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Applications and Adaptive Neuro-Fuzzy Estimation of Conductive Silicone Rubber Properties

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The paper summarizes the results of investigations on the conductive silicone rubber as strain sensor and presents a segment of the project for developing the new principle of a universal gripper with adaptable shape morphing surfaces. An experimental investigation of the sensors subjected to different time-dependent strain histories is presented. To investigate the electrical properties, the resistance of silicone was measured during the mechanical tests. An adaptive neuro-fuzzy inference system (ANFIS) was used to approximate the correlation between these measured features of the material and to predict its unknown future behavior. ANFIS has unlimited approximation power to match any nonlinear function arbitrarily well on compact set and to predict a chaotic time series.

Aplikacije i adaptivna neuro-fuzzy logička procjena svojstva vodljivosti silikonske gume

Izvornoznanstveni članak

U radu su sažeti rezultati istraživanja vodljive silikonske gume kao senzora naprezanja i predstavlja jedan segment projekta za razvoj novog principa univerzalnog stezanja s prilagodljivim oblikom površine. Prikazano je eksperimentalno istraživanje senzora podvrgnutog različitim naprezanjima ovisnim o vremenu. Kako bi se istražila električna svojstva, izmjerena je otpornost silikona tijekom mehaničkih testova. Adaptivni neuro-fuzzy logički sustav (ANFIS) korišten je za približno utvrđivanje korelacije između mjerenih obilježja tih materijala, te za predviđanje nepoznatog budućeg ponašanja materijala. ANFIS ima neograničenu moć zadovoljavajuće točnog procjenjivanja bilo koje nelinearne funkcije na kompaktnom skupu i sposobnost predviđanja kaotičnih vremenskih serija.

Keywords

Conductive silicone rubber
Adaptive neuro fuzzy network
Strain sensor
Compliant gripper

Ključne riječi

Vodljiva silikonska guma
Adaptivna fuzzy neuralna mreža
Senzor naprezanja
Prilagodljiva stezaljka

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1. Introduction

Artificial neural networks (ANNs) are flexible modelling tools with capabilities of learning the mathematical mapping between input and output variables of nonlinear systems. One of the most powerful types of neural network system is adaptive neuro fuzzy inference system (ANFIS). ANFIS shows very good learning and prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. Fuzzy Inference System (FIS) is the main core of ANFIS. FIS is based on expertise expressed in terms of 'IF–THEN' rules and can thus be employed to predict the behaviour of many uncertain systems. FIS advantage is that it does not require knowledge of the underlying physical process as a precondition for its application. Thus ANFIS integrates the fuzzy inference system with a back-propagation learning algorithm of neural network. The fuzzy inference system could be used as a controller as well. A modification of the existing analytic fuzzy controller which provides improvement of control performances was proposed in [1]. Classifications are the most frequent applications for the common artificial neural networks. In [2] was for example, described an investigation of the application of neural networks to multiple criteria classification.

In this study, based on our experimental measurements, a constitutive model was developed. This model was made using ANFIS. To date, experimental investigation of mechanical and electrical properties of conductive silicone rubber has been performed in [3]. There are many studies of the application of ANFIS for prediction and real-time identification of many different systems. In [4] the effectiveness of predicting non-uniformity of the wafer surface with ANFIS was investigated under conditions of the three process parameters. A developed finite element method was used to obtain the training data and testing data about non-uniformity on wafer surface. An ANFIS model was developed in [5] to forecast the energy requirements of different types of buildings having different properties. A neuro-fuzzy

Symbols/Oznake

t	- time - vrijeme
$t + p$	- points in the future - točke u budućnosti
x	- variable - varijabla
Δ	- time series spaced apart - razmaknute vremenske serije
D	- mapping points - mapirane točke

model was utilized to predict the hardness and porosity of shape memory alloy in [6]. The purpose of that study was the estimation of porosity and hardness of the produced samples. Paper [7] presented an improved ANFIS with self-feedback for the applications of time-series prediction. An ANFIS model was applied to predict the flow stress in hot deformation process of Ti6000 alloy in [8]. In [9], optimum cure time of the rubber compounds was predicted using an ANFIS model. Various principles of the neural network approach for predicting certain properties of polymer composite materials were discussed in [10]. The applicability of ANFIS for prediction of carbon dioxide solubility in polymers was showed in [11]. Paper [12] developed a micromechanism theory that successfully captures many of the time-dependent characteristics of filled rubber.

