Incorporating Fuzzy Logic Into An Adaptive Negative Pressure Wound Therapy Device

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Abstract— Negative pressure wound therapy (NPWT) is a technique that enhances the healing process by applying negative pressure on the chronic or acute wounds. It has been diffusely adopted for treatment of trauma wound, chronic wound, or deep sternal wound infections due to its excellent healing result. However, there were several injuries and death cases caused by the unstable pressure generated from the wound treatment. This paper aims to design a stable negative pressure regulator by using fuzzy logic controller (FLC) .The proposed control approach is able to regulate the negative pressure within the desired range for healing process. The NPWT system consists of adhesive film dressing, wound dressing, fluid collecting canister, drainage tubes, vacuum pump, and microcontroller. The NPWT system developed is able to supply negative pressure from 0mmHg to 200mmHg and the negative pressure supply can be controlled. The effectiveness of FLC pressure controlling and Boolean logic controller method is validated by experiments. In conclusion, it is proven that the proposed method is able to provide a safe wound treatment in future.

Index Terms— Fuzzy Logic Controller (FLC); Negative Pressure Wound Therapy (NPWT); Wounds Healing Device.

I. INTRODUCTION

The basic suction method utilized in NPWT is evolved from China's cupping therapy, which helps to circulating the blood flow during treatment.[1] This method was being recorded earlier in Bo Shu (an ancient book written on silk) and it was discovered in an ancient tomb of the Han Dynasty in 1973 [2].

The Bier's Hyperemic Treatment using vacuum suction apparatus was being introduced by Bier in 1908 and it is now being used for the treatment for open wounds.[3] The more advanced research studies of NPWT has been conducted by Chariker and Fleischmann in late 1980's and early 1990's [4,5]. The first device for NPWT was being marketed in the United States in 1997. The NPWT method has been widely spread throughout North America, Europe, and other parts of the world. Nowadays, NPWT is being used for treatment of hard-to-heal wounds. Some examples would be decubitus ulcers, venous leg ulcers, vascular surgery wounds, diabetic foot ulcers, burns, traumatic orthopaedic and soft tissue wounds, flaps, skin grafts, and thoracic surgery or surgical infections.

For the wound treatment using NPWT method, the wound environment is being controlled at the sub-atmospheric pressure. The sub-atmospheric pressure is usually lower than the atmospheric pressure, 760mmHg. This physics mechanics is able to induce mechanical stress to tissues and stimulate the division of cell (Mitosis). As such, the speed of growth of new blood vessels can be enhanced and wound will be drawn closed toward the center point [6]. Thus, the speed of healing process by using negative pressure method will be faster and more efficient.

Besides, NPWT method also enhances the healing process by increasing blood flow rate at wound area, maintaining the wound environment humidity, shielding the surrounding, reducing the risk of bacterial infection, decreasing interstitial oedema, contracting wound edges, and promoting the growth of granulation tissue. [7, 8, 9, 10, 11, 12, 13, 14]

Fuzzy Logic is one of the Artificial Intelligence (AI) algorithms that which is being widely adopted in various type of applications. Coupling with rule based system, Fuzzy logic enables the modeling of the approximate and imprecise reasoning processes that is common in human problem solving.[15] Fuzzy logic is a multi-valued logic system. The variable ranges of the truth value of Fuzzy logic system is between 0 and 1. There are four components required for utilizing fuzzy logic, namely fuzzification inference, rule base, decision making unit and defuzzification. The degree of membership is determined by the fuzzifying of each data point by using the input fuzzy set. The fuzzification interface will transform the crisp input data into the degrees that match with linguistic values [16]. Rule base of fuzzy logic controller containing several fuzzy if–then rules and database which define the relationship between input and output membership functions of the fuzzy logic controller. There will be a minimum and maximum range of input values, either 0 or 1 for each membership function. The membership function can be programmed by using several shapes, such as trapezoidal, gaussian, and triangular. The fuzzy logic controller will provide a decision

result based on the inference operation of fuzzy rules. Lastly, defuzzification interface will transform the fuzzy decision result into a crisp output.

Recently, there is a sharp increase in the number of cardiovascular and diabetes diseases in the world. Based on the data presented from American Diabetes Association, there are approximately 4 million diabetes patients suffer from foot ulcer. This has triggered the development of the NPWT market, which NPWT is strongly recommended to be an effective wound treatment device for diabetic wound treatment.

In 2003, Abu-Omar et al. described two cases of right ventricular rupture and mediastinitis resulted from NPWT at the sternum after coronary artery bypass grafting (CABG) [17]. The risk of by-pass graft bleeding and right ventricular rupture following NPWT of mediastinitis is approximated to be between 4 and 7% of all treated cases [18,19]. A studies from year 2009 to 2011, NPWT had caused 174 injuries and 12 deaths, nine of which were related to excessive blood bleeding case resulted from the unstable pressure control of NPWT in the U.S. alone [20]. The unstable pressure control of NPWT will reduce the efficiency of the treatment and worsen the wound condition. This might led to haemorrhage incident cases. On the other hand, the duration for the treatment and the expenses of NPWT treatment will increase due to the low efficiency of NPWT device which also causes more suffering to patient.

