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Control System Design of Syringe Infusion Pump and MATLAB Simulations

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Abstract: ***Infusion pumps have multiple uses according to their location. According to its use, there is a need to specific control parameters. The objective of this study is to implement and to assembly all the modules of an infusion pump, controlling all the functions. The control was implemented with the computer board based MATLAB and a web page was developed to assist the user to record, retrieve and access information about the operating conditions. Syringe infusion pump mechanism is controlled by an endless thread and a dc motor. A FOPID (Fractional order Proportional, Integral, Derivative) and PID controller is developed in position and velocity control of dc motor. GUI (General user interface) - MATLAB program is presented so that to help the user and patient. Performance of the control systems of infusion pump is investigated and discussed by MATLAB simulations. Finally when a classical PID and FOPID controller are implemented, the position and velocity responses of the infusion pump mechanism are compared.***

Keywords: Infusion pump, Microcontroller, Web page, Infusion rate, Infused volume. PID controller, FOPID controller

1. Introduction

An infusion pump is an electro medical equipment commonly used in hospitals and in ambulatory to introduce a liquid (other than blood) in a blood vessel, mainly medication or nutrients, since it is a very efficient, rapid and precise method [1][2]. There are several types of infusion pumps distinguished by being either, manual, or semiautomatic or fully automatic. In manual pumps, the flow control depends on the pressure created as result of gravity, since it consists in two liquid reservoirs and a three-way stopcock used to regulate the flow manually, which differs from the semiautomatic type which in turn is automatically controlled by a set of LED/phototransistor counting the number of times the beam is interrupted and emitting alarms. The automatic pumps are used when a better precision is needed. In this case, the infusion pressure is independent of gravity, allowing for greater pressures if necessary. Syringe infusion pumps are used in situations where high precision and low flow are necessary, namely for paediatric cases or in intensive therapies where small volumes of high concentration medication are applied for long periods of time [3]. The flow control may be volumetric or non-volumetric. A volumetric flow control regulates the volume infused per time (ml/h) as well as the infusing velocity no matter the type of liquid. In a non-volumetric control, the pump controls the number of drops per time (drip rate in drops/min) as well as the infusion velocity. The volume depends on the size of drop, varying with type of equipment, temperature, liquid viscosity and density. The control circuit can be either analog or digital. In this case, the computer is responsible for interpreting the information recorded on the device, for controlling the infusion mechanism, for interpreting the sensor signals and setting-off the alarms whenever necessary. The control circuits can store information, calculate the dose of the pharmaceutical agents, vary the infusion rate as well as being the interface between the pump and the microcomputer and peripherals. For this reason, the pump control panel consists usually on a keypad, for data setting to define the infusion parameters. The data output is visualized through an alphanumeric display. This display shows information on the infusion in course, the total volume to be infused, the flow rate (ml/h or drops/min), the total and remaining times and some information about the alarms. These alarms control the infusion precision, being set-off in the instant some parameter falls outside the expected operating interval. There are alarms indicating misuse or wear out of some parts, which helps to guarantee the health safety and security of the patient.

2. Controlling the Infusion Pump

In this study, a syringe mechanism was used to serve as the fluid reservoir and to create the necessary pressure for infusion. It uses an endless worm thread to position the plunger, managing in this way the liquid movement. This process is controlled by a dc motor where the rotation of the motor is transmitted to the endless thread (Figure 1). Normally, a spring is used to push the plunger with a constant force, necessary for a stable infusion pressure. This type of infusion generates a continuous high precision flow (with an error below 2%).

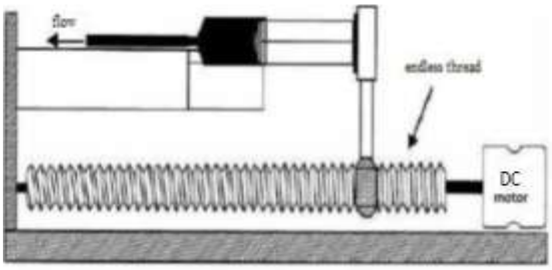


Figure 1: Syringe infusion mechanism [8].