An ANFIS model was established in this study to predict the voltage changing of conductive silicone rubber during compression tests. Many compression tests of conductive silicone rubber were conducted at different strain rates and strains to characterize the voltage changing behaviour and understand the deformation mechanisms during the deformation process. The constructed ANFIS model exhibited a high performance for predicting voltage changing of the conductive silicone rubber during compression tests.

2. Materials and Methods

2.1 Passively Adaptive Compliant Gripper

This paper presents a segment of the project for developing the new principle of a universal gripper with adaptable shape morphing surfaces. Such grippers are known as shape adaptive (Figure 1).

The development of the universal gripper as an adaptive mechanical system was intended. In it, some form of intelligence was embedded into the mechanics, while the ability to adapt to new external situations relies strictly on mechanical properties. In such a system, no complex controllers are required to perform the main task since the mechanical system itself will provide the required adaptive behaviour. Special emphasis has been placed on the reduction of the number of degrees of freedom, thereby decreasing the number of actuators.

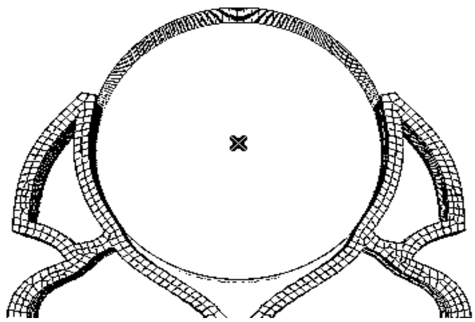

Figure 1. Shape adaptive gripper

Slika 1. Stezaljka prilagodljivog oblika

Figure 2 shows the start design of the gripper and variable parameters for topology and shape optimization.

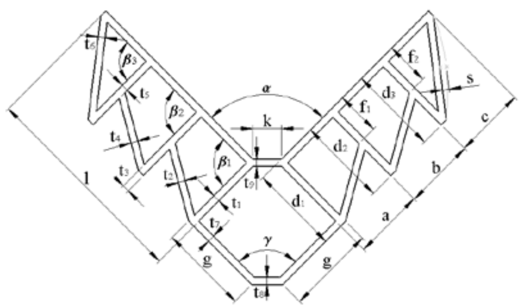

Figure 2. Initial topology of the gripper and all variable parameters

Slika 2. Početna topologija stezaljke sa svim promjenljivim parametrima

After structure optimization procedure was performed using the Finite Element Method, the topology structure for the gripper, shown in Figure 3, was obtained, with 3 embedded sensing elements and only 1 active input actuator for simple control. Figure 3a shows the unloaded state of the compliant gripper, while Figure 3b shows the state with one grasped cylindrical object.

The adaptable shape morphing surfaces will have the controllability by a compliant system with embedded actuator and sensors. The deformations of the embedded sensors will lead to its different signals for electricalresistances for regulation of desirable contact surface pressure.

