Ireneusz DOMINIK*, Janusz KWAŚNIEWSKI*

FUZZY LOGIC CONTROLLER FOR ONE-WAY SMA ACTUATOR

SUMMARY

Fuzzy logic controllers are well known and often used for their ability to control nonlinear objects in an easy and efficient way. In the article fuzzy logic controller was chosen to control displacement of one-way actuator where the movement in one-way was realized by SMA wire while an external load was responsible for the way back. The SMA wire is characterized by one of the highest in technology weight ratios, which describes the ratio of maximum external load to its own weight. It allows for building miniature devices which are extremely efficient. Mostly SMA wires are applied as on-off actuators.

Having built a test stand with SMA wire the research on selection of an appropriate method control was launched to control displacement. Eventually a fuzzy controller was implemented into PLC controller made by Omron. In that way in future it will be easier to emigrate from the PLC platform to a dedicated embedded microprocessor. The fuzzy controller was built as a task controller, where the specialized controllers for particular stages of the systems' operation were distinguished. They allowed for accurate and fast SMA wire control. The design controller allows for position control with ±0.1% accuracy with time response below 0.4 s.

***Keywords**: fuzzy controller, position controller, SMA wire, nonlinear object*

REGULATOR ROZMYTY DLA JEDNOSTRONNEGO AKTUATORA SMA

Regulatory rozmyte są dobrze znane i często stosowane z powodu ich zdolności do sterowania obiektami nieliniowymi w prosty i skuteczny sposób. W artykule regulator rozmyty został wybrany do sterowania pozycją jednostronnego aktuatora, gdzie za przemieszczenie w jednym kierunku odpowiada cięgno ze stopu z pamięcią kształtu (SMA), a za ruch powrotny odpowiada zewnętrzne obciążenie. Cięgno SMA charakteryzuje się jednym z największych współczynników wagowych, które są zdefiniowane jako stosunek maksymalnego zewnętrznego obciążenia do masy własnej aktuatora. Pozwala to na zbudowanie miniaturowych urządzeń, które są wyjątkowo wydajne. Ogólnie, cięgna SMA są stosowane jako obiekty dwustanowe.

Po zbudowaniu stanowiska badawczego przeprowadzono szereg badań w celu znalezienia sposobu regulacji, który w sposób zadowalający będzie sterował położeniem cięgna. Ostatecznie regulator rozmyty został zaimplementowany w sterowniku PLC firmy Omron. Pozwoli to w przyszłości na stosunkowo łatwą i szybką emigrację z platformy PLC do dedykowanego wbudowanego mikroprocesora.

Regulator rozmyty został zbudowany jako regulator zadaniowy, gdzie zostały wyróżnione wyspecjalizowane regulatory dla odpowiednich etapów sterowania, czego efektem było dokładne i szybkie sterowanie obiektem. Zaprojektowany regulator rozmyty pozwala na zrealizowanie sterowania pozycyjnego z dokładnością ±0,1% dla czasu odpowiedzi poniżej 0,4 s.

***Słowa kluczowe**: regulator rozmyty, sterowanie położeniem, cięgno ze stopu z pamięcią kształtu, obiekt nieliniowy*

1. INTRODUCTION

Modern technology sets increasingly new requirement for construction materials in the field of, inter alia: reliability, higher endurability or new, yet undiscovered, features, which may improve the parameters of the existing solutions.

In order to meet these requirements a new group of the so called Intelligent Materials were created. One of the subgroups are Shape Memory Alloys (SMA).

Shape Memory Alloys SMA attract more and more interest and nowadays many research centers are working on developing more accurate and better applicable actuators (Nakatani 2005, Scheibe 2006, Tabrizi 2007). A tangible effect of using SMA materials is a considerable simplification of the presently used constructions which entails obvious economic benefits. Along with an increase in the volume of production and decrease in the costs of production, SMA materials become increasingly available on the consumer market.

On the basis of the collected experiment data (Kwaśniewski 2006) it was concluded that SMA wires are nonlinear and time variant. Thus, it was decided to use one of the methods from computation intelligence area to control them. The article presents the use of a fuzzy controller. The reason is that they are most widespread among these tools and regarded as the most trustworthy.

