# Multi sensor control based on fuzzy logic

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***Abstract**: Recently fuzzy logic has increasing its popularity. One of the main reasons is that it gives abstraction, so a system could be controlled, even if it is not fully describable. On the other hand, this approach simplifies integration of data from multiple sources and its proper usage. The paper is focused on a mature area of temperature control, so the data is homogenous and simple. This applicability demonstration is not limitation and the approach could be used for any type and quantity of data. The paper shows how usage of multiple sensors improves controlled parameter's behavior, giving example with the automotive industry. In this type of products that consist of a network of sensors, it is beneficial to use all available data. The result of this research is analyzed, demonstrating better accuracy as result of a fusion of sensors.*

## 1. INTRODUCTION

Proportional–integral–derivative controller (PID) is the most common control algorithm used in industry and has been universally accepted in industrial control. Application of this control algorithm however is a specific task that requires understanding of PID theory and the best practice, but also the nature of the driven process [1]. In the best case algorithm could be optimized for one of the parameters overshoot, convergence time and oscillation (Fig. 1).

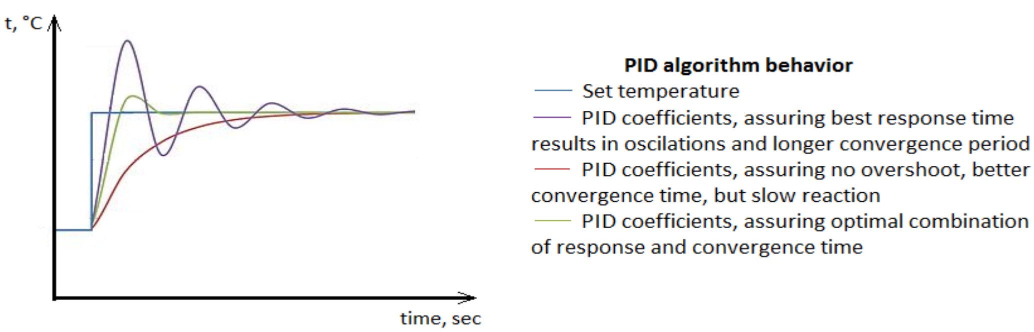


**Fig. 1.**Optimization of PID control.

From another point of view fuzzy logic based algorithms does not need this knowledge, but simply test data. A review of fuzzy methods in automotive engineering applications [2] shows the increasing part of control algorithms in automotive industry, implemented using fuzzy logic. The reason could be found in the possibility to overcome various nonlinear models and to use intuitive logical rules. Using a system with multiple sensors, benefits of this method become even bigger. In this paper, we present a multisensory-based control approach for stable and responsive control, optimizing the well-known quality parameters – overshoot, response time and convergence time. It demonstrates a relevant easiness of application of externally provided related data and the control improvement that it brings. Thus it states that there is no useless data and fuzzy control logic is a solution for utilizing all available information.

Organizationally this paper continues with description of the problem and the techniques provided with PID and Fuzzy control mechanism. In written details it comes obvious the pros and cons of the methods. Then the idea of improvement is shortly described. After that in section Details are placed more details about the simulation and decision taken in order to guarantee objectivity of the paper. Realization of modification is described. Then in Results and Discussion, the results are published with small comments. In conclusion, the results are summarized.

## THE PROBLEM

In [3] the authors give a simple and very clear definition what a control theory is. “Control systems are designed so that certain designated signals, such as tracking errors and actuator inputs, do not exceed pre-specified levels”. They enumerate the sequence of operation that should be done to achieve required control. In this sense the problem occurs were the control limits requirement get tight and more accuracy is needed.

Proportional–integral–derivative controller (PID) is a widely applied control algorithm used in industrial control. Conceptually, the PID controller is quite sophisticated and could be represented in three different ways (Fig.2) - symbolic representation, where each of the terms(proportional, integral and derivative) can be selected to achieve different control behavior, time domain  form and Laplace transform version, that gives the model s-domain operator and allows the link between the time domain and the frequency domain [4]

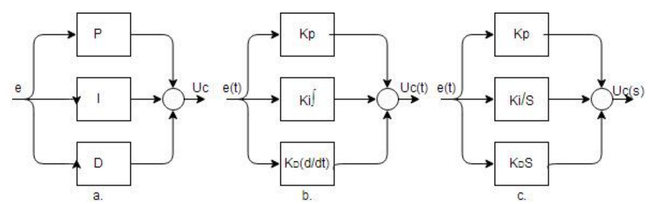


**Fig. 2.** PID representation a. Symbolic, b. Time domain, c. Laplace transformation

Generally, there are four concepts used for PID tuning:

- Model-free methods - does not use the explicit identification of the model or any of its points
- Nonparametric model methods - explicit identification of significant model points, without settling a parametric model
- Data-intensive methods – a combination of the nonparametric and parametric approach, using the grey box concept.
- Parametric model methods: the method straightforwardly depends on the use of a parametric model; usually a transfer function model.