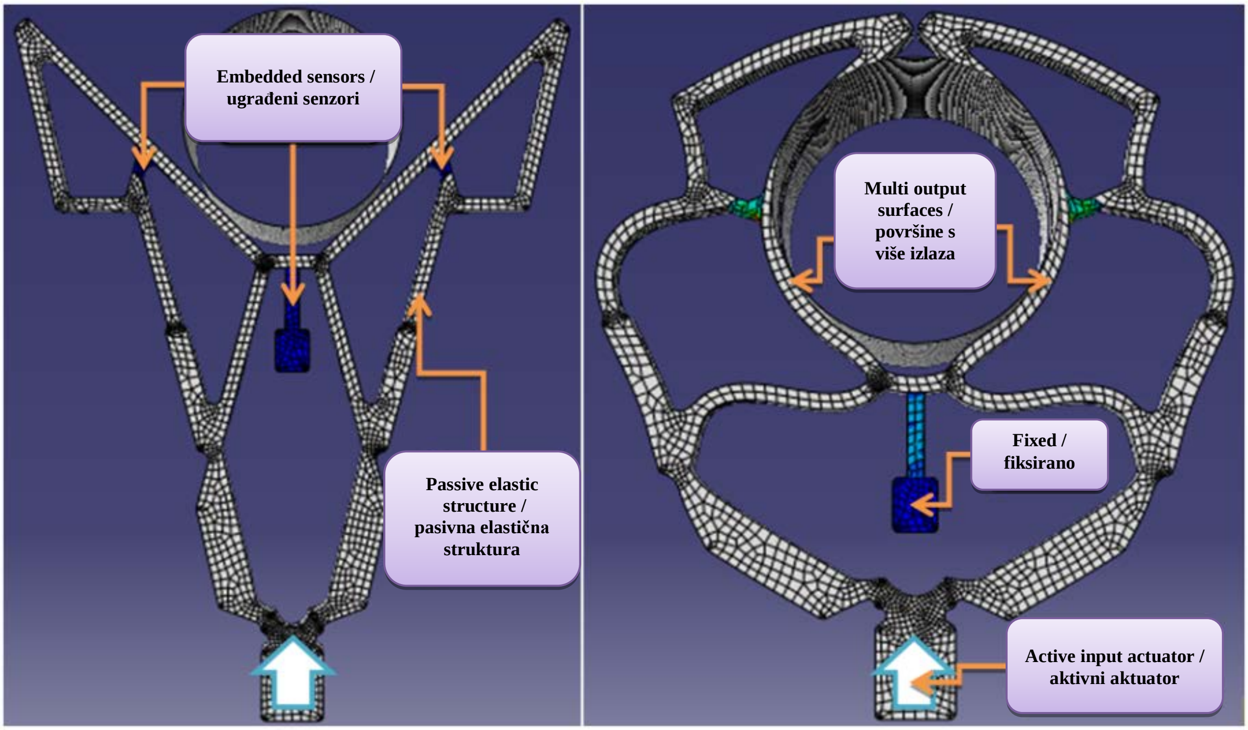

Figure 3. The main features of the adaptive gripper

Slika 3. Osnovne karakteristike adaptivne stezaljke

Figure 4 shows the contact surface pressure. The aim is to establish a relationship between the contact pressure and deformations (stress and strain) of the embedded sensors. The key goal of this study was to establish the application of the conductive silicone rubber material or foam in grippers as embedded sensing elements [13].

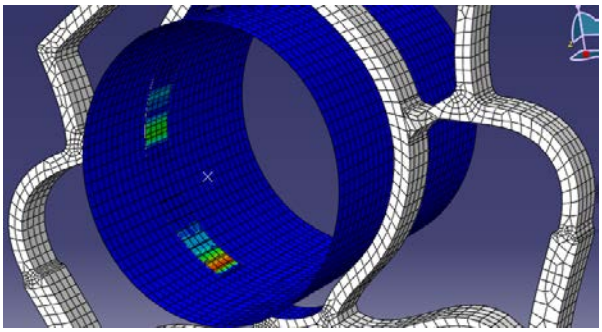

Figure 4. Contact surface pressure

Slika 4. Pritisak na kontaktnim površinama

2.2 Passively Adaptive Compliant Gripper

The carbon-black filled silicone rubber is electrically conductive and its resistance changes by deformation. These properties make this material suitable to develop force or deformation sensors [14]. The specimens were made by press-curing from carbon-black filled silicone rubber (Elastosil R570/70, Shore A 70), as shown in Figure 5. The changing of electrical resistance of silicone rubber specimens was measured with the help of a special compression tool and electrodes inserted during vulcanization on the top and bottom sides of the specimens. Measurement electrode was cured on those sides of silicone rubber specimens. The electrodes were made from soft copper weave due to its good electrical contact. Wires were soldered on the electrodes with connectors to connect to the measurement instrument.
Various compression tests of the silicone were performed. The characteristics of voltage and stress were represented as function of deformation and time.

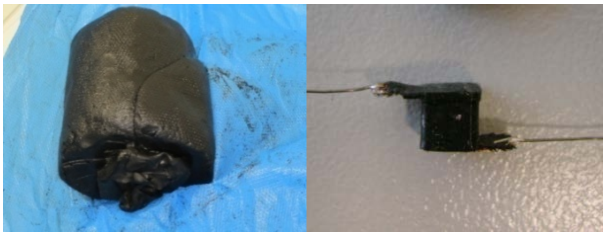

Figure 5. Raw conductive silicone rubber Elastosil R570/70 and one cubic sensor-specimen

Slika 5. Provodljivi silikonski kaučuk Elastosil R570/70 i uzorak senzora oblika kocke

Zwick ProLine material-testing machine Z005, shown in Figure 6, was used to measure the mechanical and electrical properties of the sensor-elements. Throughout the mechanical tests, the resistance-deformation and force-deformation diagrams were recorded and automatically drawn via the software testXpert II. 5V were used as input voltage for electrical source according to the initial resistance of the sensor-elements during the compression test.