The set value compared with the present value constitutes an error which amounts to the input signal of a fuzzy controller. The fuzzy controller was implemented in CJ1M controller produced by Omron (Omron 2007) from which voltage manipulated variable was transformed into current manipulated variable. The current flows through an SMA wire in the plant (the prototype of linear position actuator) causing the displacement of the load. The displacement measurement was realized by non-touch magnetic sensor produced by Balluff (Balluf 2005). So, displacement was the controlled variable.

Block diagram control system for a prototype of linear position actuator was shown in Figure 1.

---

* Department of Process Control, AGH University of Science and Technology, Krakow; dominik@agh.edu.pl, kwa_j@agh.edu.pl

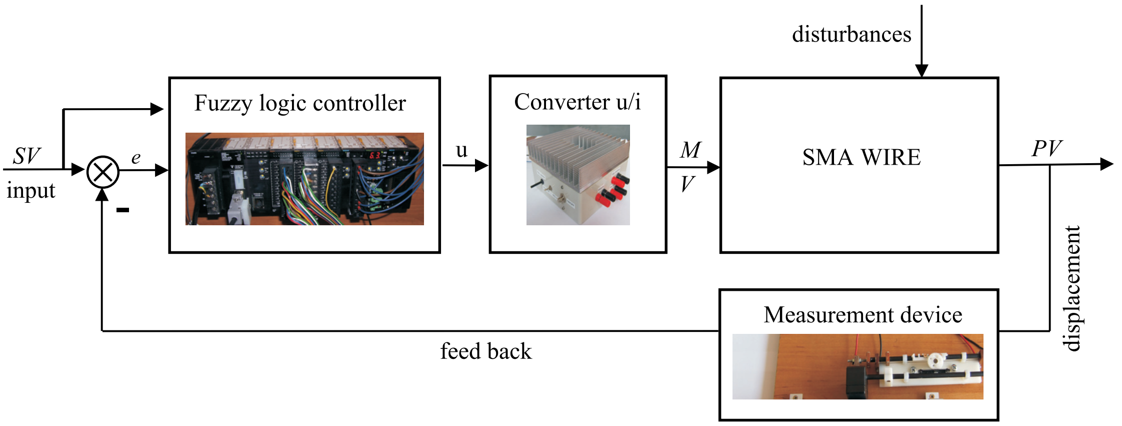
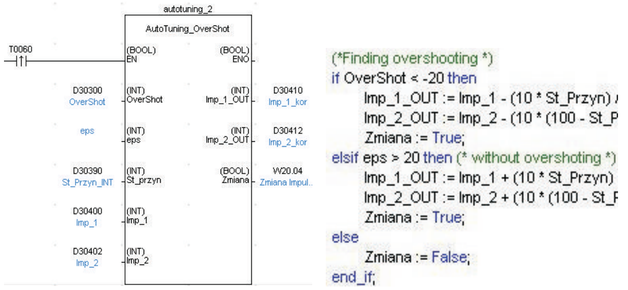


Fig. 1. Block diagram control system for a prototype of linear position actuator (Kwaśniewski 2008)

The tested element was a wire made of shape memory alloys (SMA). During heating the contraction of the wire was observed. The source of heating is the current flowing in the wire. There are two types of SMA wire actuators. In the one-way actuator the movement in one way is realized by SMA wire while an external load or a spring is responsible for the way back. Two-way actuator uses SMA wire to create the movement both ways. In our research we used one-way actuator with an external load.

The peculiar character of the research led to the building of a dedicated power amplifier, shown in Figure 1 as a converter *u*/*i*. The built amplifier differs from the standart ones by ability to keep the constant current output value. It is very important in the research of the SMA wire because its resistance under temperature influences changes. The amplifier allows to protect the wire against too high a current value. This feature is very useful because of the wire current limitation. Otherwise, the wire loses its characteristics and eventually can be destroyed.

