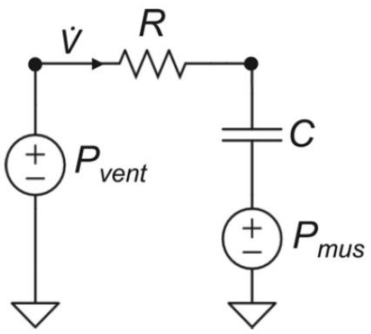

Figure 3: Single compartment model of the respiratory system.

2) *Mechanical Ventilation Device:* As mentioned earlier, mechanical ventilator devices help patients to breathe by blowing air-oxygen mix into the lungs (mandatory breaths). Today's ventilators have several modes to be used for different scenarios; however, you are expected to implement only two modes, named as PCV (Pressure Controlled Ventilation) and VCV (Volume Controlled Ventilation) in this project.

PCV: In pressure controlled ventilation mode, the ventilator device produces a periodic pressure signal ($P_{vent}(t)$) in the following square wave form.

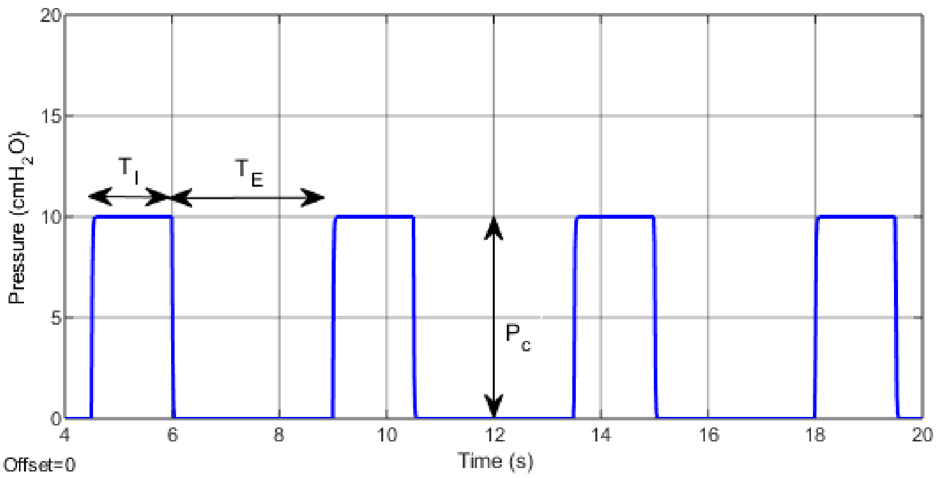

Figure 4: A typical pressure waveform in PCV mode.

As it is seen from the figure, the desired pressure value ($P_{vent}(t) = P_c$) is provided during the inspiration time (T_I) and then zero pressure ($P_{vent}(t) = 0$) is applied during the expiration time (T_E).

In addition, in the practical applications, the square wave is filtered to prevent high flow rates with the help of a first-order transfer function given below.

$$G_f(s) = \frac{1}{\tau_f s + 1}$$

Figure 5: Filter structure used in the practical applications.

In this mode, a pressure input to the system (lungs) is applied and output of the system (tidal volume) is measured. As the lung parameters (R and C) change, the tidal volume also changes; it means that the air volume blown into lungs may not be constant.

Note: In this section's questions, assume that the patient cannot breathe on his own due to the neuromuscular blockers (i.e. $P_{mus}(t) = 0$).

a. First of all, since it is already shown that the system can be represented by a single compartment model given in Figure 3, write the new open-loop transfer function:

$$G_{open-loop}(s) = \frac{V(s)}{P_{vent}(s)} = \frac{\frac{1}{R}}{\left(s + \frac{1}{RC}\right)} \frac{1}{(\tau_f s + 1)}$$

After that find the closed-loop system characteristic polynomial if the controller is given as $F(s) = k_I/s$ (unit feedback) and calculate the stabilizing range of the parameter k_I with the help of Routh-Hurwitz stability criterion. In addition, plot the variation curve of the closed-loop poles for the parameter $k_I > 0$ ($\tau_f = 0.1$).

b. If a P type controller is used ($F(s) = k$), find the k parameter in terms of the parameters R, C and τ_f such that the minimum settling time is achieved (without any overshoot) for this system. What happens to minimum achievable settling time if C is increased? Comment on this case.

c. It is now expected to design the PCV mode. For this purpose, construct a subsystem named as "PCV Mode" with four inputs (ventilator respiratory rate VRR, ventilator inspiratory/expiratory rate VIE_{ratio}, ventilator control pressure P_c and filter time-constant τ_f) and one output $(P_{vent}(t))$ which is applied to the patient. In this subsystem, inspiratory and expiratory times should be calculated and then the (filtered) periodic signal as given in Figure 4 should be created with the magnitude of P_c.

