RBE - Caderno de Engenharia Biomédica, v. 13, n. 3, p. 161-170, julho 1997
Edição Especial: Engenharia Biomédica na América Latina

DEVELOPMENT OF A PROGRAMMABLE CONTROLLER OF LIQUID FLOW

M. A. da Motta[1] and G. B. Brandão[2]

Abstracts -- The volume of liquids used in medicine, industry and laboratories, can be measured by fractionated injection devices or by means of flow control mechanisms, based on the hydrostatic pressure of these liquids. The liquid flow controller proposed here, measures flow through an electronic drop counter regulating a clamp-like mechanism, driven by a step motor, that squeezes a plastic discharge tube and so reduces the liquid flow inside, in order to maintain the drip frequency constant. Its conception is based on an infrared transducer, placed outside a transparent dropper, that transforms the dripping period into electric pulses. After digital treatment, these signals are compared to those set as reference for a desired flow-rate. The resulting electric tension is then applied to the step motor, to modulate the pincer opening that regulates the flow of the liquid column inside a polyethylene discharge tube. The hydrostatic pressure forces the liquid downwards, inside the plastic discharge tube, producing a continuous flow of drips into the dropper, closing the feedback loop that maintains the programmed dripping rate. Showing good performance and low cost, this device may be applied for medical purposes in hospitals and medical emergency services.

Keywords: Liquid flow, Programmable Controller, Dropper.

INTRODUCTION

The measurement of liquid flow requires high precision and accuracy, especially in medical applications. The injection speed of diluted drugs and medications injected in the intravenous route are controlled - routinely - by means of a clamping mechanism manually activated, placed around the discharge tube of an intravenous infusion setup. The most common devices found in medical practice for long term programmed intravenous injection of medications, are the infusion pumps (Barney, 1985). The most prevailing type used is based on a technique whereby the liquid volume is injected by a syringe whose embolus is propelled by a step motor (Chivers-Ferraz, 1993). The infusion program is set to modify the speed of the step motor, that drives the embolus of the syringe forward, at a constant rate. This method is applied chiefly for the injection of concentrated medications. If an error occurs in the operation cycle, it will be repeated and summed, resulting in a subdose or an overdose (Anonymous, 1992). This is a critical aspect concerning the utilization of this method, specially if we consider the time dependent character of the action of the medications. Furthermore, all the factors inducing a variation of downstream or upstream hydrostatic pressure

[1] Associate Professor, Departamento de Biofísica e Radiobiologia, UFPE - Av. Prof. Moraes Rego, s/n - Cidade Universitária, CEP50670-901 Recife, PE, Brazil. Email: motta@npd.ufpe.br

[2] Engineer, DSc Student, Department of Electrical Engineer, Federal University of Paraiba, Campus 2. E-mail:gbrandão@dee.ufpb.br

// Trabalho recebido em 06/03/96 e aceito em 14/04/97 //

(patient's position, liquid level inside the infusion recipient, blood clots, elbow flexure and others), provoke an alteration of the applied dose/time.

The ideal infusion system should correct through a compensating mechanism, all the small deviations and systematic errors inherent in the method (Hassapis, 1978) and some possible mechanical errors too. It should be robust and low-cost. In order to avoid the above problems, a programmed drip based controller was conceived and developed for the administration of liquids, being tested and evaluated as described below.

MATERIALS AND METHODS

The arrangement of the Liquid Flow Control System

The working principle of this system is based on the dripping rhythm of the liquid flowing inside an infusion set for intravenous injection, controlled by electric pulses generated by the interruption of an infrared (IR) beam that is intercepted by the drips. The flow of drips may modulate - by means of the electric pulses generated in its transit - the opening or closing of the descending liquid column into the plastic tube and consequently the flow-rate. This is provided by a pincer, the arms of which are attached through a mobile holder and nut to a screw connected to the axle of a step motor, that is activated by the electric pulses from the drip frequency, as shown in Figure 1.

In order to drive the step motor, the electric pulses generated by the drop flow are compared to standard pulses generated by a reference signal generator circuit, previously adjusted to a programmed frequency, as the desired drop rate. This is manually set by the operator and can be seen in a liquid crystal display, as "the number of drops per minute".