In the past an important problem, which made difficult the creation of more sophisticated algorithms, was the lack of appropriate tools for building Function Blocks in PLC. The European Norm IEC 61131-3 solved this problem by introducing standardized Structured Text (ST) language. It is based on Pascal language which can be noticed in Figure 2.



```
(*Finding overshooting *)
if OverShot < -20 then
    Imp_1_OUT := Imp_1 - (10 * St_Przyn)
    Imp_2_OUT := Imp_2 - (10 * (100 - St_P
    Zmiana := True;
elsif eps > 20 then (* without overshoting *)
    Imp_1_OUT := Imp_1 + (10 * St_Przyn)
    Imp_2_OUT := Imp_2 + (10 * (100 - St_
    Zmiana := True;
else
    Zmiana := False;
end_if;
```

Fig. 2. Example of Function Block FB with Structure Text ST

Implementing the high-level programming language allowed for the development of advanced programs inaccessible in PLC's until now. They included, among others, fuzzy logic controllers, neuron networks or genetic algorithms.

2. ZERO-ORDER TAKAGI-SUGENO-KANG (TSK) FUZZY LOGIC CONTROLLER

We can observe that in many cases highly complicated and undefined processes are well controlled by an experienced operator. Moreover, the control is based on defining the work strategy, it consists of a set of non precise, heuristic rules which are impossible to realise in a conventional control system. An operator uses quantities of a linguistic variable, e.g. velocity in a descriptive form (labels): "a bit slower", "faster", "very fast". They are not precise (fuzzy). However, a control system based on such activity works properly.

In the systems where fuzzy logic is applied, we deal with a three-phase process. In the first phase the measured variables undergo fuzzification. It means that the continuous input variable is assigned to a membership (affiliation) function, which allows determination of the degree of membership. In the middle phase, in the fuzzy reasoning (approximate reasoning, generalised modus ponens) system based on knowledge (e.g. model of a system), written as a set of rules IF-THEN, reasoning is realised mainly on qualitative reasoning. In the last phase defuzzification takes place, i.e. crisp value is derived.

The second category of model is based on Sugeno reasoning, known also as TSK because it was elaborated by Takagi, Sugeno and Kanga (Takagi 1985, Sugeno 1991). In this method the antecedent is fuzzy (linguistic), and the consequent is functional; it is a combination of fuzzy and crisp models. This model integrates features of linguistic models for representation of qualitative knowledge with the efficiency of quantitative information representation.

The standard form of rules in the model reads as follows:

$$\textbf{IF } x \text{ is } A \textbf{ AND } u \text{ is } B\text{, } \textbf{THEN } z = f(x, u) \qquad (1)$$

where A and B are sets of the linguistic labels defined in input space x and u in the antecedent, whereas $z = f(x, u)$ is a function in the consequent. This function is usually polynomial, and if the polynomial is of the first order we mean Sugeno's first order fuzzy set (Kwaśniewski 2002).

The first controller used during the research was zero-order TSK fuzzy logic controller. It had two inputs: present value *PV* and error *e* and one output: manipulated variable *MV*, which was the value of current flowing through the SMA wire.

The zero-order TSK fuzzy controller data are as follows:

- Defined membership functions for each input were shown in Figures 3 and 4.
  The membership function distributions (*MsV* – membership value) for the set value correspond to real values of SMA wire contraction measured in millimetres. The whole contraction range (10 mm) was divided into 6 equal intervals 2 mm wide each, apart from the last one which was open above the value of 10 mm.
  For the second input – error *e*, the asymmetrical membership function distributions were proposed. The mem-bership function type Π around 0 mm is an interval where there is a lack of sensitivity for input signal changing. On the other hand, a membership function with greater slope increases the system's sensitivity. The membership function distributions was based on experiment data.

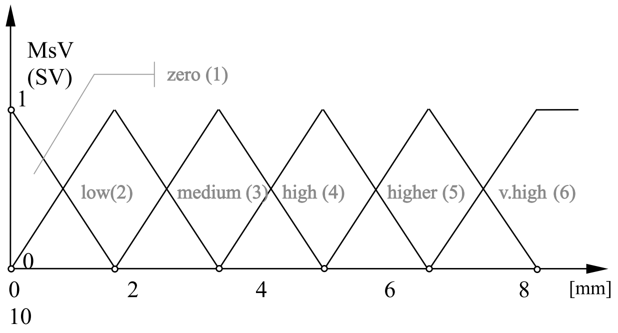


Fig. 3. Set value membership functions (first input)

