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Published

2020

Conference Title

IOP Conference Series: Materials Science and Engineering

Version

Version of Record (VoR)

DOI

[10.1088/1757-899X/922/1/012008](https://doi.org/10.1088/1757-899X/922/1/012008)

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To cite this article: S P Hettiarachchi *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **922** 012008

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Design and development of an automated fluid management system for endoscopy aided gynaecological surgeries

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Abstract. In this research, a novel Automated Fluid Management System (AFMS) was designed, analysed and fabricated for endoscopy aided gynaecological surgeries in order to prevent complications arise due to fluid overload. The proposed system consists of a peristaltic pump, suction mechanism and fluid measurement system integrated with a graphical user interface which can also control and monitor through a wireless network system. The device serves functionalities such as regulating saline flow rate, limiting saline suction rate, setting saline absorption limits for different patients and indicating real-time fluid deficit. This paper discusses designing of a non-contact pump for gynaecological surgeries, development of the control system for AFMS and the comparison of experimental results of the fabricated non-contact pump with theoretical pump characteristics.

1. Introduction

Endoscopy is one of the minimal invasive technique used to observe internal organs or tissues in detail. Those endoscopic approaches are used to visualise the uterine cavity for diagnosis and treatment of intrauterine pathology. During this procedure, either fluid or carbon dioxide can be used as distention medium in order to achieve better observations [1]. As bleeding occurs in operative procedures, it results in obstructing the visualisation of the uterine cavity. Therefore, most surgeries are carried out with fluid media such as saline because it provides a clear picture by continuous irrigation. During these gynaecological surgeries, absorption of a large volume of distension solutions can lead to serious complications arise due to fluid overload which will cause for conditions such as electrolyte imbalance, pulmonary oedema and cardiac failure [2]. Since saline is considered as one of the isotonic solutions, it is recommended that absorption of saline should be within the range of 1500-2500 ml for elderly or those women with co-morbid conditions and healthy women of reproductive age [3]. Therefore, a fluid management system with real-time fluid deficit indication is a necessity for the surgeons these days.

As the distension medium is pumped into the human body, it should be ensured that it is not contaminated in any way. In order to avoid any contact between pump parts and the fluid, a non-contact type pump should be used in the fluid management system. Peristaltic pumps are one of the main non-contact type pumps which prevent any contamination of the transported fluid [4]. These



pumps contain two or more rollers which press the flexible tube to the manifold where the pump is placed [5]. Therefore, developing a peristaltic pump with the capability to alter the flowrate as required for different surgeries is another necessity in a fluid management system.

This paper proposes a novel automated fluid management system for endoscopy aided gynaecological surgeries with design, analysis and development of a peristaltic pump, a suction mechanism with a diaphragm pump which can limit the suction flowrate, fluid volume measurement method with infrared sensor and graphical user interface to monitor and control the system. Further, the device has the capability to connect with pre-defined Wi-Fi network and provide remote access of the system as well. As a solution to minimise the error arise due to blood in the measurement of sucked out fluid a method is proposed to evaluate the blood volume using a colour code for different blood concentrations mixed in a saline solution.

2. Proposed design and working principle of the fluid management system

In the AFMS saline is fed through the non-contact pump with the help of gravitational effect. The flowrate control of the non-contact pump is regulated by the user through a graphical user interface or using wireless communication. Thereby, saline flows into the body cavity of the patient. After that, the saline inserted into the body is removed using a diaphragm pump into the fluid collector, where the output fluid is measured using sharp infrared sensor while the deficit is displayed real-time on the graphical user interface. Figure 1 shows the working principle of the proposed fluid management system graphically.

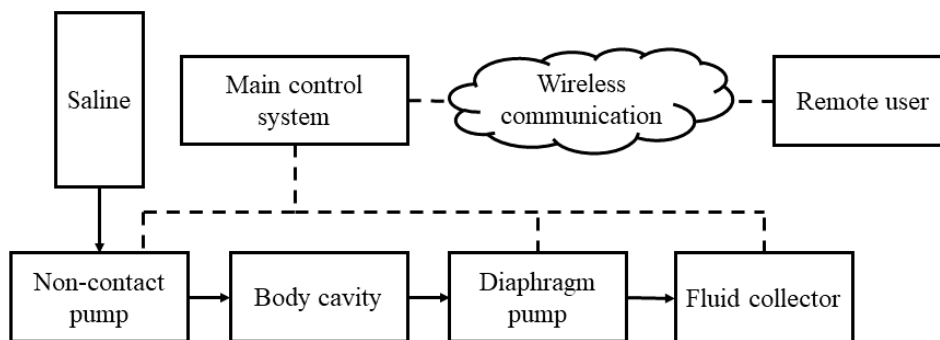


Figure 1. Graphical representation of the working principle of the proposed fluid management system

In the aspect of developing the fluid management device, the prominent focus was given to design and development of a non-contact pump for pumping the saline into the body cavity without any contamination and to the development of a control system to integrate all the components of the device.