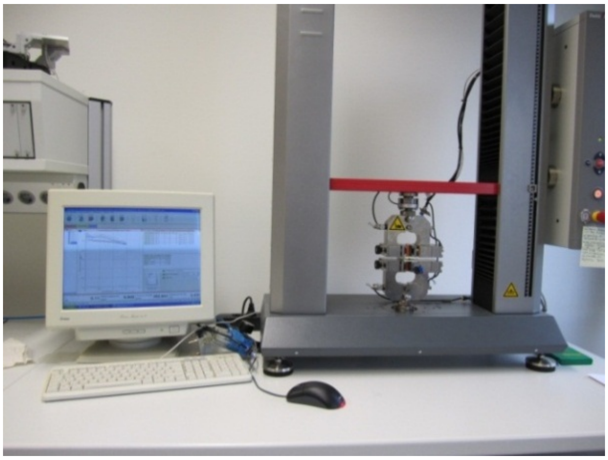

Figure 6. Experimental setup for ProLine material-testing machine

Slika 6. Eksperimentalna instalacija ProLine uređaj za ispitivanje materijala

2.3 Adaptive Neuro Fuzzy Inference System

Adaptive neuro fuzzy system (ANFIS) was suggested by Jang [15]. ANFIS can serve as a basis for constructing a set of fuzzy 'IF–THEN' rules with appropriate membership function to generate the stipulated input-output pairs. The membership functions are tuned to the input-output data. ANFIS is about taking an initial fuzzy inference (FIS) system and tuning it with a back propagation algorithm based on the collection of input-output data. The basic structure of a fuzzy inference system consists of three conceptual components: a rule base, which contains a selection of fuzzy rules; a database, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism, which performs the inference procedure upon the rules and the given facts to derive a reasonable output or conclusion. These intelligent systems combine knowledge, technique and methodologies from various sources. They possess human-like expertise within a specific domain – adapt themselves and learn to do better in changing environments. In ANFIS, neural networks recognize patterns, and help adaptation to environments. Fuzzy inference systems incorporate human knowledge and perform interfacing and decision-making.

Here ANFIS was used to approximate the correlation between measured features of the material and to predict its unknown future behaviour for voltage changing. The training data was obtained by many compression tests of the silicone specimens. One half of the data was used for training while the other half was used for checking and validation of the model. With a proper training scheme and fine filtered data-sets, ANFIS was capable of predicting voltage values quite accurately since it learned from training data. This measurement-free architecture also made it immediately available for operation once it was trained.

In time series prediction the past values of voltage changing up to time t are used to predict the value at some point in the future $t+p$. The standard method for this type of prediction is to create a mapping from D points of the time series spaced Δ apart; that is $x[(t-(D-1)\Delta]...x(x-\Delta), x(t)$ to predict a future value $x(t+p)$, where $D=4$ and $\Delta=p=6$ are used. For off-line learning data is updated and predicted only after presentation of entire data set, or only after an epoch. The number of times the entire data set is used to check and validate the prediction is called epoch number. Matlab's Fuzzy logic toolbox is used for the entire process of training and evaluation of FIS.

In order to build an ANFIS that can predict $x(t+p)$, from the past values of voltage changing, the training data format is $[x(t-18), x(t-12), x(t-6), x(t); x(t+6)]$. As can be seen, there are four inputs and one output. The inputs are $x(t-18), x(t-12), x(t-6), x(t)$ and the output is $x(t+6)$. There are two membership functions on each input since this structure has fast training procedure. In this study, bell-shaped membership functions with maximum equal to 1 and minimum equal to 0, was chosen. This type of functions has best characteristics for fuzzing the inputs. Experimental results of voltage changing are shown in Figure 7.

To avoid slow training procedure, the experimental data was trimmed. The first 10 seconds of the data were ignored to avoid the transient portion of the data. Training and checking data are shown in Figure 8 and input bell-shaped membership functions for training are shown in Figure 9.