Because of the wide applicability of PID control, there are numerous papers, describing and assessing possible tuning methods [5], [6], [7], [8], [9]. The choice depends on the pre-understanding of the system and control needs, but also experience of one, that applies it.

Fuzzy logic is an extension of Boolean logic by Lotfi Zadeh in 1965 based on the mathematical theory of fuzzy sets, which is a generalization of the classical set theory [10]. Measurement of the level of correctness of the condition statements, gives the possibility to implement a detailed logic better than true or false (Fig.3). Fuzzy logic provides a very valuable flexibility for reasoning. That makes possible to take into account inaccuracies and uncertainties. Also it simplifies the formalization of human reasoning, setting rules in natural language (Fig.4).

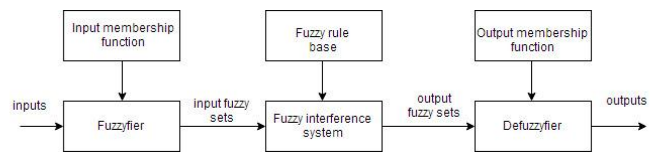


**Fig. 3.** Basic configuration of fuzzy systems

| | statement1 | | statement2 | | result |
|---|---|---|---|---|---|
| if | error is positive | and | error rate is positive | then | correction is negative |
| | error is positive | | error rate is zero | | correction is small negative |
| | error is positive | | error rate is negative | | correction is zero |

**Fig. 4.** Creating rules in natural language

This gives the possibility for relevantly easy integration of relevant data sets, giving each of them different weight.[11][12]

Fuzzy algorithm’s tuning[13], [14] currently is realized with three general methods:

- Supervised learning – there is test data available, that is able to provide the expected algorithm’s output for every step of its execution
- Reinforcement learning – the algorithm is tuned after an assessment that could be proceed after a bunch of algorithm executions
- Unsupervised learning – the presence of test data and a “teacher” giving the expectations is not assumed

It is proven, that supervised learning is the most accurate method [14]. However in most of the cases it cannot be used, because for example training data is not available or changes. There are many proposals of techniques for tuning of fuzzy controller [11], [15], [16], each of them with its pros and cons.

**Comparison**

Experimental comparison of Fuzzy and PID controller [17] indicates the better fit of the first method. The PID is shown as more responsive algorithm.

The authors of [18] also prove better behavior of fuzzy algorithm. They claim a better response, but more important – the fuzzy algorithm, being non-linear is capable to be configured with unlimited different combinations, that lead to different behavior. Their conclusion says”PID controller has only three parameters to adjust. Controlled system shows good results in terms of response time and precision”. Controversially “Fuzzy controller has a lot of parameters.”, “Once a fuzzy controller is given, the whole system can be considered as deterministic”. Authors’ conclusion is that fuzzy controller doesn’t have much better characteristics, but it can deal with nonlinear systems. Problem of the fuzzy logic is high computational time. PID controller can’t be applied with systems with fast changing parameters.

The current paper tries to improve the accuracy of control methods. In [19], the authors use different tuning approaches, comparing the results that both kinds of control systems give. They claim that “the use of soft-computing technique resulted in a better outputs”. However for PID tuning, used for benchmark, they use Zeigler Nichols method that is known for the high overshoot that it carries.

There are many papers on the field of comparison [18], [20], [18], [21]. It should be noted that results vary a lot with different methods of control tuning. Deep analysis is needed so to keep the paper objective.

## THE IDEA

In [22] the authors gives definition of sensor-fusion as “a software approach for improving reliability of information obtained from a sensory system using aggregation of multiple sensors’ information”. They note that “aggregated information also refers to optimal or maximum information, conveys valuable and reliable data that cannot explicitly be found in primary sensor values”. Commonly, the sensor-fusion is used for masking errors, noises, lost data etc. It is expected to lead to better and more accurate estimation of the measured data.

This paper is based on different approach. It doesn’t try to get more accurate measurement, but tries to predict their behavior, based on relevant parameters. It tries to obtain controller’s accuracy using extra data. For example, if one tries to estimate the traction of car’s tires the main dynamic parameter is applied torque. However, having extra information like temperature, tire pressure, etc could be beneficial.