2.1 Pump and Control System Block Diagram

The developed system to control the syringe pump is depicted in the block diagram of Figure 2.

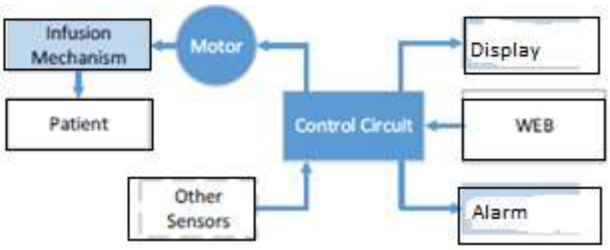


Figure 2: Infusion pump block diagram

The patient is connected to the pump, which in turn is completely controlled by the developed system. The pump sensor and alarms are used and the control circuit manages all the necessary input and output data. Data is sent to the pump through user web interface [6][7].

As depicted, the system is divided in four units:

1) Electrical/mechanical unit of the infusion pump;
2) Module with a dc motor and its controller and alarms (buzzers and syringe presence led);
3) Computer module controlling the operation of the pump;
4) Display LCD for visual feedback of the information.

Introducing all the control parameters in the web interface, the information is processed in the computer and the pump is set to work as defined.

2.2 Web Interface

Through the web interface, the different infusion parameters are sent to the computer [4], which communicates with the pump through the serial port. This interface also allows managing the patients' records by accessing their electronic medical record, thus allowing the health professionals to have more detailed information on the patient. All the information [5] sent to the computer, as well as the data related to the patient and the health professional operating the equipment is stored in a database developed in easyphp [8].

After receiving data from the web interface, the computer module calculates the different infusion parameters necessary to set the pump operating mode. The several alarms are also controlled by this computer. One of the alarms indicates the absence of the syringe, not allowing the infusion if set-off. There are alarms corresponding to the end of the infusion (acoustic alarm) and also to indicate the battery voltage level. All this information is also sent to the computer display so that the user can visualize what is going on.

3. Mathematical Model and Control of Infusion Pump System

3.1 DC Motor Speed and Position Control

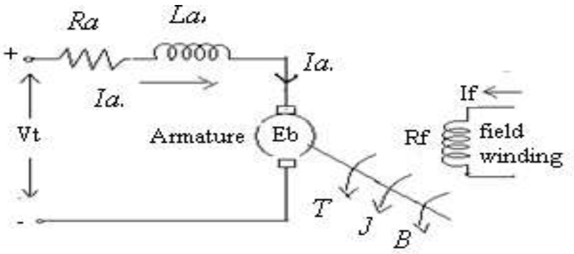


Figure3: DC motor model.

A general model of a DC motor is shown in Figure3. Applied voltage V_a, which is the manipulated variable, For the position control Θ(t), which is the control variable. For the speed control, the controlled variable is the angular velocity w(t) and the load transfer function has the form in (1):

$$\mathrm{Pdc}(s) = \frac{W(s)}{V_a(s)} = \frac{Km}{(l_a s+R_a)(Js+b)+K_b K_m} \qquad (1)$$

However, for many dc motors the time constant of the armatüre $\tau_a=L_a/R_a$ is negligible and therefore the model can be simplified to:

$$\mathrm{Pdc}(s) = \frac{Kdc}{\tau s+1} \qquad (2)$$

Where $\tau=JR_a/(R_a\, b+K_bK_m)$ and $K_{dc}=K_m/\ (R_a\, b+K_bK_m)$

The transfer function from position Θ(t) as output (controlled variable) to armatüre voltage V_a as input (manipulated variable) will be :

$$\mathrm{Pdc}(s) = \frac{\theta(s)}{Va(s)} = \frac{K_{dc}}{s(\tau s+1)} \qquad (3)$$

Injection mg is calculated based on 10 cc injector. The dose formula for the infusion pump mechanism is given by (4).

$$\mathrm{Dose\ (mg)} = (\theta\ /\ 2\pi)\, a.\, \pi r_{en}^{2} d_{ilaç} \qquad (4)$$

Where, the angular position of the θ (rad) shows the screw density, the screw pitch a (mm), the injector radius r_{en}_(mm) and the drug concentration d (mg/mm^3).

