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Diagnosis and Fault Detection of a Mechatronic Hydrocephalus Shunting System

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ABSTRACT

Accurate detection of faults in hydrocephalus shunt is a crucial and equally challenging. It is desirable to have an intelligent method that would be used to detect any shunt faults or complications without making the patients suffer from frequent hospital visits and shunt revisions. A complementary fuzzy logic-based fault diagnosis system was developed to diagnose the simulated faults of an implantable shunting system. By using such method, various current shunt malfunctions can be early detected and their types can be also predicted. The input variables of the fuzzy logic classifier were acquired from numerical simulations which have been performed using a Simulink model that simulates intracranial hydrodynamics of hydrocephalus patients who are shunted with mechatronic valve. In order to evaluate system performance, the accuracy of the fuzzy logic classifier was tested. Six faults were successfully diagnosed in real time. Simulation results showed that fuzzy logic is more sensitive and informative regarding the simulated faults conditions.

INTRODUCTION

The human brain is immersed in cerebrospinal fluid, which protects it from mechanical stresses and helps support its weight through buoyancy. A constant overproduction, blockage or reabsorption difficulty can result in a build-up of fluid in the skull (Hydrocephalus), which can lead to brain damage or even death. Existing treatments rely on passive implantable shunts that drain the excess fluid out of the skull cavity.

These devices are prone to malfunction. Shunt systems are not perfect devices and complications often arise. Generally, they require monitoring and regular medical follow up. Shunt complications, mainly of ventriculo-peritoneal and atrial shunting systems have been frequently reported in literature (Albala, D.M., 1989; Aoki, N., 1990). These complications could be due to one of the following reasons: valve is blocked by products of the CSF, some of its components get disconnected, it breaks (usually the distal end), any of the catheters come out of their place, the shunt drains less or more fluid than it is supposed to hunt malfunction is one of the most common clinical problems in paediatric neurosurgery (Pitetti, R., 2007). The diagnosis of such malfunctions can be both difficult and perplexing even for the experienced clinician. The methods used to date have been based on clinical presentation of shunt malfunctions, clinical data, imaging techniques and evaluation of valve function in mechanical terms. Unfortunately, symptoms of various shunt complications (e.g seizures, a significant change in intellect, school performance, or personality) can be very similar and difficult to spot thus complicating the diagnosing process. On other hand, the possible presentations of acute shunt malfunction in early stages are innumerable for many reasons such as the lack of noninvasive intracranial pressure (ICP) and flow monitoring. In addition, shunt malfunctions might be present even if they have not shown on a CT or MRI scans where as the number of these should be minimized due to the use of radiation and are therefore not desirable for regular use (Sood, S., 1993).

The early detection and recognition of shunt malfunctions to prevent or minimize complications and maximize shunt functioning has long been accepted as a desirable goal in the treatment of hydrocephalus. One method of achieving this goal is through the use of real time non-invasive ICP monitoring for hydrocephalus patients. Thus, the main goal of this study is to develop an effective method to give endowment to the current implanted shunting system with ICP sensor, flowmeter and transceiver to be able to achieve real-time self-diagnosis of any faults.

Today, artificial intelligence technology (e.g. fuzzy logic) is increasingly deployed for the diagnosis of faults. Fuzzy logic is a rule-based system that successfully combines fuzzy set theory with the inference

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capability of human beings. It makes use of the knowledge of experts which is possible through its transformation into linguistic terms. The accuracy of the formulation can be determined during the testing of the system or duringreal-time working by observation. This feature provides major flexibility for fuzzy logic.

Fuzzy logic has been effectively used in the engineering studies, such as detecting faults in internal combustion engines (Celik, M.B. and R. Bayir, 2007) and motors (Soliman, A., 1999). It also has been widely used in medical applications where it works as assistant system that supports the physician to identify malfunctions, e.g. malnourished patient. The need for such system in the medical field necessarily arises from the fact that the late fault detection could be life threatening. As far as the author's knowledge, fuzzy logic was not implemented in fault detection of implanted device inside the body of the patient.