Particularly discussed is heat controller, used in car’s seats. The paper is a trial to improve it using available (“for free”) data that is part of every car, but commonly not used. The body temperature highly depends on ambient temperature, because of energy loss, so it is suitable extra data. Similarly could be used environment’s type, flow, etc. if it is available.

There are several points that the results highly depends on, sequentially discussed in the next section.

- Complexity of heating model
- Physical dynamics restrictions – range of the heating model’s parameters
- Model’s tunings algorithms
- Utilization of the extra data. Sensor data fusion
- Implementation

## DETAILS

### *Complexity of heating model*

”A synthesis problem is a theoretical problem, precise and unambiguous. Its purpose is primarily pedagogical: It gives us something clear to focus on for the purpose of study.” [3]

PID works very well with simple linear models. The paper tries to improve more complicated heat systems. The analysis [23] was used for synthesis of a complicated, nonlinear temperature model (Fig.5).

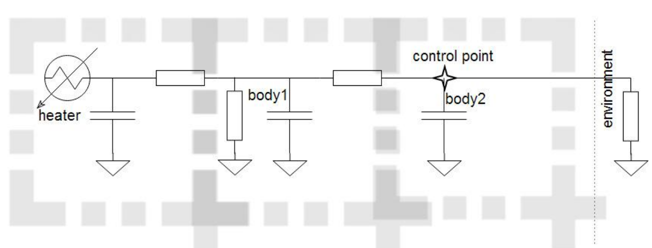


**Fig. 5.** System heat model

The heat model is created with matlab. Same environment is used for control model development and tuning.

***Physical dynamics restrictions – range of the heating model's parameters.***

Volatility of system's parameter is a method for demonstration of control stability [23]. However dynamic systems need to be controlled with dynamic tuned (runtime) control algorithms [24], which is out of the range of this paper. This is the reason why for simulations are used typical use case parameters.

- All the heat system variables(capacity, resistivity, power) are constant
- The other parameters vary, relevant to real use case: Environment temperature varies between -40 and 60; Requested temperature is between 20 and 50

***Model's tunings algorithms***

Previously in this paper the question of tuning the control algorithms was discussed. There are too many methods with different pros and cons. This is the reason why writing this paper objectively is not easy task. The paper aims to show how the fusion of any relevant data with the main one would bring extra control accuracy, thus the results of PID, fuzzy and modified with extra data fuzzy is going to be compared. While both fuzzy applications may be tuned with same method, PID may not.

After revising [15], [18], [20], [21] [25], [26], it was concluded that objectivity would come using the same method in all algorithms. It was noted, that approach, that fits well to all kind of controllers is the genetic algorithm, since it is a general optimization technique. The fitness function that is used calculates the sum of absolute value of errors. In current case it is more accurate than quadratic algorithm, because the second one neglects the errors smaller than one. For extra objectivity, after genetic tuning algorithm, manual one will be done, trying to improve the worst result.

***Utilization of the extra data. Sensor data fusion***

The aim of performing data fusion is to improve the quality or quantity of information so to have better results in some sense. This process is also known as synergy. The basic problem of this approach is to determine the best procedure for data combination. It is required to understand variables' correlation, but also their type, accuracy, frequency of measurement and many others [27].

In the particular case the temperature of environment is an indicator for energy loss of the body. Thus, the difference of required and environment temperatures would be used for indicator of needed power with hi probability of correctness. Thus it could be used as base starting point of control operation.

Unfortunately application of such kind of data is case by case decision, based on analyses or experience. Searching of a unified method of application could be noted as open point for future work.

***Implementation***

Based on the available input data (temperature of controlled body and environment temperature) are synthesized the algorithm's input parameters. Difference between the environment temperature and required one is the parameter that mostly assesses needed power, so required temperature to be met(Table 1a). Optimization of convergence time and oscillation is reached with a correction based on the temperature error and error rate (Table 1b).

**Table 1.** Fuzzy rules.

| EnvDif | HeatLvl |
|---|---|
| large | big |
| medium | medium |
| small | small |

| TempErr | Error rate | HeatLvlAdj |
|---|---|---|
| positive | positive | zero |
| positive | zero | positive |
| positive | negative | positive |
| zero | positive | smallNegative |
| zero | zero | zero |
| zero | negative | smallPositive |
| negative | positive | negative |
| negative | zero | negative |
| negative | negative | zero |

Table 1a(left side) fuzzy rules for power estimation

Table 1b(right side) optimization fuzzy rules.

Here is important to be noted that Mamdani algorithm is used in all the implications. Additionally, the control of needed power is implemented with fuzzy logic, even though using simple look up table would simplify the experiment. The reason is that fuzzy gives the opportunity for easy future utilization of more data.