2.1. Design and development of a non-contact pump

A non-contact pump is essential for the device as it is recommended that the saline should not be contaminated with any of the pump parts or abrasive media. After a careful study of existing non-contact type pumps, it was identified that peristaltic pumps are widely used in medical applications due to its reliability of providing contamination-free liquids with better accuracy of flow control and suitable for these kinds of applications [6].

A peristaltic pump is a type of positive displacement pump where the fluid is contained within a flexible tube fitted in a circular pump casing. A rotor with several rollers, wipes or shoes attached to the external circumference compresses the flexible tube [7]. Major design considerations of the peristaltic pump were continuity and flowrate. It was identified that the maximum flowrate requirement of the surgeons for this particular application as 1000 ml/min. The pulsating effect of a peristaltic pump is unavoidable due to its nature of the operation. Therefore, in order to obtain a nearly continuous flow, the pump the occluded length due to the rollers should be minimised. To minimise this length the only option is to increase the number of rollers in a fixed rotor. Because of that total of

six rollers were used in the design of the peristaltic pump. The detailed representation of the designed non-contact pump with its components is shown in figure 2.

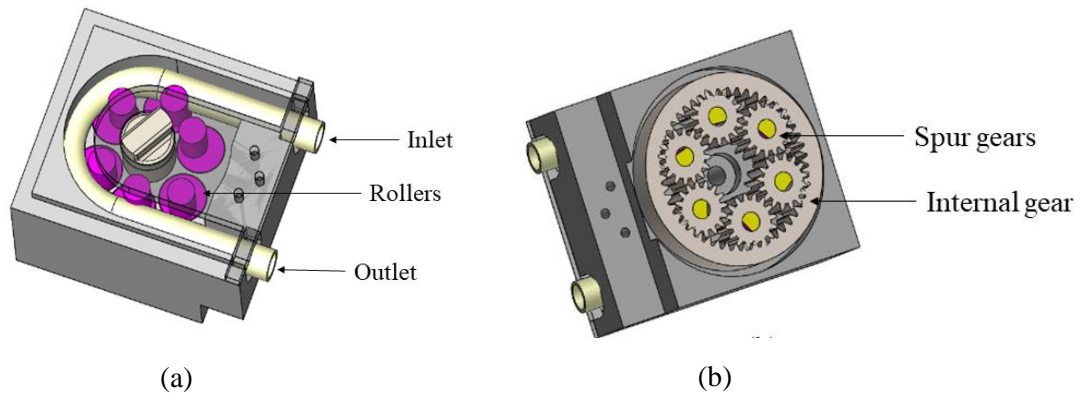


Figure 2. 3D model of the pump mechanism (a) Top view (b) Bottom view

The theoretical flow rate of a peristaltic pump is given in equation (1).

$$\text{Theoretical flow rate} = A \times L \times N \times \omega \text{ ml/min} \quad (1)$$

Here 'A' is the area of the tube, 'L' is length occluded by rollers, 'N' number of rollers and ' ω ' is the angular velocity. The tube diameter of the design used is 5 mm and the radius of the curvature of the rotor was 22.3 mm. Due to the gravitational effect on the saline pumping used for gynaecological surgeries, it was observed that an average of 82 ml/min can be achieved at that specific height. Therefore, equation (1) can be modified to equation (2) in order to provide an understanding of how the flowrate of the design peristaltic pump varies with the angular speed of the motor.

$$\text{Flow rate} = 1.834 \times \omega + 82 \text{ ml/min} \quad (2)$$

Equation (2) can be used as the pump characteristic equation for the designed peristaltic pump. According to that, to obtain a maximum flow rate of 1000 ml/min the pump should have an angular velocity around 500 rpm. A gear mechanism with a gear ratio of 3.43 was implemented to the design to obtain the required angular velocity with high torque motor.

All the components of the proposed design were fabricated using 3D printing technology with acrylonitrile butadiene styrene material.

2.2. Development of the control system for AFMS

The control system of the device includes actuator and sensor assembly, main control system, graphical user interface and wireless sensor network system. Integration of the system components with the control system is shown in figure 3.