In this study, a complementary fuzzy-logic-based fault diagnosis system was developed to diagnose the faults in hydrocephalus shunting system. Numerical simulations have been performed using Simulink model that reproduces intracranial hydrodynamics of hydrocephalus patients using historical ICP data. Various expected shunt faults have been modeled using Simulink. The model of a patient with a faulty shunting system was interfaced with the fuzzy logic model in Simulink. The fuzzy logic classifier model was developed using MATLAB. The accuracy of the fuzzy logic classifier for different fault conditions was determined. Using the developed fault diagnosis system, six general faults were successfully diagnosed.

Mechatroinc Shunting System:

The authors have previously proposed an intelligent implantable wireless shunting system for hydrocephalus patients with features that help in reducing or eliminating the problems with current shunts (Momani, L., 2008). Such a system would provide an inductively powered sensing and transmitting unit which is completely implantable with no wires or tubes penetrating the skin.

A bidirectional communication protocol has been proposed and developed to wirelessly manage such a mechatronic shunting system. Such a protocol was proposed to manage all the proposed shunt functions. An external unit outside the body would receive signals from the implanted unit. The received signals may be recorded, displayed, or analyzed, or all of these manifestations of the signals may be produced simultaneously.

The mechatronic shunting system shown in Figure 1 would consist of two subsystems; implanted and external subsystems. The implanted subsystem would mainly consist of ultra low power commercial microcontroller, mechatronic valve, pressure sensor and low power transceiver. This implantable shunting system would wirelessly communicate with a handheld smart phone operated by the patient, or on the patient's behalf by a clinician or guardian. This device would have a graphical user interface and an RF interface to communicate with the user and the implantable wireless shunt respectively.

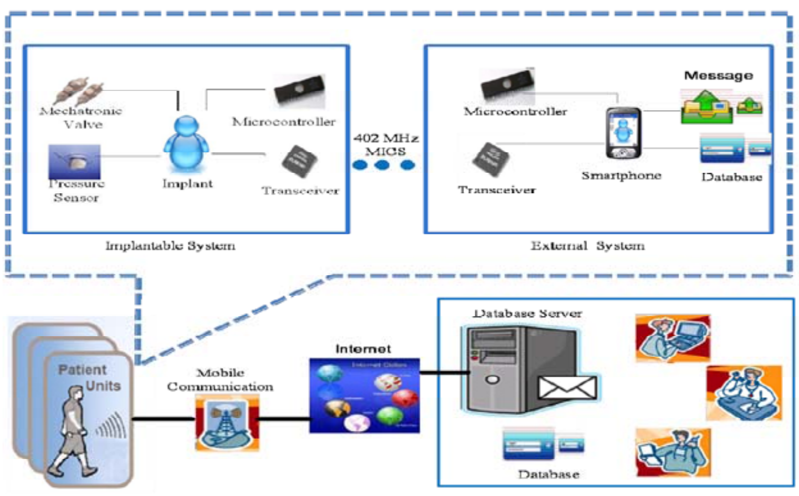

Fig. 1: The proposed mechatronic shunting system.

The current method measurement and monitoring of intracranial pressure requires the patient to be in the hospital and most likely in an intensive care unit. By using such mechatronic system, measurements of intracranial pressure are taken remotely and accordingly the condition of the patient is remotely monitored by remotely communicating ICP data between an implantable unit and central database through external unit. Such monitoring approach would improve the outcome in patients with hydrocephalus. The external system will automatically request this data every day. This data is utilized by the external system to manage and treat of hydrocephalus and mange the shunting system itself.

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Methods and Experimental Work:

A Simulink set-up was constructed in order to build the rule base of the shunt faults diagnosis system. It also served to detect the faults in real-time while the model of shunted patient was running under various faults. In addition, such set-up can be utilized as a dynamic environment to evaluate the performance of the fuzzy logic fault diagnosis system. The Simulink set-up consists of a hydrocephalus patient model, a data pre-processing model and fuzzy logic controller. This is illustrated in Figure 2. While the patient model is made up of intracranial hydrodynamics of hydrocephalus patient, a mechatronic valve, ICP sensor, flow meter, and faults models.