The objective of this research is to design a highly efficient negative pressure pump controller which is able to generate stable negative pressure for the wound treatment as well as reduce the risk of the NPWT injuries.

II. MATERIAL AND METHODS

A. Hardware Part

Figure 1(a) shows the overall NPWT system. This NPWT system consists of fuzzy logic controller and system hardware part. The negative pressure is being controlled within the range by fuzzy logic based pressure regulated system. Figure 1(b) shows the schematic of NPWT system hardware which consists of vacuum pump, pressure sensor, fluid collection canister, Arduino Uno R3 microcontroller board and drainage tube.

The negative pressure is being generated by the vacuum pump to create a suction force at the other end of drainage tube which is connected to the canister. The canister is being used to collect the waste, while the vacuum pump is being protected by the floating ball inside canister, to prevent the waste being sent to the vacuum pump. The fuzzy logic based pressure regulated system is being uploaded into Arduino Uno R3.It will regulate the negative pressure at the desired level based on the input data obtain from the pressure sensor. The speed of vacuum pump is being controlled by varying the analog output signal, Pulse width modulation (PWM) which is being generated by fuzzy logic based pressure regulated system.
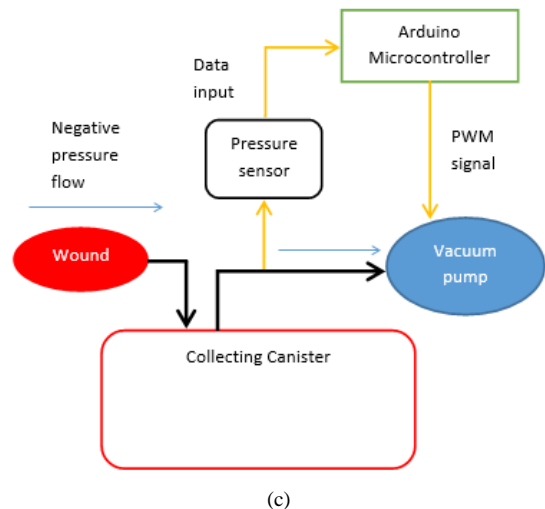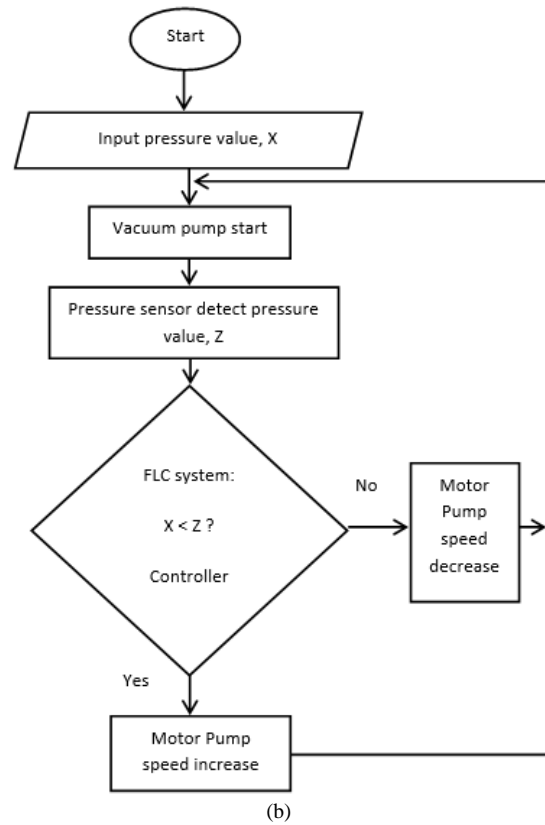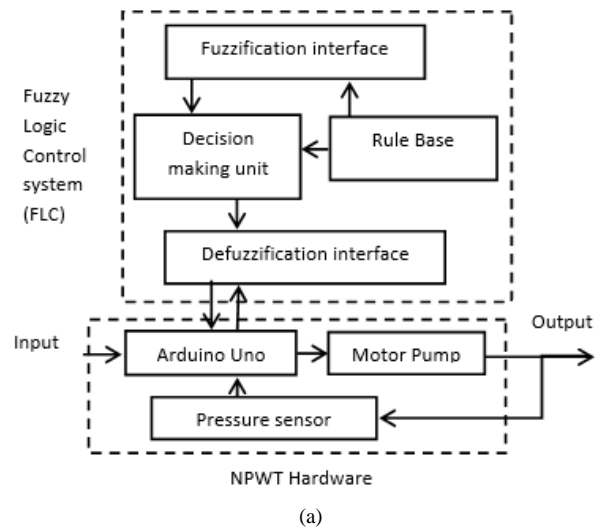

(a)

(b)

(c)

Figure 1(a) The NPWT system block diagram; (b) Flow chart of the NPWT system; (c) Schematic diagram of NPWT system.