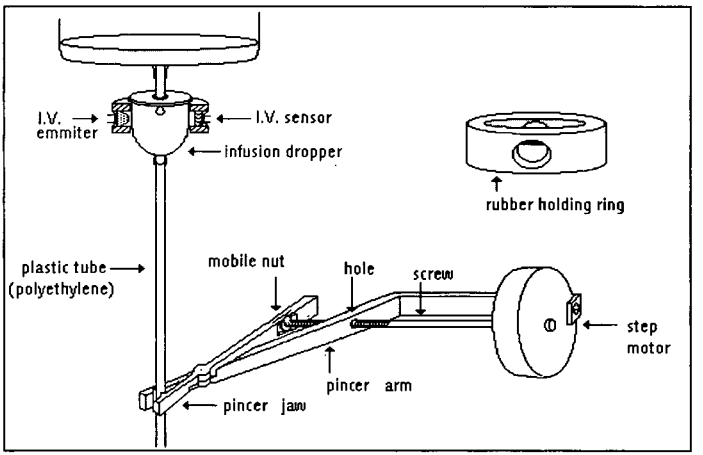

Figure 1- View of the main mechanical components of the controller.

Secondly, the pulse frequency (real dripping) is compared with the reference frequency (the programmed dripping). If the periods of the signals are not the same, the step motor control circuit compensates for the difference, generating the electric pulses necessary to balance both frequencies and these pulses are applied to the step motor. Thus it can rotate in one or the other direction - depending on the polarity of the output signals - and by means of the metal screw connected to the pincer arm nut and mobile holder, the step motor increases or decreases the compression of the pincer jaws over the plastic tube conducting the liquid. This mechanism can modulate the drip flow. If the periods of both the signals are equal, no signal is applied to the step motor and it stops; in this case, the drip flow remains constant.

Framework

The flow control is composed of three modules: the optoelectronic, the electronic and the electromechanical modules, as shown in Figure 2. The first module is composed of an IR transducer (drip detector), assembled into a rubber ring. It may be placed outside the infusion dropper of a commercial intravenous infusion set, if applied for medical purposes. This set, sold in drugstores, is composed of a flexible plastic (polypropylene) tube, a manual controller (here it is discarded) and a dropper. This last part is a plastic transparent and closed recipient, with a thin inner open tube. This thin rigid plastic open tube placed into the drip counter at its superior wall, is connected to the reservoir of liquid and is responsible for the drop formation. At its base, the dropper has a funnel shaped ending that connects to the plastic tube. The drip detector is set in place by the rubber holding ring in order to detect the drip-frequency of the drops falling into the dropper; it is composed of an infrared transducer embedded in the rubber ring and arranged in such a manner that the IR emitter is placed diametrically opposite the IR detector.

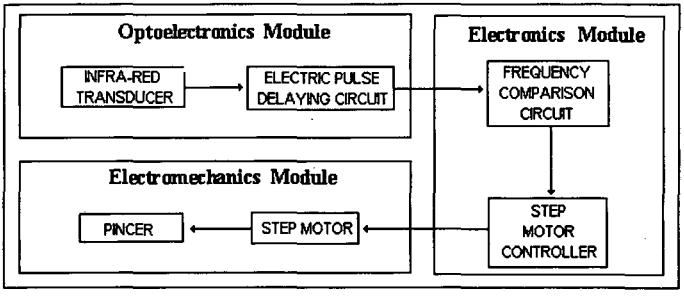

Figure 2 - Block diagram of the programmable controller.

When a falling drop intercepts the IR beam, an electric signal is sent to the electronic module through an equalizer circuit. This is an electric pulse-delaying circuit inserted in the optoelectronic module in order to avoid the effects of the sprinkling of liquid when the drop falls, inducing a false count, at higher drip frequency rates. This delayed detection of drops avoids this kind of error mainly when measuring low density liquids.

The second module is constructed of a trigger circuit, memories, period-tension and tension-period converters and a differential tension comparison circuit, coupled to an error detection circuit, that together compose the pulse comparison circuit. The latter is connected to the digital step motor control circuits, forming the motor controller.

The signal coming from the optoelectronic module is then fed to the comparison circuit, in the electronic module, after its conversion into pulses. Its frequency is analyzed by an error detection circuit that verifies its value as compared with the reference signal: if the difference in frequencies is less than 2% the signal is canceled: if not, it continues to activate the step motor. Thus, is assumed that when the difference between the scheduled and the actual rate of drops per minute is not significant, the step motor is immobilized; else, it moves searching for this condition.

A sampling circuit, added to the electronic module, allows the frequency comparison circuit to calculate the number of turns to be made in the step motor to make the system reach, after three drops, the frequency requested in the program schedule. This fast-adjusting circuit is based on the mean period of the samples and accordingly, the step motor control activates one of four existing bandwidths of pulse frequency drives, to activate the step motor. Further dripping variations are detected and are automatically compensated.