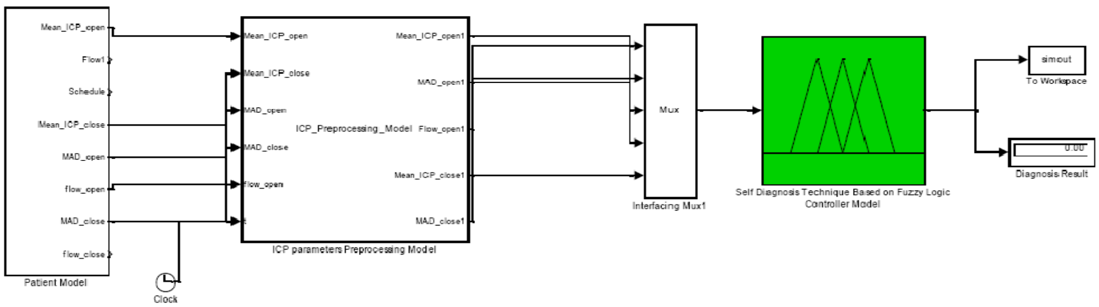

Fig. 2: A block diagram of the Simulink set-up for the self diagnosis system.

A. ***Intracranial Hydrodynamics and Faults Modeling:***

Numerical simulations have been performed using Simulink model that reproduces intracranial hydrodynamics of hydrocephalus patients using historical ICP data (Momani, L., 2009). This model is illustrated in Figure 3 and was used as a dynamic environment to reflect the effect of adding a mechatronic valve on the intracranial hydrodynamics.

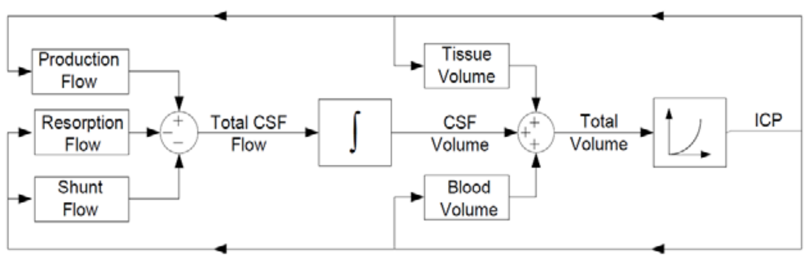

Fig. 3: A block diagram of the Simulink intracranial hydrodynamics model.

A valve schedule as shown in Figure 4 was used to control the opening and closing of this valve where d is the duration of opening valve and p: the length of period. An initial period of 24 hours after implanting the shunt has been simulated and the ICP data was recorded then used to derive and calculate the values of reference parameters that were used for the diagnosis purposes.

Early diagnosis of shunt dysfunction is not always straightforward. Leading symptoms such as headache, vomiting and drowsiness may all overlap with a variety of other more common conditions seen in paediatric practice. Therefore, most common shunt faults, as described below, and their effect on the intracranial hydrodynamics were modeled using Simulink where they were randomly incorporated into the intracranial hydrodynamics model.

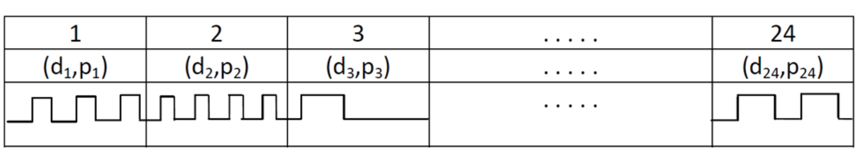

Fig. 4: Time-Based Valve Schedule.

1) Disconnection of the shunt is considered the second most common cause of shunt failure. Disconnection may occur at any site of connection along the course of the tubing. This is usually related to improper technique

(loose ligature) or excessive strain along the shunt tube between two points of fixation. It is simulated by introducing abrupt change in ICP readings.