4. PID and FOPID Controllers for DC Motor

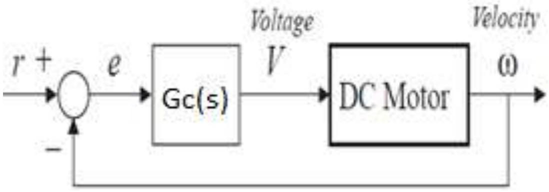


Figure 4: Block diagram of DC motor speed control

Block diagram of DC motor speed control is shown in Figure4. Where r is reference input, e is error and $G_c(s)$ is controller transfer function. In our study two types of controller. are used and first classical integer order PID has the following transfer function:

$$G_c(s)= K_p + K_i\, s^{-1} + K_d\, s \qquad (5)$$

Here , the orders of integration and derivation are both unity. Where K_p, K_i and K_d are proportional, integral and derivative constants respectively. A fractional order PID transfer function is given as

$$G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu} \tag{6}$$

The orders of integration and differentiation are respectively λ and μ (both positive real numbers, not necessarily integers).Taking $\mu = 1$ and $\lambda = 1$, we will an integer order PID controller. So we see that the integer order PID controller has three parameters, while the fractional order PID controller has five. The first experimental set-up consists in the control of the speed of a dc motor using a fractional order PID controller. The design of the controller is based on a phase margin and again crossover condition, to which we add a criteria regarding the robustness to gain variations.

4.1 FOPID Controller Design in Frequency Domain

In the frequency domain design method for fractional areas, the controllers first start with the linear model of the system. The transfer function of the Gp (s) and Gc (s) controllers supports the properties of the following equations [9, 10]:

a) An imposed phase margine of the open loop system

$$\arctan\left(G_c(j\omega)G_p(j\omega)\right) = -\pi + pm \tag{7}$$

b) An imposed gain crossover frequency of the open loop system

$$\left|G_c(j\omega)G_p(j\omega)\right| = 0\ \mathrm{dB} \tag{8}$$

c) A condition for robustness to gain variation

$$\frac{d}{d\omega}\arctan\left(G_c(j\omega)G_p(j\omega)\right) = 0 \tag{9}$$

d) An imposed remove high frequency noise

$$\frac{G_c(j\omega)G_p(j\omega)}{1+G_c(j\omega)G_p(j\omega)} = B\ \mathrm{dB} \tag{10}$$

e) An imposed remove the output distortion

$$\frac{1}{1+G_c(j\omega)G_p(j\omega)} = A\ dB \tag{11}$$

Controller saturation determines the physical systems of the agents. For the motor-generator system, the control operation is limited to 10 V. All equations should be used from the equation (7) to the equation (11) to design features such as phase margin, frequency shift gain, amplitude of sensitivity function (A) and size of complementary sensitivity function (B) for efficient desired design features of the FOPID controller

4.2 Discrete Time FOPID Controllers

Discrete time transfer function for FOPID controller is defined as

$$\frac{u(z)}{e(z)} = k_p + k_i\alpha^{-\lambda}\frac{z+1}{z-1}\sum_{k=0}^{N} f_k(1-\lambda)\omega^{-k} + k_d(\alpha^{\mu}\sum_{k=0}^{N} f_k(\mu)\omega \tag{12}$$

Total transfer function is presented as the sum of three components, respectively proportional, integral and derivative parts

$$U(z) = U_p(z) + U_i(z) + U_d(z) \tag{13}$$

From this definition and using Tustin methods following discrete equations can be obtained as

$$u_p(k) = ke(k) \tag{14}$$

$$u_i(k) = [\frac{k_i}{\alpha^{\lambda}}(e(k) - e(k-1)] \tag{15}$$

$$\begin{aligned} ui(k) = {} & -(\alpha_5 - 1)u_1(k-1) - (\alpha_4 - \alpha_5)u_i(k-2) - \\ & (\alpha_3 - \alpha_4)u_i(k-3) - (\alpha_2 - \alpha_3)u_i(k-4) \\ & -(\alpha_1 - \alpha_2)u_i(k-5) - (\alpha_0 - \alpha_1)u_i(k-6) + (\alpha_0) \\ & u_i(k-7) \end{aligned} \tag{16}$$

$$u_d(k) = [k_d\alpha^{\mu}(e(k) - e(k-1)] \tag{17}$$

$$\begin{aligned} u_d(k) = {} & \alpha_4 e(k-2) + \alpha_3 e(k-3) + \\ & \alpha_2 e(k-4) + \alpha_1 e(k-5) + \alpha_0 e(k-6) \end{aligned} \tag{18}$$