The third module - electromechanical - controls the liquid flow through the infusion equipment dropper by the mechanical pressure applied to a pincer holding the plastic tube of this set, thereby constricting the passage of liquid and so reducing the dripping upstream. This action is obtained through the electrical pulses coming from the electronic module, which makes the step motor turn clockwise or counter-clockwise.

The step motor axle transfers its rotational force through the pincer arm screw to activate the metal pincer. In this way, the screw passes through a hole in one pincer arm that is screwed to the step motor and reaches the other arm where it is fixed by means of a mobile coupling holder - a nut with two axles fitted in grooves in the handle. This allows the lateral and rotational displacement of the nut when the screw turns right or left, but retains the movement to close or to open the pincer, as seen in Figure 1. A supplementary circuit provides for the wide opening of the pincer at the beginning of operation, to facilitate the insertion of the plastic tube between the pincer jaws.

In one pincer jaw there is a concavity and a corresponding convexity in the other. They match up when the pincer is closed. This was conceived in order to keep the plastic tube (that will be compressed) at a constant distance from the pincer axle, during the compression and decompression. The pincer arms, 6 times longer than the jaws, operate a cantilever system that increases the precision of the flow regulation by reducing the angular movement speed of the pincer arms but increasing its torque.

RESULTS

Laboratory tests were performed to find the best static and dynamic characteristics of the new-developed device. They were monitored by a HP 54600B Oscilloscope linked to a 486DX66 computer by a HP54659B interface measurement/storage module in order to record the data during the drop frequency change.

The first test was long term to evaluate the system oscillations before it reached a steady state and was directed towards the evaluation of the stability, error and energy consumption of the device. It involved 15 series of measurements with a saline solution (NaCl 15%) at dripping rates varying from 5 drops/min to 90 drops/min, with an increment of 5 drops and with a decrement from 90 drops/min to 5.

At each new programmed value, the time required to reach the correct dripping rate was measured, i.e. the time required to stabilize the pincer adjustments for the flow into the plastic tube, equalizing the dripping rate to the programmed one, here called stabilization time or ST. The results (Table 1) show an increased ST mainly at the lower extreme values of dripping, where the low dripping frequency causes some difficulties for a rapid achievement of the programmed value of drop count per minute. In general the drop-rate increments demand more time than the decrements.

The second test, consisted of 10 series of short term trials focused on the velocity of the flow rate adaptation after a pressure variation, under the reservoir, at a fixed dripping rate. The programmed drip rate was set at 20 drops/min. In order to alter the hydrostatic pressure into the reservoir, the end of the open plastic tube was closed and placed at the level of the dropper and then the drip stopped. Following a vertical scale, the end of the plastic tube was taken down to a level 50 cm lower, causing modifications in the pressure inside the dropper.

Table 1 - Dripping rate (drops/min) and the mean ST at the programmed value, together with its standard deviations (after 15 series of measurements).

Drops/min	ST (s)	Std. Dev.	Drops/min	ST (s)	Std. Dev.
05 - 10	91.33	1.53	85 -90	4.33	1.15
10 - 15	60.77	9.84	80 -85	4.33	0.58
15 - 20	33.43	4.71	75 -80	5.53	0.50
20 - 25	17.03	1.67	80 -85	6.00	1.73
25 - 30	17.00	1.73	65 - 70	6.33	1.53
30 - 35	16.97	1.00	60 - 65	10.00	2.65
35 - 40	15.03	0.96	50 - 55	10.67	0.58
40 - 45	16.02	1.00	50 - 55	14.00	1.00
45 - 50	6.50	1.32	45 - 50	14.67	0.58
50 - 55	6.33	1.15	40 - 45	15.00	1.00
55 - 60	5.67	0.58	35 - 40	16.67	1.53
60 - 65	5.57	0.45	30 - 35	17.40	0.53
65 - 70	5.20	0.26	25 - 30	20.53	0.92
70 - 75	4.93	0.12	20 - 25	26.67	0.58
75 -80	5.17	0.72	15 - 20	34.67	3.06
80 -85	5.23	0.68	10 - 15	1.15	2.52
85 -90	5.33	0.58	05 - 10	0.63	
Average	15.24	1.33		10.53	

This induced an increase in the dripping rate, proportional to the level difference: the higher the tip of the tube, the lower the dripping rate for the same pincer opening.

The pressure (P) inside the dropper was calculated from:

$$P-P_o = \rho \cdot \Delta h \, g \qquad (1)$$

where: ρ = density of the liquid
g = acceleration of gravity
Δh = difference of height between the tip of the tube and the dropper
P_o = ambient pressure (1 Atmosphere) into the reservoir, above the dropper.