Definitive diagnosis is made by visualizing the disconnection and simulating it using patient Simulink model, and then its effect over the ICP signals is observed.

2) Technical complications occur while using ICP sensor in monitoring ICP such as breakage, dislocation or failure of ICP recording for unknown reasons. These problems also would affect the performance of the shunting system. To increase the efficiency of shunting system and save patient's life, self diagnosis of the implanted pressure sensor has been studied, where a Simulink model for hydrocephalus patient with sensor immigration problem has been used to illustrate such problem. It is simulated by introducing abrupt change in ICP readings, leading to zero ICP values.

3) Shunt systems are prone to blockage. The rate of blockage can be as high as 20% in the first year after insertion, decreasing to approximately 5% peryear. Detection of shunt blockage is vital as delay in diagnosis can lead to coning and death. Thus a Simulink model with Matlab GUI has been used to simulate different degrees of valve blockage by manipulating the resistance of the valve.

4) Other shunt malfunctions also have been studied and simulated such as flowmeter faults, power failure and microcontroller faults. Most of hydrocephalus shunt faults and the probable source of these faults was taking into consideration and summarized in Table 1.

Table 1: Hydrocephalus Shunt Faults.

Fault Type	Probable source of fault
ICP signals and flow are normal	No fault
ICP gradually increases Flow gradually decreases	Partial valve blockage
ICP gradually increases, ICP is very high Flow gradually decreases, flow is very low	Full valve blockage
ICP suddenly becomes very high Flow becomes zero	Valve disconnection
ICP suddenly becomes zero or close to zero Flow is normal	ICP sensor dislocation
ICP is normal Flow becomes zero	Flowmeter fault
ICP and flow suddenly becomes zero	Shunt fault

B. Fuzzy Logic Controller Design:

Fuzzy logic is a rule-based system that successfully combines fuzzy set theory with the inference capability of human beings. As rules, linguistic terms are used and are modeled through membership functions that represent simulation of the comprehension of an expert. Membership functions give the scaled value of definite number values that are defined by linguistic labels. Rules are defined such as IF (condition) THEN (result). The conditions and results are linguistic terms that represent the input and output variables respectively. A rule base of the fuzzy logic classifier consists of many rules. It is used to obtain a definite output value according to the input value. The simplest fuzzy logic controller is mainly consisting of input variables, fuzzifier unit, interface unit, defuzification unit, output variables and knowledge base (Mi, C., 2000). A fuzzy logic fault diagnosis system was implemented to detect any faults in the shunting system. Figure 5 illustrates the flow of data through the fuzzy logic fault diagnosis system. Many parameters which are deflected from normal (i.e. no fault) values were monitored while the Simulink was running. In addition, the fuzzy logic fault diagnosis system, connected to the hydrocephalus interactive patient models, was working on detecting the faults in real-time. In this study, the number of detectable faults were increased as well as the reliability of the detection system were improved by measuring more than one intracranial pressure parameter (mean ICP, mean absolute deviation) as well as the valveflow rate which are generated from patient Simulink model

Based on valve and ICP sensor schedule. These parameters have been optimized in previous research and it was noticed that there is a strong correlation between these parameters and the effect of various shunt faults over their behaviors. The results of the numerical simulation were used to create a rule base. The developed fuzzy logic classifier model was designed in the MATLAB fuzzy inference system editor.

Figure 6 presents a flow chart of the fuzzy logic classifier design. The most important feature in the stage of fuzzy logic classifier design is selecting membership functions that represent input and output parameters in a way that can absolutely define the system. The proposed fuzzy logic system consists of five inputs and seven outputs. The selected input variables were Mean ICP, Mean Absolute Deviation of ICP(MAD), and flow rate at opening and closing times of the valve. Each input variable consists of five membership functions. These functions are in the form of very low, low, normal, high, and very high. Each membership function of the output variable indicates one or more faults. For example, a rule base was generated in case of valve disconnection fault is: IF mean ICP after valve open is very high, AND