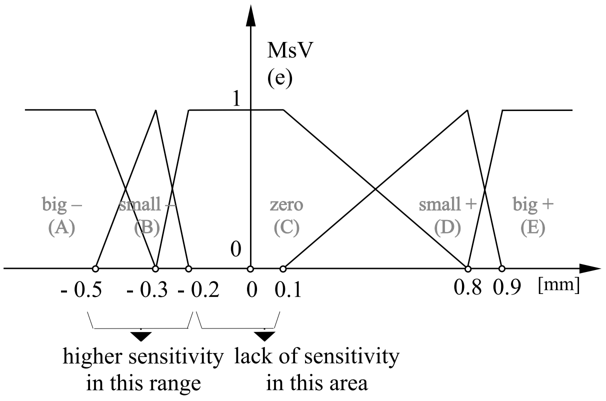


Fig. 4. Error membership functions (second input)

- The rules.
  The knowledge base was built as a 2D matrix where internal elements were singletons. The singleton value is constant and physically constitute the value of current flowing through the SMA wire.

The singleton values were matched in a way that ensured lack of overshooting. It was critical because just after heating the SMA wire gives extra resistance which prolongs the response time. Thus, a much better solution was to select appropriate singleton values (Fig. 5).

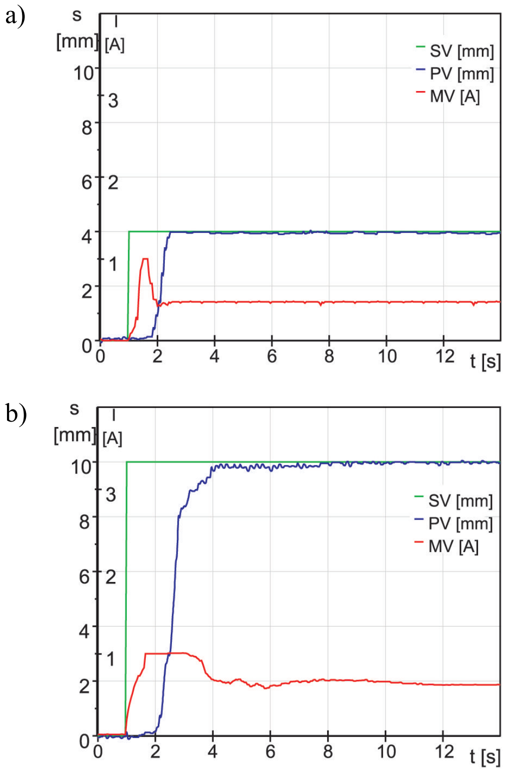


Fig. 5. Step response for 0.20 mm SMA wire controlled by zero-order TSK fuzzy controller: a) set value 4 mm; b) set value 10 mm

3. ACCELERATING IMPULSE

The preliminary research proved that it is possible to use high value currents applied within short periods (hereinafter referred to as acceleration impulse) in such a manner that the wire is displaced at high speed without being damaged. The following research aimed at determining the maximum current value which can flow through the wire to maximize the speed of its work. The next task was to find impulse width which in connection with the given value of current intensity does not damage (overheat) the SMA wire. In other words, such a surface area of the current impulse (its integral) was desired as to maximally increase the wires' work without damaging them at the same time.

There is a lack of data on this phenomenon in the literature. Thus, a number of experiments were conducted using different diameter wires and different loads.

As a result of experimental data the general relationship for each SMA wire diameter was found: the maximum current value used to accelerate contraction equals the current value where the position (error) to switch off the impulse is at the very most half of the set value. It means that if a current is higher, the SMA wire position (error) to switch off the impulse is higher than SV/2 value. As a result, the above mentioned critical overshooting can appear.

For example, for an SMA wire of 0.20 mm diameter and for error SV/2 = 4 mm where the impulse turns off, the current value equals about 2 A. This is double the nominal current value recommended by the producer (Dynalloy 2004). For this values the SMA wire contracts in time 0.28 s without overshooting. It is about 4 times faster than in standard conditions. This is a really good result, especially that the wire remains stable (without oscillations) and the step response experiment is repeatable. As an example, a comparison of characteristic values of the acceleration impulse of the 0.20 mm wire obtained from diagrams similar to the diagram in Figure 6 are presented in Table 1.