## RESULTS

In order to compare the controllability, the experiment sets environment temperature to constant value and changes the required temperature with large step (80% of maximum), middle step(30%) and small step(10%). In this case the range is 50-20 = 30 degrees, and step is 24, 9 and 3. The results captured are not clear, because of the complicity of thermal model, the speed of process and its resolution. This is the reason why they are separated Fig.6 is rising of the temperature in PID system, Fig.7 rising in modified Fuzzy, Fig 8 fall in PID and Fig. 9 fall in fuzzy.

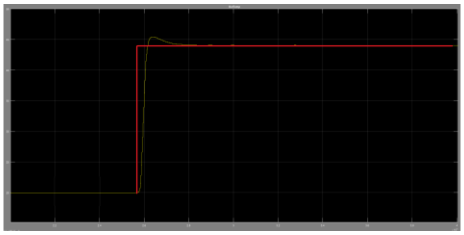

**Fig. 6. PID response to rising temperature request**

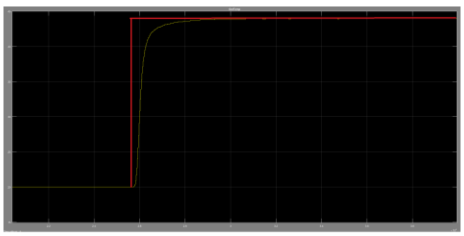

**Fig. 7. Fuzzy response to rising temperature request**

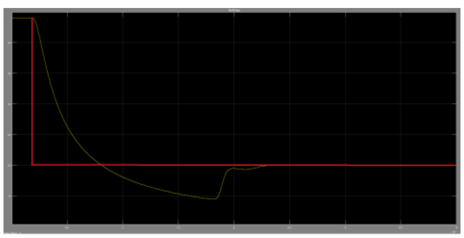

**Fig. 8. PID response to falling temperature request**

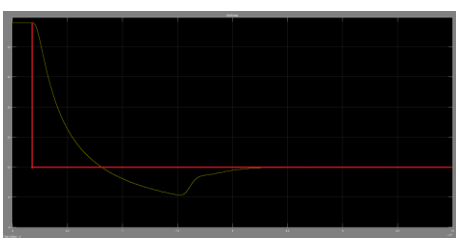

**Fig. 9. Fuzzy response to falling temperature request**

Since the results were not capable to be visualized in a readable form they are posted in Table 2.

Absolute error sum accumulated during execution of step test is 2119 for PID controller and 1973 for Fuzzy, but it should be noted that it highly depends on the set step data sequence.

## CONCLUSION

Data fusion is powerful tool for improving the control in complicated systems. It is important to be noted, that it brings extra complexity of the algorithm and if simple control like PID works good enough in particular use case, it is the better option.

Current paper shows an example of complicated system improvement. Unfortunately the results are good only in particular cases.

When the step is relevantly large, the results in PID and modified fuzzy are relevantly equal and the difference could be taken as negligible because of the tolerance that is a matter of algorithm tuning. The significant difference is measured, when the system parameters got minor changes. In such circumstances there is a major improvement in overshoot and also the convergence time. Response time of PID is still better.

An option for improvement of Fuzzy algorithm, when applied in a system with large changes is to include the temperature difference in main fuzzy logic that calculates the correction of requested power. The fuzzy logic has the feature of exponentially increasing the rules with increasing of input variables, that makes tuning more complicated, calculation – slower, and the result not sure, but it is something to be worked on in the future. Till then, this methodology usage makes sense only for system that work in small deviations.

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**Table 2.** Step test results

| | rising temperature | | | | | | falling temperature | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | fuzzy | | | PID | | | fuzzy | | | PID | | |
| dTrequired (step) | response time, s | overshoot, degreese | convergence time, s | response time, s | overshoot, degreese | convergence time, s | response time, s | overshoot, degreese | convergence time, s | response time, s | overshoot, degreese | convergence time, s |
| **24** | 4.72 | 0.13 | 4.4 | 4.43 | 1.63 | 6.54 | 6.12 | 4.31 | 16.38 | 5.98 | 5.89 | 17.31 |
| **9** | 1.46 | 0.08 | 1.13 | 1.39 | 0.82 | 2.66 | 2.5 | 1.12 | 5.76 | 2.41 | 1.92 | 5,28 |
| **3** | 0.51 | 0 | 0.11 | 0.44 | 0.19 | 0.91 | 0.85 | 0.08 | 0.14 | 0.79 | 0.64 | 1.92 |

helping me with AI application and tuning. All of this would have been impossible without the support of Prof. Boris Tydjarov, as my co-tutor.

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