B. Software part: Fuzzy Logic Controller

Figure 1(c) shows the flow chart of the NPWT system. Initially, a desired input pressure value, X is being entered into the system software program. The values valid for the NPWT system operation are from 0mmHg to 200mmHg. Next, the vacuum pump will run at the required speed to generate the desired negative pressure level. Pressure sensor will then detect the current negative pressure, Z and send this input data to analog input pin of Arduino Uno R3 microcontroller board. The fuzzy logic controller will make a decision based on the input data which the decision result is able to control the negative pressure at the desired level. Let "Z" be the current pressure and "X" be the desired negative pressure value. If Z is less than X mmHg, the motor will increase the speed until it reaches the desired negative pressure value. If the negative pressure is in X mmHg, the motor pump will continue operate at its current speed. If Z is more than X mmHg, the motor will stop running until it drops to the desired value and start running again until the negative pressure generated is smaller than the input desired value.

The fuzzy logic based pressure regulator system consists of one input and one output, the input variable is the error between current pressure and desired pressure level whereas the output variable is the value of analog voltage supply for vacuum pump.

From Figure 2(a), there are 5 triangle membership functions for the input variable "pressure difference" (Low-2, Low-1, Normal-0, High-1 and High-2). Table 1 shows the range setting for each membership function of input variable. The meaning of each membership function of input variable is defined as follows:

i. Low-2: The error between current pressure and desired pressure is very high.
ii. Low-1: The error between current pressure and desired pressure is high.
iii. Normal-0: The error between current pressure and desired pressure is negligible.
iv. High-1: The error between current pressure and desired pressure is low.
v. High-2: The error between current pressure and desired pressure is very low.

The analog "Motor Voltage", which is the output variable fed into vacuum pump. The output variable membership function is shown in Figure 2(b) above and Table 2 shows the range setting for each membership function of output variable. There is a total of 5 triangle fuzzy set of membership function for output variable. The meaning of this 5 membership functions is defined as follows:

i. Decrease-2: The voltage supply for vacuum pump is very low and the motor speed is very low.
ii. Decrease-1: The voltage supply for vacuum pump is low and the motor speed is low.
iii. Normal-0: The voltage supply for vacuum pump is medium and the motor speed is medium.
iv. Increase-1: The voltage supply for vacuum is high and the motor speed is fast.
v. Increas-2: The voltage supply for vacuum is very high and the motor speed is very fast.

The rule base system of fuzzy logic controller:

The rule base system of fuzzy logic plays an important role in the pressure regulation process which it will affect the performance of the pressure regulation. Fuzzy logic system will make a decision based on this rule based system and the output value will be the value of analog voltage (PWM) which is being supplied to vacuum pump. There is a total of 5 rules in this fuzzy logic rule based system.

Fuzzy logic rule based system rule list:

1. If (pressure difference is Low-2) then (motor voltage is Increase-2).
2. If (pressure difference is Low-1) then (motor voltage is Increase-1).
3. If (pressure difference is Normal-0) then (motor voltage is Normal-0).
4. If (pressure difference is High-1) then (motor voltage is Decrease-1).
5. If (pressure difference is High-2) then (motor voltage is Decrease-2)
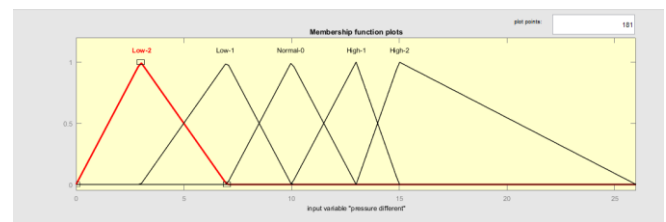
(a)
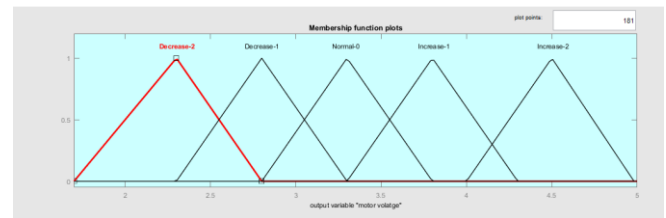
(b)

Figure 2(a) Input variable of fuzzy logic based pressure regulator; (b) Output variable of fuzzy logic based pressure regulator.