Table 1. Comparison of characteristic values for accelerating impulse for 0.20 mm wire and 8 mm set value (according to the producer the maximum current value equals 1 A)

Impulse turn-off error * G_{wyl} [mm]	Current I [A]	Response time t_r 5% [s]	Impulse duration t_{imp} [s]
0.75	1	1.07	1.02
1.70	1.25	0.62	0.56
3.10	1.5	0.42	0.37
4.05	1.75	0.28	0.25
5.10	2	0.25	0.17
5.65	2.25	0.24	0.14
5.64	2.5	0.2	0.11
5.64	2.75	0.2	0.11
5.64	3	0.2	0.1

* G_{wyl} – error limit below which impulse turns off

The values G_{wyl} and $G_{100\%}$ determine the borders for turning on and off the accelerating impulse. Above the error $G_{100\%}$ current value is about 2–3 times higher than the nominal value. Below the error G_{wyl} the impulse is turned off (Fig. 6).

During the research there were used both simple shape accelerating impulses (Fig. 7) as well as gradient impulses (Fig. 8). It appears that the impulse gradation hardly changes the response time so we decided to use a single (1 step) accelerating impulses.

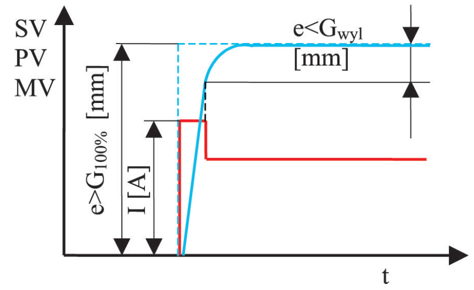


Fig. 6. Two values of errors $G_{100\%}$ and G_{wyl} and current density I determine the accelerating impulse

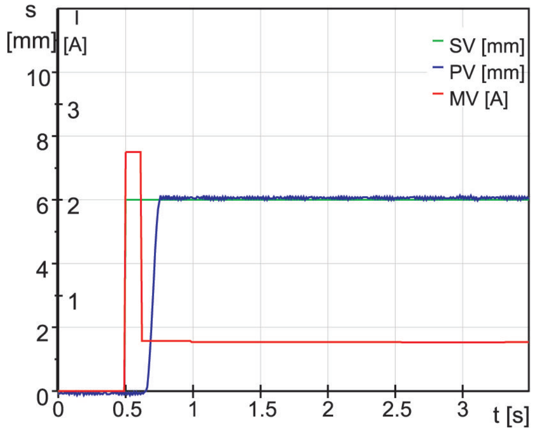


Fig. 7. Step response for 0.20 mm SMA wire – 1 step accelerating impulse (SV = 6 mm; I = 2.5 A, t_r = 0.21 s)

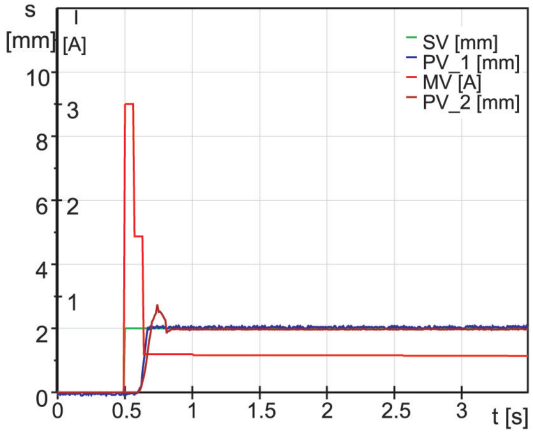


Fig. 8. Step response for 0.20 mm SMA wire – 2 steps accelerating impulse (SV = 2 mm; I = 3A i 1.5 A, t_r = 0.14 s)

4. TASK FUZZY LOGIC CONTROLLER

To control the above mentioned accelerating impulse a zero-order TSK fuzzy controller R_{imp} was used. Its performance was not good enough for correct work in the steady state so the separate steady state controller R_{ust} was added. Together these two controllers constitute a zero-order task fuzzy logic controller, which is illustrated in Figure 9.