Where α_i is control constant and they can be selected from the control constant table. Here u_p, u_i , u_d are proportional part , integral part and derivative part of FOPID controller respectively. Simulink diagram of the DC motor speed control is shown in Figure 5[11].

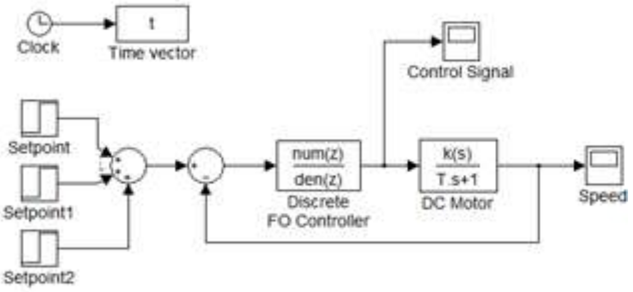


Figure5. Simulink diagram of fractional order PID controler for the DC motor speed control

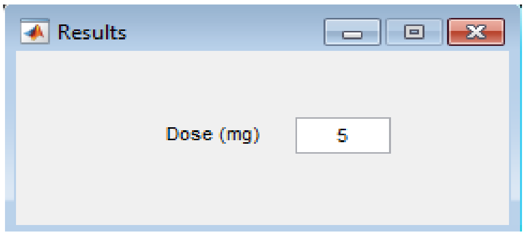
In Figure 5, a Simulink diagram of the fractional order PID controller for speed control is illustrated. Block constants were set according to parameters of DC motor and fractional-order controller. The simulation results for fractional order feedback loop by using the Simulink model are presented in Section 5..

5. Simulation Results

A MATLAB-GUI program is developed for the dose calculation is depicted in Figure 6.When input parametes are entered, we can observe the dose value (mg) on the screen. System parameter values used in simulation is prepared as a MATLAB m-file. Control system output is w angular velocity at the control system block diagram. If position is considered as an integral of angular velocity, same block diagram of control system can be used in position control. In order to compare controller performances, both type controller respectively PID and FOBID are used in simulations. A MATLAB-GUI program is developed for the chosen of FOBID parameters. Simulation results are shown the following Figure12, 13, 14 respectively. Also simulation results obtained from Simulink program show dose injection according to the position and speed of DC motor. In the MATLAB simulations, the following parameter values are used and controller parameters are selected from Simulink GUI screen shown in Figure 6.

Motor parameter values: R_a=6 ohm, L_a=0.5H, R_f =240 ohm, L_f=120mH, K_e=0.1, K_t=10, J=1, b=2. Pump mechanism parameters: a=0.1mm, r_{en}=0.7mm, r=0.5mm