After each change of pressure caused by the displacement downwards, from 0 to 50 cm with steps of 5 cm, some time (± 30 sec) was required for the liquid stabilization and to start the next pressure step. Reaching the level of 50 cm below, the end of the tube remounted the scale up to the 0 cm level, following the same procedure used in the previous trials for stabilizing the liquid flow. Making the ambient pressure equal to 100, the applied pressure was expressed as a percentage of the atmospheric pressure.

Table 2 - Relationship between the variation of the reservoir pressure level and the mean ST for a fixed value (20 drops/min) and 30 series of measurements.

Atm.press.%	ST (s)	Std.dev.	Atm.press.%	ST(s)	Std.dev.
1.455	25.77	0.40	5.822	72.07	1.78
1.941	25.57	1.36	5.337	67.33	3.06
2.426	26.50	0.44	4.851	66.00	2.00
2.911	28.07	1.01	4.366	59.67	3.22
3.396	28.29	0.26	3.881	45.67	8.16
3.881	31.87	0.85	3.396	26.67	3.06
4.366	55.20	1.06	2.911	24.07	1.22
4.851	60.73	0.64	2.426	22.47	1.01
5.337	64.34	0.57	1.941	21.67	0.58
5.822	65.33	6.43	1.455	17.03	0.45
Average	41.17	1.30	-	42.27	2.45

This test was repeated three times with the objective to estimate the repeatability of the measurements of different flow rates and the time necessary to attain equilibrium after each flow rate change, making the programmed value (20 drops/min) equal to the real flow, as shown in Table 2. The pressures are given as percentage of the atmospheric pressure. The test showed the reliability of this system, in that it is able to compensate quickly for any deviations of the dripping regime previously programmed, induced by an increase in the venous pressure from eg. raising of the limb where the infusion needle is inserted.

The hysteresis of this system, as shown in Figure 2, was observed for the data from the drop rate per minute obtained by one step increments of the step motor driving the pincer opening, up to a total of 37 steps that lead to maximal opening. At this point the flow rate was 98 drops per minute. Then, the step motor motion was inverted, and the flow-rate decreased progressively following the compression of the discharge tube and after 37 steps reached the value of 0 drops/minute.

The maximal input hysteresis was calculated from the highest level of input/output difference: the 24th step. At this point a difference of 15 drops/min was observed, between the curves, equivalent to 15.3%. The maximal output hysteresis was evaluated from the difference of 5 steps, found at a value of 43 drops/min (difference of 13.5%). This is due to the shape of the pincer jaws' concavity/convexity compressing the tube and to the viscoelastic properties of the plastic used in the tubes. The pincers and the step motor are the only mobile parts of the controller and are well fitted and adjusted to each other leaving no opportunity to cause an imprecise operation.

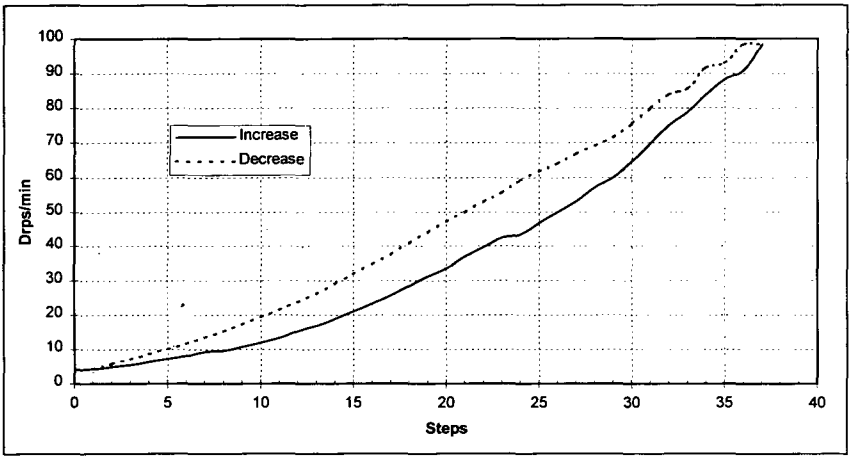

Figure 2. Graph of the hysteresis from 0 to 98 drop/min flow rate (dotted line = compression of the plastic tube ; solid line = opening of the pincer jaws).

DISCUSSION AND CONCLUSIONS

All the tests undertaken to evaluate the capabilities of this system demonstrate the high performance achieved, not only in the fast stabilization of the flow control to a new drop regime, but also the capacity to maintain the programmed flow after alteration of hydrostatic pressure. The strong hysteresis is of mechanical origin and does not affect the precision and accuracy of the system operation, on account of the existing automatic compensation in the design of this system. The cause of this hysteresis is due in part to the internal shape of the pincer jaws, whose concavity/convexity, despite being the best solution to fix the plastic tube, do not cause a linear

reduction of its inner cross section during the compression and decompression cycles. This lack of linearity, mainly at median values, induces the above mentioned hysteresis.