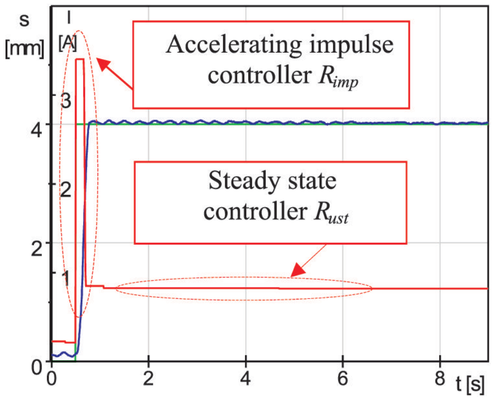


Fig. 9. Schematic division application area of steady state and accelerating controller

The controller R_{ust} is sufficient to operate as an SMA actuator for the whole displacement range. The controller R_{imp} serves only to accelerate displacement. It is superior to the controller R_{ust}, so during their action the controller R_{ust} does not work. In that way it additionally shortens the cycle time.

The steady state controller R_{ust} was a fuzzy controller similar to the single controller described in chapter 1. The membership function distributions for the set value (first input) was the same as for the single fuzzy logic controller (Fig. 3) for both the steady state controller R_{ust} and the accelerating impulse fuzzy controller R_{imp}. On the over hand, the error membership function (controller second input) was changed and was dedicated to the particular task controllers. Figure 10 shows the error membership function distribution for steady state controller R_{ust}, whilst Figure 11 shows the same distribution for the steady state controller R_{imp}.

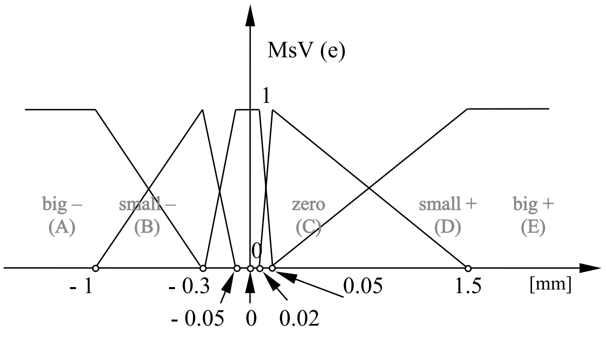


Fig. 10. Error membership functions (R_{ust} controller)

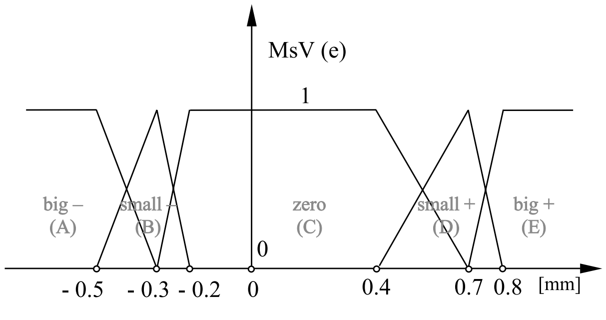


Fig. 11. Error membership functions (R_{imp} controller)

set value	error big – (A)	small – (B)	zero (C)	small + (D)	big + (E)
zero (1)					
low (2)					
medium (3)	**0**	**T_b**	**St**	**R_b**	**Imp**
high (4)					
higher (5)					
v. high (6)					

Fig. 12. The rules for the accelerating impulse fuzzy controller R_{imp}

Apart from changing the error membership function, the rules for the controller R_{imp} were different, as shown in Figure 12.

The rules create the relation matrix and for the controller R_{imp} it consists of 6 lines (according to 6 equal intervals each 2 mm wide in set value membership function) where every line includes the same descriptions (but with different values for every line).

The data in the matrix rows are as follows:

- Impulse value (Imp) – the maximum value of the impulse current flows through SMA wire for maximal error big +.
- Rising braking value (R_b) – the intermediate current value between turn off an impulse and transition into the steady state value. It means that an impulse has vertical rising edge and strong steep trailing edge which helps to control wire braking during fast approaching the set value. The braking value is at the average 0.05 A from steady state value, it lasts about 0.1 s.
- Steady state value (St) – the current value in steady state. In this area after 2÷5 ms the steady state controller R_{ust} indeed takes the control over wire.
- Trailing braking value (T_b)– if the set value is changed from higher value to lower just before approaching this lower value through wire flows current equal to 2/3 of a steady state current for a given position.
- 0 – if an SMA wire position is much over the set value (error *big* –) no current flows through the wire.

The sample results of using a zero-order task fuzzy logic controller are illustrated in Figures 13 and 14.

