Baumgartner B., Mendoza A., Schreiber U., Eichhorn S., Krane M., Bauernschmitt R., Knoll A.

A Simple Fuzzy Controller for an Extra-Corporeal Circulation System - Limitations and Potentials

Introduction

Fuzzy control is a well-established method in control engineering and has been applied to a wide range of problems in diverse disciplines. It is especially useful if a direct analytical description of the control process seems unsuitable. Since fuzzy logic is able to interpret vague and subjective knowledge and allows qualitative system descriptions it is highly qualified for medical decision making.
In this work we present a simple fuzzy-based controller for a mobile extra-corporeal circulatory support system (ECCS). We clarify why fuzzy control is an appealing technique for this task but also discuss its difficulties.

Heart-lung-machines (HLM) are indispensable in today's cardiac surgery. When used in an operating theater expert knowledge is always on-hand. The HLM and the patient are constantly supervised by surgeons, perfusionists and anesthesiologists.
However, patients suffering from cardiogenic shock would benefit from an early application of an ECSS, preventing multi organ failure. For that reason the LIFEBRIDGE B_2T was designed. It is a mobile HLM that can be used in non-clinical environments.
In emergency situations trained personnel might not be available. An automated ECCS could help to guarantee optimal perfusion of the patient while minimizing the workload of a human operator in stressful situations. The goal of this project is to develop a self-contained system that is able to regulate perfusion based on online data of the patient. Because of the application in a non-clinical environment special requirements have to be fullfilled: the control system has to be highly dynamic, so it can adapt to different situations and different needs of the patient. At the same time it must be robust and patient safety must be ensured at all times.
The non-trivial task of extra-corporeal circulation control has already been adressed in numerous publications. Back in 1978 Prilutskii et al. considered design principles for an automatic ECC [12]. Misgeld et al. compared three different control schemes to regulate blood flow [11]. Boschetti et al. developed an ECC simulation that can be used to identify control strategies [3] and Meyrowitz developed a prototype of an automatically controlled HLM [10]. In most of the works a standard PID controller was used.
Fuzzy logic has also been applied to various medical control problems [1, 2, 7, 8]. Fuzzy systems seem to be well-suited for this task, since they are able to handle vague data and the design process allows a straightforward implementation of expert knowledge, e.g. from perfusionists.

To test the control scheme, animal experiments, using pigs, are conducted. The experiments follow an elaborate protocol. We evaluate a fuzzy controller that regulates pump speed of the HLM based on the mean arterial pressure (MAP) of the test animal.

Material and Methods

ECCS.
The LIFEBRIDGE B_2T is a rather new circulatory support system. It is a portable, modular and easy-to-use ECCS, designed to be applied in emergency transportation or resuscitation. A field report of the system is given in [6]. Machine parameters, i. e. pump speed (revolutions per minute, rpm), flow (liters per minute, lpm), inlet, outlet and pressure before oxygenation (all in mmHg) are recorded via a RS232 interface. The pump speed can be controlled via serial communication.

Animal Experiments and Data Recording.
The control performance is validated in animal experiments, using pigs. During experiments sensor data from both the patient and the HLM is recorded and visualized. Among others we record ECG, temperature, blood flow, blood pressures (MAP, CVP), SpO2, heart rate and blood gases. The recording system and animal experiments are elaborately described in [9].
To test our control system drugs are administered successively. First 0.1 mg of a vasoconstrictor (Arterenol) is given, making the MAP increase. After the controller has regulated the MAP back to a normal range we administer 2 mg of a vasodilator (ISD). As an effect the MAP decreases.

Fuzzy Controller.
We use a standard fuzzy system with Mamdani inference to control the pump speed of the HLM. In a first approach the input parameter to the control loop is the MAP, since it is a major variable for optimal perfusion. For the input variable 3 sets are defined, labled as “low”, “medium” and “high”. The controller output is a correction factor of the current pump speed (Delta_RPM). The pump speed is increased if the MAP drops below 50 mmHg (low). It is decreased when the MAP is above 80 mmHg (high). For a pressure value in between these limits, the pump speed remains constant (medium). The fuzzy sets for both input and output are displayed in Figure 1. The controller is operating at 1 Hz, that means every second the current MAP is obtained and a new pump speed is set accordingly.

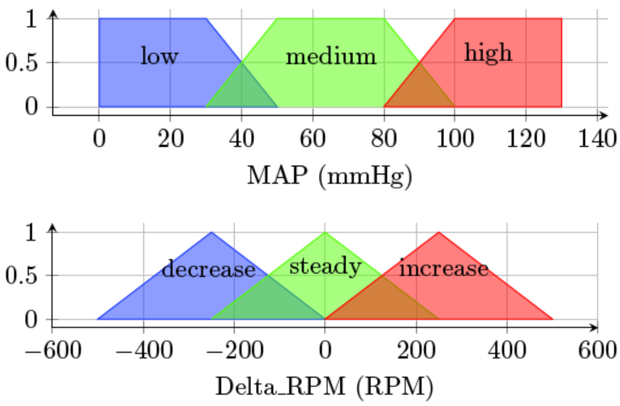

Fig. 1: Fuzzy sets for input variable MAP and output value Delta_RPM.

In terms of software the MATLAB Fuzzy Toolbox is used to design the controller. Moreover, a C++ wrapper for the MATLAB Fuzzy Inference System was developed that can be used as a stand-alone application and integrates into our data acquisition and recording software.