Table 1
The range setting for each membership function of input variable

Input Field	Range	Fuzzy set
	0 to 7	Low-2
The differences between input value, X with pressure sensor detect value, Z (X-Z)	3 to 10	Low-1
	7 to 13	Normal-0
	10 to 15	High-1
	13 to 26	High-2

Table 2
The range setting for each membership function of input variable

Output Field	Range	Fuzzy set
	1.7 to 2.8	Decrease-2
	2.3 to 3.3	Decrease—1
The motor speed	2.8 to 3.8	Normal-0
	3.3 to 4.3	Increase-1
	4.3 to 5	Increase-2

III. RESULTS AND DISCUSSION

The experiment of negative pressure controlled using fuzzy logic based pressure regulator and conventional Boolean logic pressure controller had been carried out. The desired negative pressure level is being set at 15kPa and operated for 200 second. Figure 3(a) and 3(b) above show the result of negative pressure controlled by using these 2 types of pressure controller.
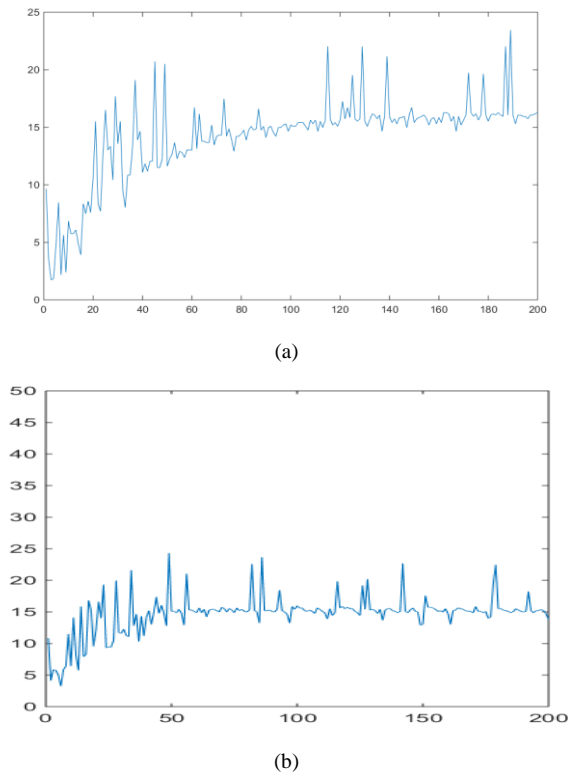

(a)

(b)

Figure 3(a) Negative pressure control with Boolean logic base pressure controller; (b) Negative pressure control with Fuzzy logic base pressure regulator.

Based on the result shown above, the rise time of the Boolean logic pressure controller is longer than that of fuzzy logic based pressure regulator, where the rise time of Boolean logic pressure controller is 60 seconds while that of fuzzy logic based pressure regulator is 45 seconds. Besides, the settling time for fuzzy logic based pressure regulator is around 60 seconds, whereas that of Boolean logic pressure controller is around 140 seconds. The speed for fuzzy logic based pressure regulator in achieving the desired negative pressure level is faster than that of Boolean logic pressure controller.

From the result in Figure 3(a) and 3(b), the performance of fuzzy logic based pressure regulator is smooth and less overshoot is being observed ,whereas more ripples and overshooting are being observed in the waveform of Boolean logic pressure controller. The result shows that fuzzy logic based pressure regulator is able to minimize the percentage of overshooting. This is very important in NPWT as too many overshooting might cause sudden pain to the patient, which is caused by the dramatic change of negative pressure generated.

From the discussion above, it is clear that the performance of fuzzy logic based pressure regulator is better than the conventional Boolean logic pressure controller. The research

on the advance fuzzy logic algorithm or other type of artificial intelligence algorithm for the pressure regulator of NPWT system can be further explore in future research The discussion result is being well presented in the Table 3 below.

Table 3
The rise time and settling time of Boolean logic based pressure controller and fuzzy logic based pressure regulator

	Boolean logic based pressure controller	Fuzzy logic base pressure regulator
Rise time (s)	60	45
Settling time (s)	140	60

IV. CONCLUSION

In this study, NPWT with a new fuzzy logic based pressure regulator is being demonstrated. Based on the result and discussion above, it is obvious that the negative pressure is able to be controlled by using the fuzzy logic controller and the performance of fuzzy logic based pressure regulator is better than that of conventional Boolean logic. The stable negative pressure generated for wound treatment is able to increase the wound healing efficiency and reduce the risk of injuries or death from happening. On the other hand, the time required for the negative pressure wound therapy treatment can be reduced by using this new fuzzy logic based pressure regulator since the settling time of it is faster than that of conventional Boolean logic pressure controller. As such, the energy required for the treatment will also be reduced. In conclusion, a more efficient and promising treatment can be provided for patient by applying fuzzy logic based pressure regulator in NPWT.

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