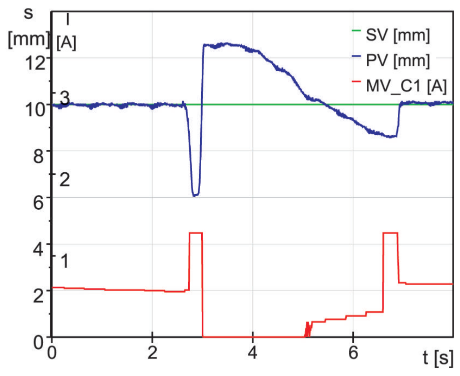


Fig. 13. Actuator output for disturbance

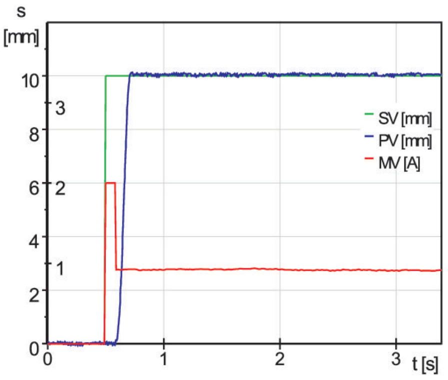


Fig. 14. Actuator step response for 0.30 mm SMA wire controlled by zero-order task fuzzy controller

5. SUMMARY

In order to compare the results the following performance criteria of control were taken into consideration: response time 5% [s] and standard integral criterions: Integral of the Absolute Error IAE (I_{1m}) and Integral of Squared Error ISE (I_2) (Tab. 2). These criteria are based on the measure of transient states in a system.

Table 2. Comparison performance criterions of quality of control

	$t_{5\%}$ [s]	IAE	ISE
Single fuzzy controller SV = 4 mm SV = 10 mm	1.45 1.78	4.62 17.51	0.82 7.39
Task fuzzy controller SV = 4 mm SV = 10 mm	0.34 0.38	0.59 0.87	0.19 0.38

The comparison clearly indicates both the improvement of time response (4 times) and quality of control (20 times for SV = 10 mm).

In the future we plan to modify our controller in such a way that it works in a more repetitive, predictable way. The controller we have designed allows for accurate work for the changes in the set values when the actuator initial position was 0 mm. Unfortunately, during changing intermediate set values e.g.: from 2 to 5 mm, about 20% of responses have overshooting, which, as mentioned above, is highly undesirable in controlling SMA actuators. This will be the subject of future research.

Acknowledgement

The research work was supported by the Polish government as part of the research programme No 3767/T02/2006/31 conducted in the years 2006–2007.

References

Balluf 2005, *Liniowe przetworniki drogi Micropulse AT.* Operation Manual.

Dynalloy, Inc. 2004, *Technical Characteristics of Flexinol Actuator Wires.*

Kwaśniewski J., Rączka W., Dominik I. 2006, *Conception of a line driver based on Shape Memory Effect SME.* 7th International Carpathian Control Conference ICCC, Czech Republic.

Kwaśniewski J., Dominik I., Sitko M. 2008, *Controller for nonlinear SMA wire.* 9th International Carpathian Control Conference ICCC, Sinaia, Romania.

Kwaśniewski J. 2002, *Programmable logic controllers*. Kraków, ROMA-POL, ISBN 83-86320-45-1.

Nakatani, Masashi, *et al.* 2005, *Control Method for a 3D Form Display with Coil-type Shape Memory Alloy.* s.l.: The University of Tokio, Japan.

Omron 2007, *Operation Manual Function Blocks/Structured Text.* CX-Programmer ver. 7.2 WS02-CXPC1-E-V7 Revised July.

Sugeno M., Tanaka K. 1991, *Successive Identification of a Fuzzy Model and its Applications to Prediction of a Complex System*. Fuzzy Sets and Systems.

Takagi T., Sugeno M. 1985, *Fuzzy identification of systems and its application to modeling and control*. IEEE Trans. On Systems, Man, and Cybernetics, No 15.

Scheibe R., Moehring M., Froehlich B. 2006, *Tactile Feedback at the Finger Tips for Improved Direct Interaction in Immersive Environments 1.* Weimar: Volkswagen AG Group Research, Bauhaus-Universität Weimar.

Tabrizi V.A., Moallem M. 2007, *Nonlinear Position Control of Antagonistic Shape Memory Alloy Actuators.* New York City, USA: The 2007 American Control Conference.