Results

In experiments the fuzzy controller displayed its expected behavior. During vasoconstriction (see Fig. 2), the controller reacts with a decrease of the current pump speed until the MAP is in a convenient pressure range again. During vasodilation (Fig. 3) the pump speed is increased to counteract the drop in MAP. Both experiments show smooth control characteristics without overshoots and oscillations.

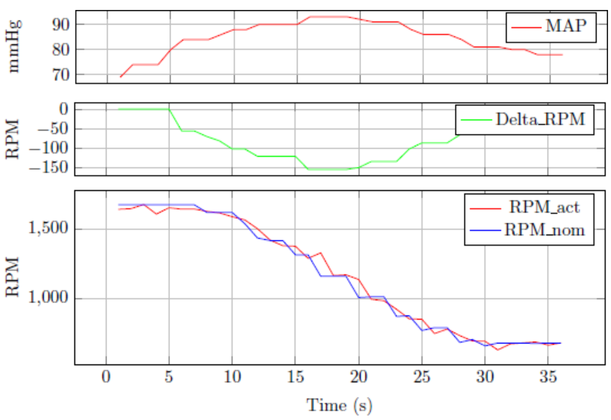

Fig. 2: Vasoconstriction. From top to bottom the mean arterial pressure (MAP), the controller output (Delta_RPM), the nominal and current pump speed (RPM_nom, RPM_act) are shown.

It takes about 25 seconds to regulate the effect of vasoconstriction. Looking at the vasodilation case, the MAP first drops below 50 mmHg, resulting in an increase of the pump speed. After about 70 seconds, the MAP reaches the value of 50 mmHg again, which makes the controller to keep the current speed for a while, before pressure drops again and the speed is further increased.

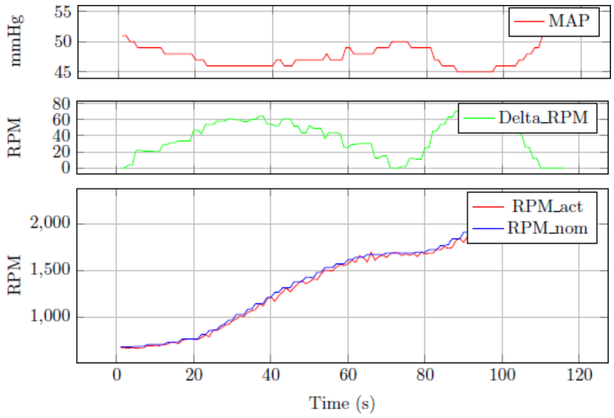

Fig. 3: Vasodilation. See Fig. 2 for details.

Discussion

Fuzzy Logic was introduced by Zadeh in the 1960s [14]. By now it is widely used for all kind of control problems. In Fuzzy Logic, complex systems are described on a verbal or symbolic level [4]. The use of IF-THEN rules, such as “IF MAP is high, THEN decrease Pump speed”, facilitates the design process of the controller and helps to understand system behavior. Expert knowledge can be implemented ad hoc. Compared to a PID controller, no system of equations is needed and no experimental and mathematical system analysis is needed. Also system maintenance is simple. Rules can be added or deleted easily.

Fuzzy systems are especially popular in medical applications, since it is often impossible to give a precise, analytical description of the control system. Hanson [5] states, that medical practitioners strive for objectivity and precision while dealing with data that are inherently imprecise. Fuzzy Logic permits simultaneous membership in more then one set (see Fig. 1) and thus is able to model systems with roughly known response characteristics.

However, disadvantages of the method must not be ignored. Also fuzzy controllers might have tuning problems. An optimal rulebase needs to be defined and, consequently optimal fuzzy sets must be found. This might be a difficult task and a fuzzy controller is only as good as the expertise of its designer.

Looking at the presented system, its drawback is obvious. Since the controller only monitors the MAP, the pump of the HLM might even be stopped, if the pump speed is decreased due to a high MAP. But also if the MAP is within the given bounds the pump speed might be set too low to generate sufficient blood flow. Thus, favorable perfusion is not guaranteed anymore.

An improvement of the system would be to integrate the pump flow value that is recorded by the HLM.

New rules would have to be determined. For example, “IF MAP AND Flow are low, THEN increase pump speed“. More instructions are displayed in Table 1. However, some theoretically possible cases are not that easy to interpret. How should the controller react, if MAP is low and Flow is high or vice versa?

MAP	Low	Medium	High	Low	High
Flow	Low	Medium	High	High	Low
RPM	Increase	Steady	Decrease	?	?

Table 1: Possible instruction sets for a fuzzy controller with MAP and Flow as input variables and RPM as output value.

Adding more variables to the system implies another problem. In optimization this is often refered to as the “curse of dimensionality“. The complexity of a problem increases exponentially with the number of variables involved. Generally spoken, there are m^n rules for a system with n inputs and m fuzzy sets. System interpretation and design becomes more and more complex, when adding more variables. The problem of dimensionality can be approached by the use of hierarchical fuzzy systems [13]. However, this would require a control system that can be naturally decomposed into a hierarchical structure.

Especially in medical applications where variables are highly correlated and the captured signals strongly depend on the patient's condition, the design of fuzzy systems with adequate rulebases can quickly become complex. Such systems have to be robust, cover all possible circumstances, but at the same time an automated ECCS must guarantee reliability and never expose the patient to any risk.

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Affiliation of the first Author

Baumgartner Benedikt
Technische Universität München
Department of Informatics
Robotics and Embedded Systems
Boltzmannstr. 3
85748 Garching
Germany
baumgarb@in.tum.de