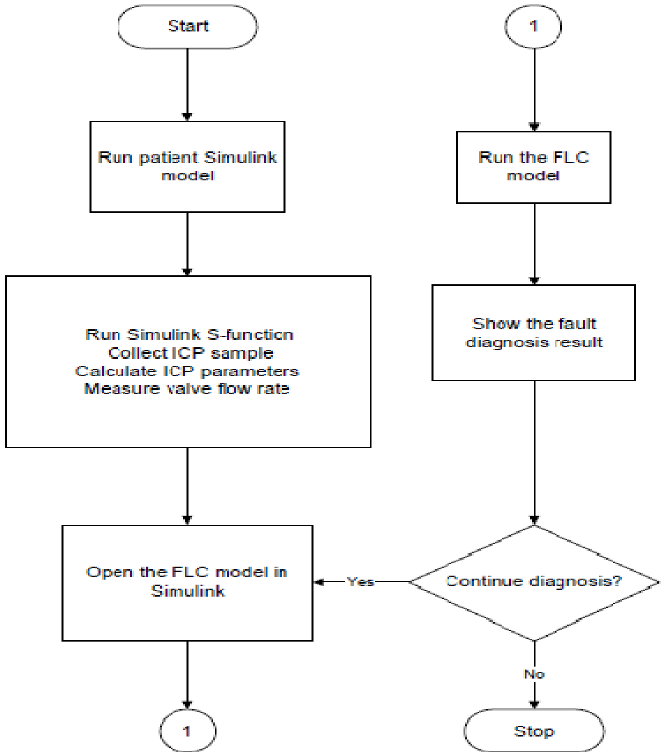

Fig. 5: A flow chart of the fuzzy logic fault diagnosis system.

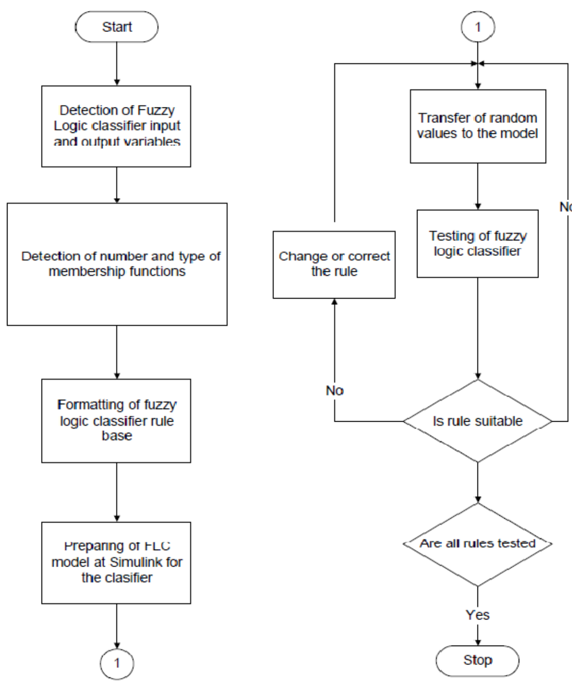

Fig. 6: A flow chart of fuzzy logic classifier design.

MAD after valve open is very high, AND valve flow unavailable, AND mean ICP before valve closed is very high, AND MAD before valve closed is very high) then the diagnosis result is that the valve is disconnected. Based on the values of the selected parameters, the rule base of shunt diagnosis system is generated and illustrated in Table 2.

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Table 2: Rule-Based of shunt faults diagnosis using fuzzy logic.

Mean ICP after valve open	Mad after valve open	Valve flow	Mean ICP before valve close	MAD before valve close	State of shunt
Normal	Normal	Normal	Normal	Normal	No fault
Normal	Normal	Unavailable	Normal	Normal	Flowmeter fail
Unavailable	Unavailable	Normal	Unavailable	Unavailable	Sensor dislocation
High	High	Low	High	High	Valve partially blocked
Very high	Very high	Very low	Very high	Very high	Valve fully blocked
Unavailable	Unavailable	Unavailable	Unavailable	Unavailable	Shunt fault
Very high	Very high	Unavailable	Very high	Very high	Valve disconnection