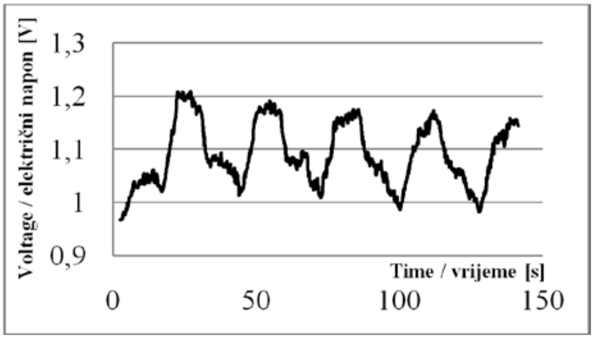

Figure 7. Voltage changing curve from experimental measurements

Slika 7. Krivulja izmjerene promjene napona

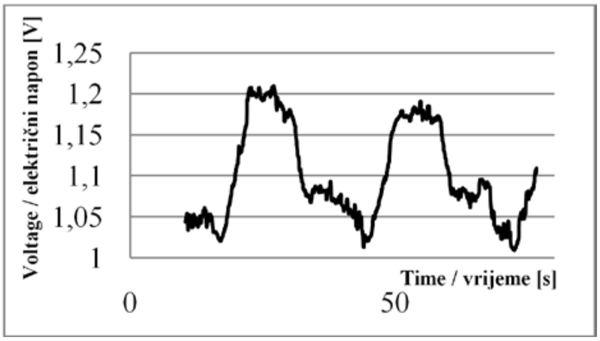

Figure 8. Voltage changing curve from experimental measurements trimmed for ANFIS

Slika 8. Krivulja izmjerene promjene napona prilagođena za ANFIS mrežu

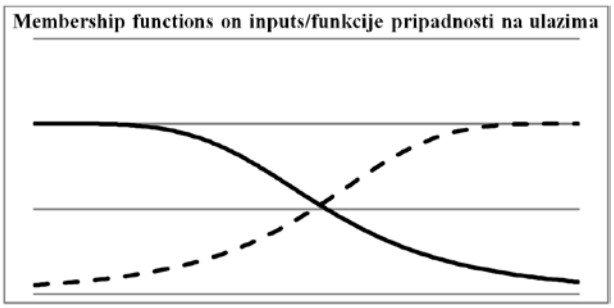

Figure 9. Initial membership functions on inputs

Slika 9. Inicijalne funkcije pripadnosti na ulazima

One half of the data was used for training while the other was used for checking and therefore the number of rules was 2^4=16 rules. Fuzzy Logic Toolbox of MATLAB was used to develop the ANFIS model with four inputs and single output as given in Figure 10.

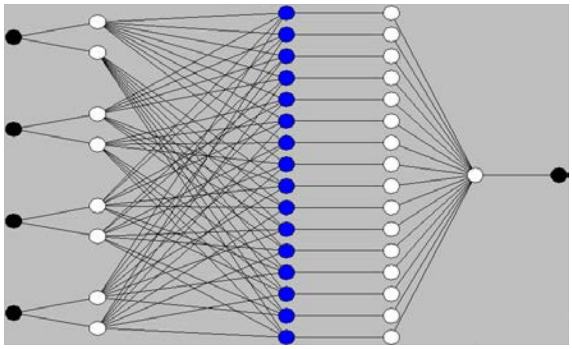

Figure 10. ANFIS structure

Slika 10. ANFIS struktura

In the generating FIS matrix the number of fitting parameters was 104, including 24 non-linear parameters and 80 linear parameters. Most of the fitting was done by the linear parameters. The non-linear parameters were mostly used for fine tuning for further improvement. We applied the hybrid learning algorithms to identify the parameters in the ANFIS architectures. This algorithm had a forward and a backward pass which resulted in very good and fast learning error decrese.

3. Results

The error curves for both checking and training data are shown in Figure 11. Training error is represented by circles and checking error by squares. It can be noted that training error is higher than checking error, which is a common process in non-linear regression. It could indicate that the training process is not close to being finished yet. It can be also seen that the training procedure lasted for 10 epochs.