d. In this stage, you have designed a MV device which is able to operate in PCV mode. Test your MV subsystem on the first order respiratory system model (with the same calculated R and C values) given in Figure 3 using the following parameters:

$P_c = 8\ cmH_2O$	$\tau_f = 0.1\ s$
$VRR = 10\ breaths/min$	$VIE_{ratio} = 0.5$

Plot the produced signal $P_{vent}(t)$, airflow $\dot{V}(t)$ and tidal volume $V(t)$ on the same figure (subplot). Repeat the same question by decreasing the magnitude of applied pressure to $P_c = 4\ cmH_2O$ (Run all simulations during 60 seconds).

e. Increase the airway resistance (R) by 100% and plot the produced signal $P_{vent}(t)$, airflow $\dot{V}(t)$ and tidal volume $V(t)$ again on the same figure. Discuss the differences from the previous results ($P_c = 8\ cmH_2O$).

VCV: In volume controlled ventilation mode, ventilator device applies a pressure to the lungs such that the desired tidal volume (output of the considered system) is achieved. Thus, the reference volume is always guaranteed even under parameter changes (if the controller is designed well enough). However, it means that there should be a closed-loop control system to control the tidal volume (V) by adjusting the control signal (applied pressure) as required.

In this project, it is also required to design the VCV mode in order to guarantee the desired tidal volume. For this purpose;

f. Create a new subsystem named as "VCV Mode" with the inputs of VRR, VIE_{ratio}, τ_f and V_{Ref} and the output of $P_{vent}(t)$. First of all, create a square wave reference signal (as in Figure 4) with the magnitude of V_{Ref} inside this subsystem as you have done in PCV mode (here, the τ_f input will not be used yet). Run the simulation and show that it produces the desired square wave signal with the arbitrary parameter values (for V_{Ref}, VRR and VIE_{ratio}).

g. In order to achieve the desired tidal volume during inspiration time, a closed-loop control system should be constructed. Here, the PI-PD structure which is illustrated in Figure 6 is used as a controller. The controller takes the obtained error signal $\left(e(t) = V_{Ref} - V\right)$ and output of the system $(y(t) = V)$ and creates a control signal $\left(u(t) = P_{vent}(t)\right)$ to satisfy any desired performance criteria.

PI and PD controllers are also given as follows:

$$F_{PI}(s) = K_{pi} + \frac{K_i}{s}$$

$$F_{PD}(s) = K_{pd} + K_d s$$

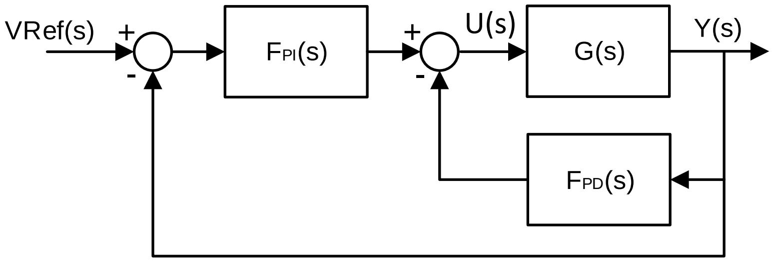

Figure 6: PI-PD controller structure.

After you successfully create the desired reference signal in Step 3f, write a MATLAB function in Simulink which calculates the controller parameters given as follows in terms of the system parameters:

$K_{pi} = \dfrac{16R}{25\tau_f}$	$K_i = \dfrac{64R}{25\tau_f^2}$
$K_{pd} = \dfrac{32R}{5\tau_f} - \dfrac{1}{C}$	$K_d = \dfrac{23R}{5} - \dfrac{\tau_f}{C}$

h. Find the closed-loop system transfer function and calculate the poles, zeros and gain when the above controller parameters are used. Estimate the desired settling time and overshoot from the system with the above controller parameters ($\tau_f = 0.1\ s$).

i. Using "Varying PID Controller" blocks in Simulink, construct the closed-loop control system (Figure 6) and finalize the VCV mode of the mechanical ventilator device. After that test your design on the respiratory system model with following parameters (Saturate the PI-PD controller output $U(s)$ between $[0, 30]\ cmH_2O$):

$V_{Ref} = 400\ mL$	$\tau_f = 0.1\ s$
$VRR = 10\ breaths/min$	$VIE_{ratio} = 0.5$

Plot the control signal $P_{vent}(t)$, airflow $\dot{V}(t)$ and tidal volume $V(t)$ on the same figure. Is the designed PI-PD controller able to control the considered system successfully? Comment on the results you have obtained.

j. Pulmonary emphysema is a type of chronic obstructive pulmonary disease (COPD). It involves the loss of elasticity and enlargement of the air sacs in the lung; therefore, the lung compliance is increased [3, 4].