C. Numerical Simulations:

Initially, the data were acquired from a shunted patient model with no faults. Then, different faults according to Table 1 were randomly introduced into the shunt. Then the intracranial hydrodynamics data was monitored and measured with six different faults for 12 hours. The patient model was running under different conditions such as no shunt fault, valve block age, valve disconnection, ICP sensor dislocations and flowmeter fault. Figures 7- 10 show samples of the effect of the previous faults on the trace of the ICP and valve flow. Figure 7 presents the case of no fault, in this case the value of mean ICP is within normal range (0- 12mmHg) and the average of flow also within normal range (flow=0.03ml/min). Figure 8 presents the case of partial valve blockage, in this case the value of mean ICP is rising due to blockage (ICP greater than 15mmHg) and the average of flow also reduced (Flow less than 0.02 ml/min). Figure 9 shows the case of valve disconnection, in this case and at the disconnection time the value of mean ICP is rising due to blockage (ICP greater than 15mmHg) and the flow is missing due to valve disconnection (flow=0 ml/min).Figure 10 shows the case of ICP sensor dislocation, in this case the ICP signal is missing due to sensor dislocation (ICP=0 mmHg).

The next step was transmitting the measured data to the pre-processing model. The pre-processing model is mainly used to extract and optimize the selected parameters from the transmitted data. Samples of ICP readings (600 readings per sample)were taken at specific periods (before the scheduled opening and closing time of the valve) and were used in the derivation of the parameters. Simulation run duration was 12 hours, in which 48 samples of intracranial hydrodynamics data were collected based on valve schedule (that opens for 10 minutes every 30 minutes) and used in this test to derive the parameters. Accordingly, these parameters were implemented as input variables for the fuzzy logic controller system. The derived parameters were used as inputs for the fuzzy logic controller to recognize the faults, and to discriminate between faulty and normal operation.

RESULTS AND DISCUSSION

As a result of this work, a fuzzy-logic-based fault diagnosis system was developed. By using the developed system, various simulated shunt faults were successfully detected and classified. A rule-base summarized in Table 2 was used to detect and classify various shunting system faults. The fuzzy logic shunt fault diagnosis system was evaluated using the numerical simulation results. Table 3 summarizes the results of detecting and classifying various shunt faults. The fuzzy logic classifier was found to classify the faults with more than 99 % accuracy. With these characteristics, the system could easily be used as intelligent technique for self diagnosis of hydrocephalus shunting system.

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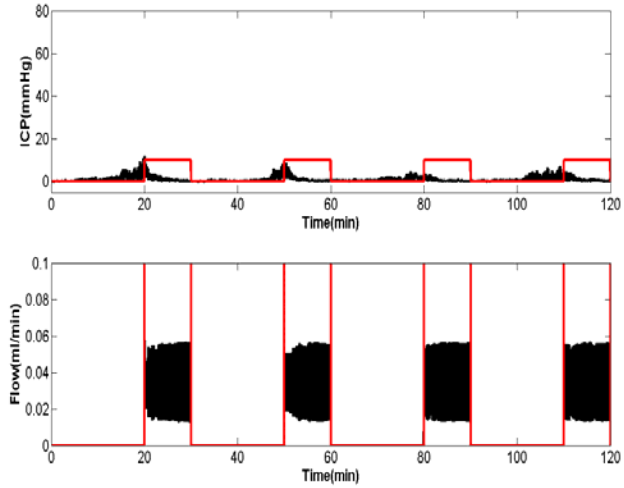

Fig. 7: ICP traces for normal shunt.