Figure 6: Matlab GUI Anesthesia Injection system user interface



Dose (mg) 5

Figure 7: Matlab GUI Anesthesia Injection System User Evaluation Screen

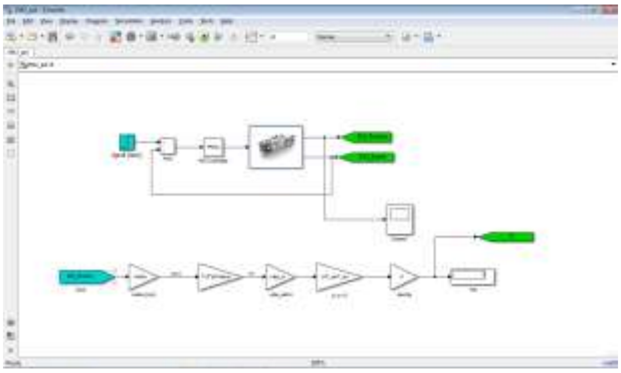


Figure 8: General Block Diagram of Injection System

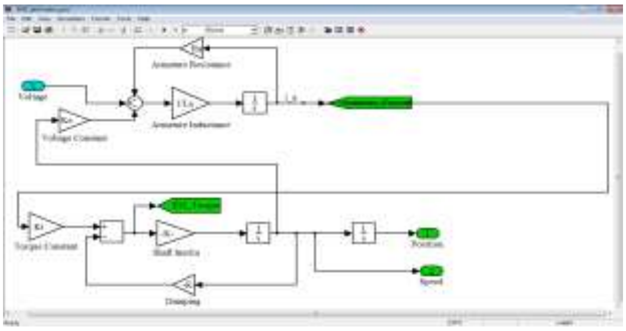


Figure 9: Speed and Position Controlled Block Diagram of DC Motors

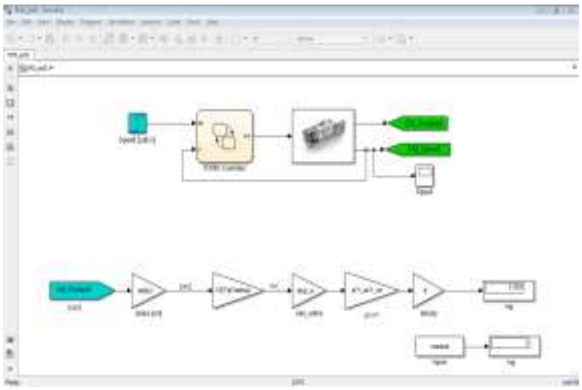
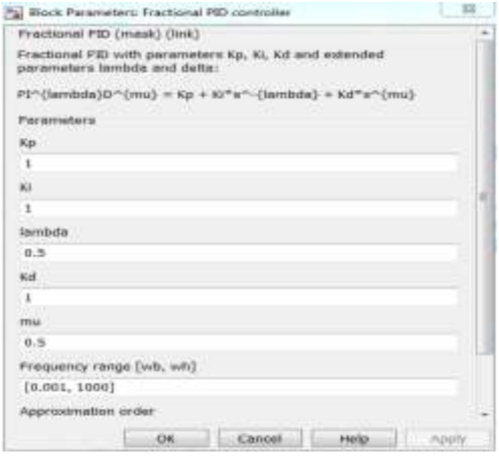


Figure 10: Design of Injection System with FOPID Controller



Block Parameters: Fractional PID controller

Fractional PID (mask) (link)

Fractional PID with parameters Kp, Ki, Kd and extended parameters lambda and delta:

PI^{lambda}D^{mu} = Kp + Ki*s^-{lambda} + Kd*s^{mu}

Parameters

Kp
1

Ki
1

lambda
0.5

Kd
1

mu
0.5

Frequency range [wb, wh]
[0.001, 1000]