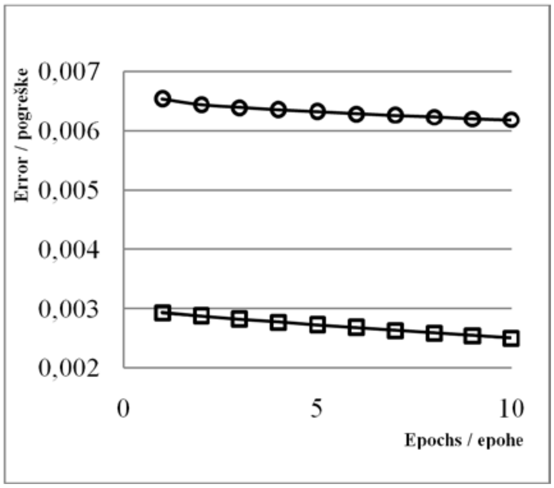

Figure 11. Error curves: training error (circle), checking error (square)

Slika 11. Krivulja pogreške: pogreška učenja (kružići), pogreška provjere (kvadratići)

Figure 12 shows the time series prediction of voltage changing obtained using ANFIS. The ANFIS prediction results are represented by red dotted line and experimental results by black solid line. Here the difference between predicted values and measured values is negligible. Figure 13 shows the prediction error. It is determined that the maximal error is 0,06V which does not result in any change in the control signal since this conductive silicone rubber cannot be used for accurate measurements because of strong non-linearity. The selection of number of membership functions, training data and epoch was obtained by trial and error. For further improvement, the number of membership functions has to be increased which results in a slower training procedure.

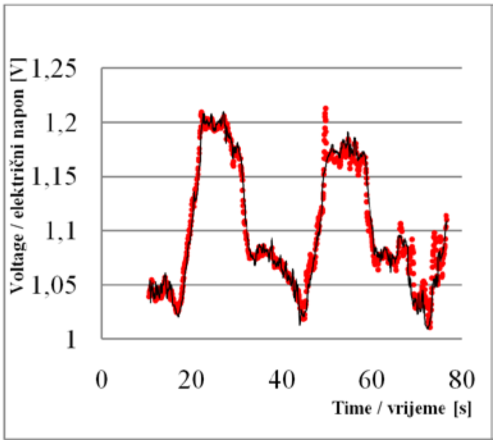

Figure 12. Voltage changing curve predicted by ANFIS (red dotted line) and curve obtained by measuring (black solid line)

Slika 12. Krivulja promjene napona određena ANFIS predviđanjem (crvena točkasta linija) i krivulja izmjerenih vrijednosti (crna puna linija)

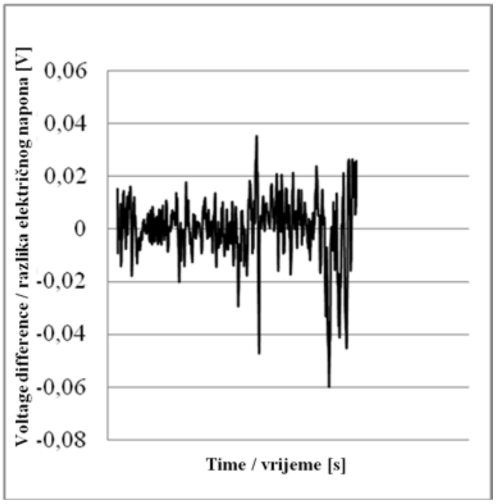

Figure 13. ANFIS prediction errors

Slika 13. Pogreška s ANFIS predviđanjem

4. CONCLUSION

In this paper a new constitutive model was presented that allows predictions of the voltage changing behaviour of elastomeric materials. The most important advantage of such a model is the ability of real time identification of conductive silicone rubber electrical behaviour, which can be used for strain sensing structure or other applications of this material. ANFIS is used to approximate the correlation between measured features of the material and to predict its unknown future behaviour for voltage changing. The implementation of ANFIS model is less complicated than that of sophisticated identification and optimization procedures. Compared to fuzzy logic systems, ANFIS has automated identification algorithm and easier design, and compared to neural networks it has less parameters and faster adaptation. The non-linear characteristics of the conductive silicone rubber can be tolerably handled in the proposed system. This prediction could be utilized as the input for the strain sensing control system. The possibility to reduce the number of sensors and connections improves the performance of control strategy. The ANFIS based time series prediction model for voltage changing of conductive silicone rubber is unique and novel as it is simple, reliable and easily accessible for different compression conditions. The results obtained in this work indicate that ANFIS is an effective method for the prediction of voltage changing in conductive silicone rubber and that it has better accuracy and simplicity compared with the classical methods.

Acknowledgments

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