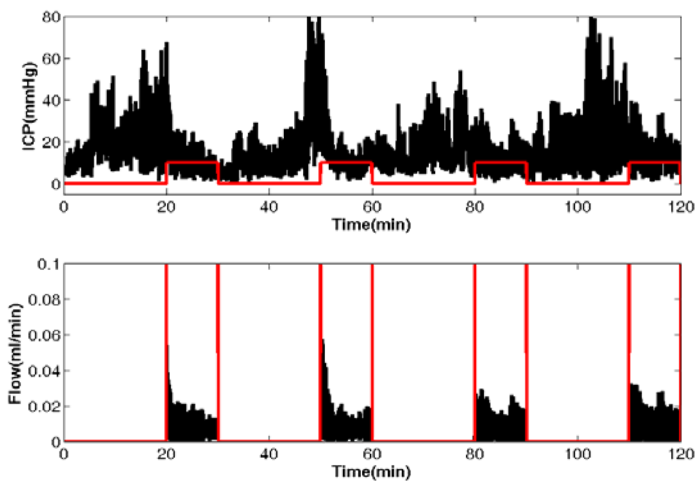

Fig. 8: ICP traces for Partial shunt blockage.

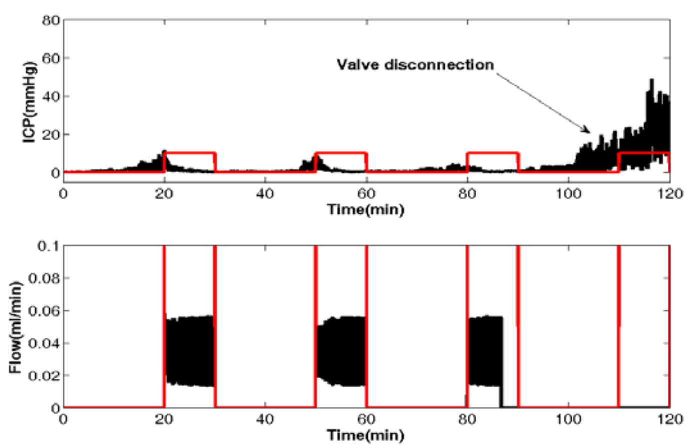

Fig. 9: ICP traces for valve disconnection.

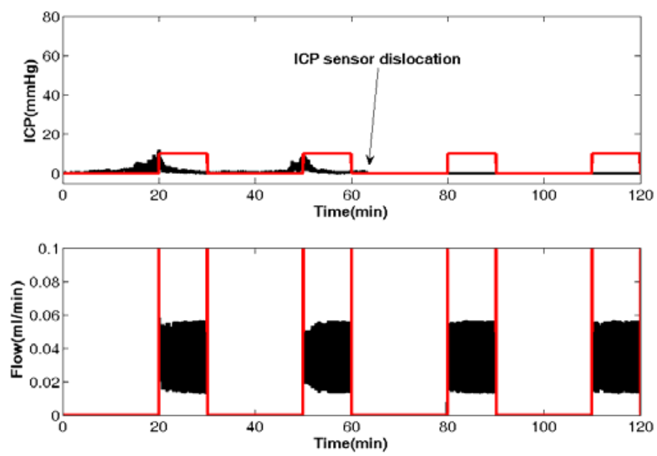

Fig. 10: ICP traces for ICP sensor dislocation.

Table 3: Shunt faults diagnosis results.

Number	State of shunt	Number of samples	Correct classifications	Wrong classifications	Result of wrong classifications
1.	Normal	48	48	0	
2.	Valve disconnection	48	48	0	
3.	Sensor dislocation	48	48	0	
4.	Flowmeter fault	48	48	0	
5.	Partial blockage	48	35	13	Overlapping with full blockage
6.	Full blockage	48	39	9	Overlapping with partial blockage

Conclusion:

Missing the diagnosis of shunt malfunction may lead to permanent neurologic injury or death. According to this study, even though the shunt is implanted inside a human body, it is possible to early detect any faults, blockage or complications. Fuzzy logic-based approaches (fuzzy logic controllers and fuzzy models) are used effectively to deal with the lack of rule-base method of self diagnosis system. With high accuracy of faults detection, fuzzy logic-based strategies have proven to be a good choice for self diagnosis of a proposed mechatronic hydrocephalus shunting system.

The advent of such a shunting system would give a more advanced enhancement to the proposed self-diagnosis method and promising future for such method.

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