Approximation order

Figure 11: Simulink GUI screen for the selection of FOPID controller parameters

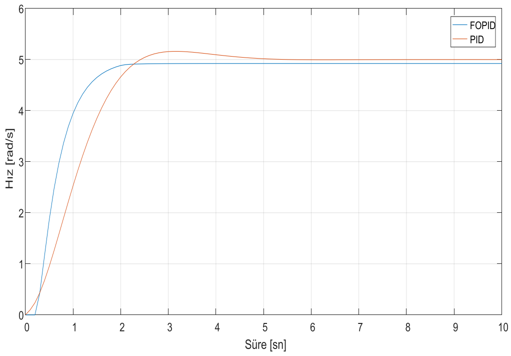


Figure 12: Step responses of velocity with PID and FOPID

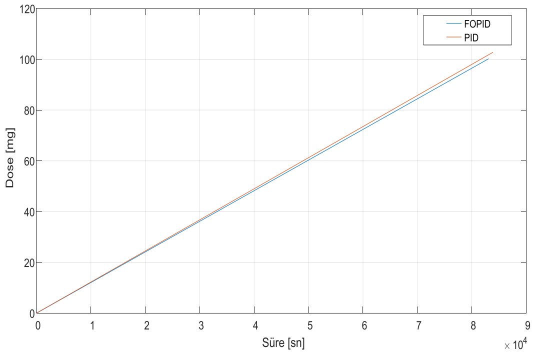


Figure 13: Position outputs with PID and FOPID controllers

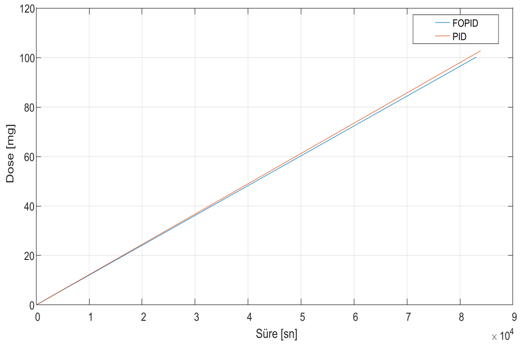


Figure 14: Dose outputs with PID and FOPID controllers

The fractional order PID controller is compared with the integer order PID controller. The integer order PID controller has been designed using the same performance specifications and the same tuning algorithm as for the fractional controller. Hence, the fractional order is M = 1 and the tuning parameter are: k_p = 1.23 and ki = 2.41. As observed from the simulation results, the fractional order controller outperforms the classical controller.The simulated output dose values for the same parameter values were compared in the injection system simulation environment with the PID and FOPID controllers realized with Matlab Simulink and it was observed that values closer to the reference with FOPID controller were obtained.

6. Conclusıons

The system developed allows to controlling all the parameters necessary to the syringe infusion pump. The mechanical parts used were part of the original pump but the control hardware and the user web interface was completely designed. Apart from the infusion parameters, all the alarms triggered during an infusion, the battery level – which are parameters related to the equipment, the health professional handling the pump and the medical records related to the patient are also recorded in a database for later information. This system could also be improved, mainly the interface with the mechanical part and the microcontroller, specifically inserting a numerical keypad and a command pushbutton to better control the infusion pump, deal with different syringes for specific volumetric flows, and other anesthetic details. Due to time restraints, more emphasis was given on the development of the connections to the database and remote controlling the pump.

The characteristics of the anesthetic drugs used in the study are explained. The side effects and dosing calculations that should be considered in anesthetic drugs are explained. On the device side, all the components of the device parameters and injection system are introduced. These components include injection shaft, injection device feeder card, main board, DC motor, DC motor control which is frequently used in injection systems. The mathematical model of the simulation system of the device. The system fault was analyzed using Matlab Simulink with PID and FOPID and this error was corrected with the designed controllers. As mentioned in the discussion section, simulation results are shown because the injection system simulation results in users' calculations in mg. In the case of device realization, how much ml of anesthetic agent is to be injected from the syringe will be determined by the sensors to be used as the calculation result for the patient. Since no single anesthetic agent was used in the simulation, the user interface was created using the Matlab GUI to use the anesthesia injection unit. This intermediate percentage provides the patient with the age, weight, medication list, the use of push buttons to give the injection according to the situation of the medicine and the patient. The processes created in Matlab GUI are completed by calling the m-file file used for dose calculation and the simulation created for the system in Matlab GUI environment. After the selection of these operations, the injection is calculated in the simulation environment by calculating the dose and the application of the injection automatically to the person after the calculation of the injection dose is displayed on the user interface screen. Today, target controlled injection systems are used. The purpose of the targeted controlled injection system is to shorten the time of the patient's healing and reduce the side effects of the drugs. In this target-controlled injection system, the injection is designed for approximately five different agents on average as it is only used intravenously. Some agents can be given intramuscularly because they can not be given intravenously according to the condition of the patient.
The simulated output dose values for the same parameter values were compared in the injection system simulation environment with the PID and FOPID controllers realized with Matlab Simulink and it was observed that values closer to the reference with FOPID controller were obtained. In later studies, however, the methods used for the patients during the realization phase (intravenous and intramuscular) are intended as an analysis of the clinical situation of the patient and the patient should be automatically injected by the device with an automatic anesthetic injection device when neuroscirological findings are observed.

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