Consider a patient whose lung compliance is increased by 150% (i.e. $\tilde{C} = 2.5C$) due to the emphysema. In this case, without changing the controller parameters, plot the control signal $P_{vent}(t)$, airflow $\dot{V}(t)$ and tidal volume $V(t)$ on the same figure. Discuss the resulting plots by considering the previously obtained ones in Step 3i.

3) *Spontaneous Breathing:* As the patient's condition gets better, neuromuscular blockers are stopped and it is allowed patient to breathe on his own. Thus, the pressure provided by respiratory muscles $\left(P_{mus}(t)\right)$ is no more zero when the patient is awake.

$$P_{vent}(t) - P_{mus}(t) = R\dot{V}(t) + \frac{1}{C}V(t)$$

However, the patient's respiratory effort will be limited and it means that the tidal volume will also be limited. For this reason, the patient's spontaneous breaths should be assisted by the mechanical ventilator.

In this case, you should update your MV design such that your device provide the set pressure (in PCV mode) or volume (in VCV mode) when the patient tries to take a breath. Hence, if the airflow $\dot{V}(t)$ (caused by patient's own breathing) exceeds a specified positive threshold (flow trigger limit, typically 2-5 L/min), MV device gives a full breath to the patient (by setting P_{vent} in PCV mode or V_{Ref} in VCV mode) without waiting for the next mandatory breath time ($T = T_I + T_E$).

Note: After the breath is delivered to the patient by MV, the next breath will be delivered after the respiratory period (T) or again with a patient (flow) trigger! So you have to reset the timer which checks the mandatory breath period (the square wave period).

a. Consider the "PCV Mode" subsystem you have created earlier. Add two more inputs which are the measured airflow $\dot{V}(t)$ and flow threshold. Update your subsystem such that the set pressure ($P_{vent}(t) = P_c$) is applied if the flow exceeds the given threshold value (Please note that if the mandatory breath is already applied $(t \leq T_I)$ you don't have to do anything else even if the patient tries to trigger a breath).

b. Now apply both $P_{mus}(t)$ and $P_{vent}(t)$ to the first order respiratory system model according to the above equation in Step 4. Show that your MV device applies a breath with the patient's spontaneous activity as well as the mandatory breath using the following parameters in PCV mode:

Patient's Activity:	
$P_{mus,min} = -2\ cmH_2O$	$RR = 4\ breaths/min$
$\tau = T_E/20$	$IE_{ratio} = 1/4$
Mechanical Ventilator:	
$P_c = 8\ cmH_2O$	$VRR = 8\ breaths/min$
$\tau_f = 0.1\ s$	$VIE_{ratio} = 1/2$

c. Observe the plots $P_{mus}(t)$, $P_{ao}(t) = P_{vent}(t) - P_{mus}(t), \dot{V}(t)$ and $V(t)$ and try to understand the differences with the plots obtained in Step 3d. Compare and give your final comments.

d. Modify your "VCV Mode" subsystem as mentioned above. This time you have to apply a tidal volume reference (V_{ref}) to the controller when the patient triggers a breath. Test your MV device in VCV mode as well and give the necessary plots using the same parameter values given in the above table (Just take $V_{Ref} = 500\ mL$ instead of the $P_c = 8\ cmH_2O$ in VCV mode).

e. Comment on the term project.

- This assignment is planned to be done by teamwork; therefore, you are expected to form teams of 5 students on DOST.

- Students are expected to prepare a detailed report and a presentation about the term project. Every question should be answered separately; it means that for each question, you should create a new MATLAB and Simulink file. In addition, MATLAB/Simulink files should be delivered together with the project report at least a day before the presentation.

- Please also note that you will have 20 minutes (+5 minutes for the questions & answers session) to present your project at the end of the semester.

References:

[1] M. Tobin and C. Manthous, "Mechanical Ventilation", *Am J Respir Care Med*, vol. 196, pp. 3-4, 2017.

[2] A. Albanese, L. Cheng, M. Ursino and N.W. Chbat, "An integrated mathematical model of the human cardiopulmonary system: model development", *American Journal of Physiology-Heart and Circulatory Physiology*, vol. 310(7), pp. H899-H921, 2015.

[3] Url-1: https://www.medicalnewstoday.com/articles/8934.php, reached in 02.11.2019.

[4] D. Papandrinopoulou, V. Tzouda and G. Tsoukalas, "Lung compliance and chronic obstructive pulmonary disease", *Pulmonary Medicine*, 2012, doi:10.1155/2012/542769.