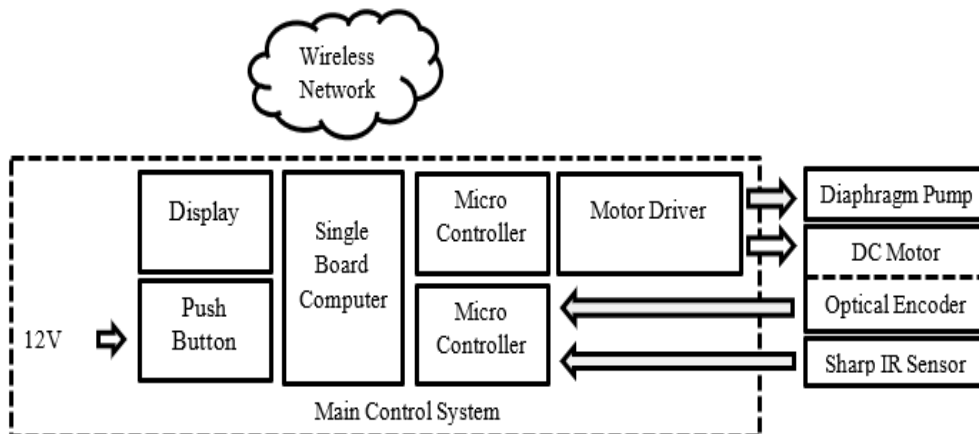


Figure 3. Graphical representation of the proposed control system

2.2.1. Main control system.

The main control system of the device consists of HDMI touch display, power on/off button, a single board computer, two microcontrollers and a motor drive. Single board computer helps to process all the data that are collected from sensors and inputs and controls entered from the user through the display. The software for the AFMS was developed using Python programming language on Raspberry Pi 3 single-board computer. Serial communication is used to distribute the collected data to relevant microcontrollers. Two Arduino microcontrollers were used for reading the sensor values and to reduce the processing time of the graphical user interface operation. The motor drive has the ability to change the speed of the DC motor and it has the controlling of the suction flow rate of the diaphragm pump which has a set maximum from the user.

2.2.2. Sensors and actuators.

A DC gear motor with inbuilt encoder, a DC diaphragm pump and a sharp infrared sensor were used as actuators and sensors. The DC gear motor is connected to the fabricated peristaltic pump which has an inbuilt encoder to obtain motor feedback to the controller. Using Proportional-Integral-Derivative (PID), it helps to maintain a constant rpm for the motor resulting in a constant flow rate for saline pumping. Diaphragm pump was used as the suction pump to remove saline from the body cavity. This removed fluid is collected to a container which has a constant cross-section area. To obtain the volume of sucked out fluid sharp infrared sensor was integrated after calibrating it using the floating duck mechanism.

2.2.3. Graphical user interface.

Graphical user interface development is required in order to provide external inputs to the control the device by authorised personnel. User has the ability to choose the required surgical procedure, where predefined values for the flow rates and limits for that certain procedure can alter manually depending on the patient. After proceeding and initiating the suction process the saline deficit value updates in real-time. The device provides a warning when the saline deficit reaches to the maximum allowable absorption volume. The developed graphical user interface is shown in figure 4.

2.2.4. Wireless communication.

The device has the ability to connect with a predefined Wi-Fi network allowing remote access of the system to the user. User can alter or examine the set parameters of the interface providing flexibility in controlling and monitoring of the device remotely.

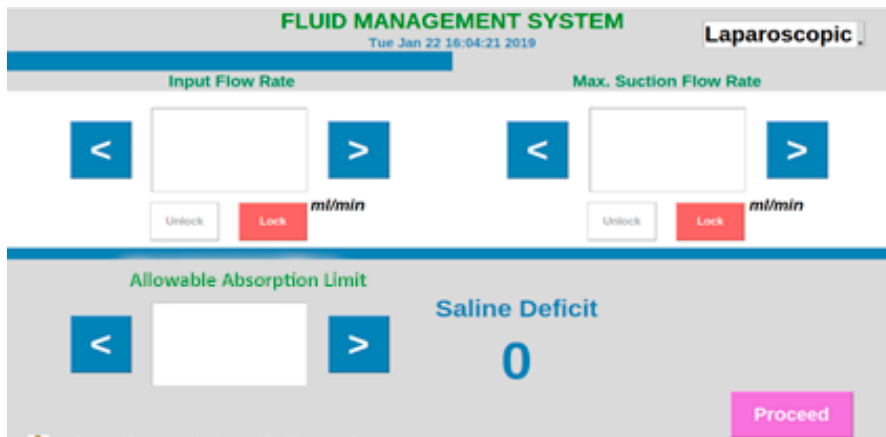


Figure 4. The graphical user interface of the device

3. Results and discussion

The testing of the fabricated pump was conducted in order to obtain the theoretical and experimental pump characteristic curves. In the experiment, DC gear motor voltage values were mapped to the voltage values (0-12V to 0-255) and with its angular velocity allowing it to change the flow rate of the pump accordingly. Following results in table 1 were obtained for varied rpm values and pump characteristic curve obtained from equation (2) with the experimented results obtained were plotted as shown in figure 5.