The main difference of this device from others of the same category are the frequency bandwidth circuits that produce a fast balance between the scheduled and the real flow rate. Its stability is good, as seen in Table 1, as is its accuracy due to the digital control of the step motor. Hassapis (1988) and Petrou (1975) developed computer based systems, satisfactory but very bulky for routine use in medicine. Chivers-Ferraz (1993) developed a computer based programmable system with analog control of the step motor, but it needed almost five minutes to reach the programmed rate.

This device is being currently developed in association with temperature, heart beat and respiratory sensors for medical intensive care applications. The proposed device is light, portable and able to reach the programmed flow rate in 5 to 95 seconds (see Table 2).

Other features of this system are: Drift - 1.2 %; Error - 0.87%; Maximal consumption: 50 mA; Operation temperature: 38 ± 1°C (Electronic module); Maximal drip frequency: 90 drops/min; Minimal drip frequency: 5 drop/min. Electric source: 1 battery 12 V - 0.5 Ah (lifetime:10 h).

The applications of the proposed system are wide, in the general use for medical purposes, the routine in laboratories, or in industry for reagents of critical utilization, such as starches, concentrated or diluted acids and basis or catalysts/enzymes. The volume of a liquid drop varies depending on its chemical nature, ambient pressure and temperature. For medical purposes, it depends on the composition of the administered solution, which must be taken into account, when considering the volume administered to the patient.

ACKNOWLEDGEMENTS

We are thankful to Dr. Desmond Gilmore, for the revision of this article and to FACEPE for the financial support in this research .

REFERENCES

BARNEY, G.(1985). *Intelligent Instrumentation.* London: Prentice Hall.

CHIVERS-FERRAZ, C. H. (1993). *Um sistema controlador de infusão intravenosa multi-paciente para salas de operação hospitalares.* M.Sc. Dissertation. Programa de Engenharia Eletrônica. UFPE. Recife. 112 p., July.

ANONYMOUS (1993). *Decca 460 Drip-feed Unit - specifications sheet.* New York: Decca, 2 p.

HASSAPIS, G. D.(1978). *Applications of microprocessors in control system technology.* Ph.D. Thesis, University of Manchester, Institute of Science and Technology. Manchester. 104 p., May.

HASSAPIS, G. D. (1988). "A Microcomputer-Based Drip-Feed Unit". *IEEE Transactions on Instrumentation and Measurement*. v.37, n.1, p.39-44.

PETROU, L. P. (1975). *The development of a digital drip-feed controller*. M.Sc. Dissertation, University of Manchester. Institute of Science and Technology. Manchester. 98 p., October.

DESENVOLVIMENTO DE UM CONTROLADOR PROGRAMÁVEL DE FLUXO LÍQUIDO

M. A. da Motta[1] e G. B. Brandão[2]

RESUMO -- O volume dos líquidos utilizados em medicina, indústrias e laboratórios, pode ser medido por injeção fracionada ou através de controladores de fluxo utilizando a pressão hidrostática do próprio líquido. O Controlador de Fluxo Líquido proposto aqui mede o fluxo através de contador eletrônico de gotas que atua sobre uma pinça cuja abertura é controlada por um motor de passo, comprimindo o tubo plástico pelo qual passa o líquido, afim de manter o gotejamento constante. Sua concepção é baseada em um transdutor infravermelho que transforma a freqüência de gotejamento em pulsos elétricos. Após um tratamento digital, estes sinais são comparados aos que foram programados como referência para uma freqüência desejada. A tensão elétrica resultante é então aplicada no motor de passo, para modular a abertura da pinça, regulando assim o flowo líquido que desce pelo tubo plástico. A pressão hidrostática força o líquido para baixo, produzindo um fluxo contínuo de gotas, fechando o circuito da autoregulação do volume líquido desejado. Com baixo custo e bom desempenho, este sistema pode ser aplicado em hospitais, ambulatórios e serviços de emergência médica.

Palavras-chave: Fluxo Líquido, Controlador Programável, Contrololador Eletrônico de Gotas.

[1] Professor Adjunto, Departamento de Biofísica e Radiobiologia, UFPE - Av. Prof. Moraes Rego,s/n - Cid. Universitária CEP50670-901 Recife, PE. E-mail: motta@npd.ufpe.br

[2] Engenheiro, aluno do Curso de Doutorado em Engenharia Elétrica, Campus 2 UFPB. E-mail:gbrandão@dee.ufpb.br