Table 1. Theoretical and experimental flow rates for fabricated peristaltic pump.

Voltage mapped value	Motor rpm	RPM of rollers	Flow rate	
			Theoretical (ml/min)	Experimental (ml/min)
255	160	548.80	1088.50	1053
220	138.04	473.47	950.35	918
200	125.49	430.43	871.41	845
180	112.94	387.39	792.47	780
160	100.39	344.35	713.53	682

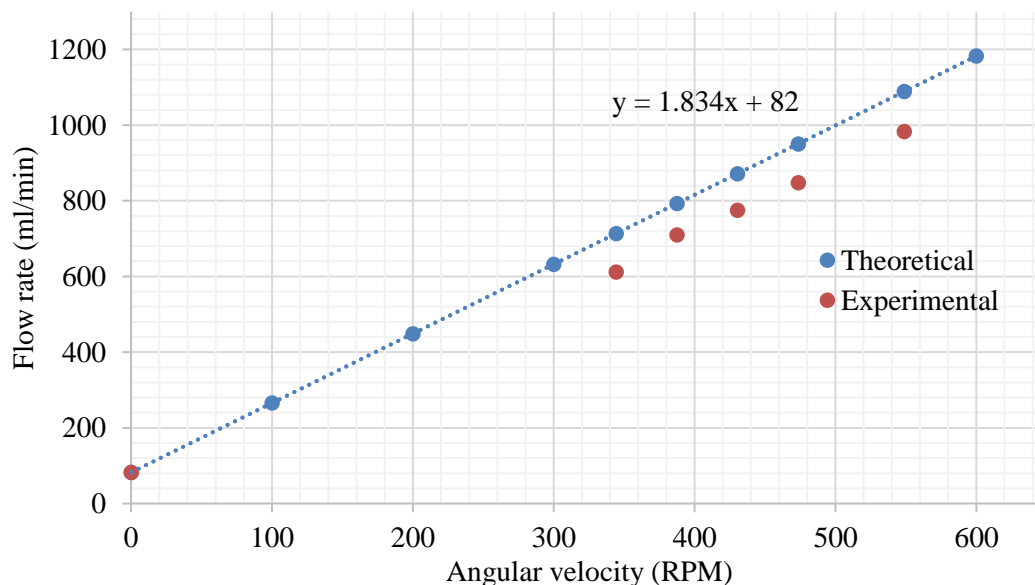


Figure 5. Pump characteristic curve and experimented results

As per the experiment results, it has an error of 11.23% with the theoretical values. This variation is mainly due to the precision of manufacturing of the pump. Since all the components of the pump were 3D printed, obtaining a better surface finish to precise control of the mechanism is harder.

With compared to the volume of saline inserted into the body cavity, it was identified that the amount of blood coming out with the saline is negligible. But it is inevitable that the sucked-out fluid containing a certain amount of a blood volume and therefore, a colour code was introduced in order to minimize the error in calculating absorption of saline volume. In preparing the colour code a known amount of blood was mixed with a known amount of saline and observed the colour variation with respect to the concentration of the blood volume. Therefore, the user can have an idea about the exact saline volume that has been absorbed into the body thus can prevent fluid over absorption complications.

4. Conclusion

An automated fluid management system with a novel design of a peristaltic pump, a fluid measuring system and control mechanism was developed under this research for endoscopy aided gynaecological surgeries. Results obtained from the experiment showed a deviation from the theoretical pump characteristic due to the quality of the fabricated pump. The deviation can be minimised by developing the pump using advanced manufacturing technologies. All the functionalities of the device can be accessible via developed wireless network system providing convenient for surgeons in monitoring and controlling of the device. In order to minimise the error, arise due to blood containing in the sucked-out fluid mixture, a colour code was introduced for various blood concentrations. In future, the device can be further optimised with image processing instead of colour code for accurate measurement of the blood volume in the sucked-out fluid mixture.

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Acknowledgement

The authors would like to express their gratitude to the Department of Mechanical Engineering, University of Moratuwa and Accelerating Higher Education Expansion and Development (AHEAD) project of Centre for Advanced Mechatronic Systems, University of Moratuwa for their valuable advice and guidance towards the success of the research.