2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Dielectric Elastomer Actuators – On the Way to New Actuation-Systems Driving Future Assistive, Compliant and Safe Robots and Prostheses*

S. Reitelshöfer, M. Landgraf, I. S. Yoo, J. Hörber, C. Ramer, C. Ziegler and J. Franke

Abstract— **For almost 20 years, dielectric elastomer actuators (DEAs) have been the subject of intense research in material science. A large number of publications describe artificial muscles based on DEAs as a promising alternative for an energy efficient, lightweight and flexible actuation architecture. DEAs could improve and extend the capabilities of robotic and prosthetic devices in terms of their dynamical performance and their eligibility for energy autarkic operation. However, up to now DEAs are not available on a large scale with reproducible characteristics nor are they yet usable on a system integration level. In this paper we present recent findings of our ongoing five-year project to qualify DEAs as feasible artificial muscles for usage in compliant robot kinematics and soft prosthetic devices. The focus of this contribution lies on a new automated production process using Aerosol Jet Printing for stacked DEAs with very thin layers for reduced driving voltages and improved mechanical characteristics resulting from the additive manufacturing. Secondly, a new set of lightweight power electronics based on pulse width modulation (PWM) is presented which aims at the improvement of the overall specific power of DEA driven kinematic systems.**

I. INTRODUCTION

Actual high-DOF robotic systems show an astonishing set of capabilities like, for example, walking in difficult, unstructured terrain or advanced grasping based on sensor data fusion. However, as the prevailing actuation principles of those systems are geared servomotors, hydraulic systems or pneumatic actuators, nowadays robots suffer from severely limited dynamical capabilities. In addition, nearly none of them can be operated untethered for a sufficient amount of time. Many mechatronic prosthetic devices are also driven by servomotors and are therefore affected by a lack of compliance due to the rigid mechanic coupling, for instance of the fingers in a hand prosthesis.

Reasons for the widespread use of geared servomotors in kinematic systems are the good understanding of those actuators in terms of control and modelling, their ability for fine positioning due to high gear ratios and finally their availability. The problem of this type of actuator is that, if it must be small, lightweight, efficient and fine-positionable at the same time, the system architecture leads to an optimal operating point at high rotational speeds with low torques. In contrast, for a typical robotic application, smaller displacements and higher torques are needed. Therefore gears are inevitable to transform high rotational speeds into high torques. Unfortunately, gears severely limit the dynamical capabilities of servomotors [1], the backdriveability is low or lost and lightweight gears are not suitable to bear repetitive impulsive loads as they would occur in a running biped robot for instance. The drawback regarding dynamic, impulsive loads is connected to the incapability of geared servomotors to realize an inherent damping behavior. This problem can be addressed by adding serial elastic elements like springs to the actuation chain, but this approach adds additional mass to a kinematic system and therefore reduces the overall specific power. To gain better dynamic capabilities more often hydraulic or pneumatic actuation systems are used in robotic systems. Those actuators can provide a very high energy density [2] and hence allow the reduction of the moving mass in the extremities of a motion system. In addition they are suitable to realize a compliant actuation behavior. The main disadvantage is the low overall efficiency of pneumatic or hydraulic systems that prevents the energy autarkic, untethered operation of robots bases on those systems or makes the usage of combustion engines necessary as described in [3].

In contrast to the previously depicted systems, natural archetypes of actuators like skeletal muscles of mammals in combination with tendons are capable to sustain repetitive impulsive loads because of their damping properties and their inherent elasticity. These are fundamental prerequisites making tasks like jogging or the usage of a forge hammer possible. Elastic deformation also contributes to the effectiveness of a motion system. For example while running humans can reuse up to 50 percent of the energy of the last step for the following one [4]. In addition elasticity in the kinematic chain can be one option to reduce control complexity, for instance in grasping, when absolute position control is no longer needed due to the passive, flexible adaption of soft gripping systems. Therefore a technical equivalence to the described natural model is desirable.

Dielectric elastomer actuators (DEAs) have been the subject of intense research in material science for more than a decade. Their potential capability is emphasized by their commonly used description as, "artificial muscles". Biological archetypes, like the previously mentioned skeletal muscles of mammals, are exceeded pertaining to energy density and efficiency [5][6]. In addition, compared to classic electro-

*Research supported by Bavarian State Government.

S. Reitelshöfer is with the Institute for Factory Automation and Production Systems (FAPS), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91058 Germany (corresponding author to provide phone: +49-(0)9131-8527962; fax: +49-(0)9131 302528; e-mail: reitelshoefer@faps.uni-erlangen.de).

M. Landgraf, I. S. Yoo, J. Hörber, C. Ramer, C. Ziegler and J. Franke are with the Institute for Factory Automation and Production (FAPS), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, 91058 Germany, Erlangen, 91058 Germany.

mechanic actuators, the advantages of natural muscle tissue like inherent flexibility and damping characteristics are inherent features of DEAs.

Generally, a DEA can be described as a simple plate capacitor with a flexible and incompressible dielectric medium and two deformable electrodes as shown in Fig. 1 b). If the capacitor is charged the opposing electrodes attract each other and the dielectric medium is deformed. The natural analogue of this elementary functional unit of a DEA is the sarcomere in natural muscle tissue depicted in Fig. 1 a). Both the DEA cell and the sarcomere contract on a microscopic scale. To gain an actuator which is usable on a macroscopic scale single DEA cells can be stacked on top of each other. This corresponds to myofibrils integrating sarcomeres. Finally, the applicable force of a DEA depends on the dimension of its electrodes. For several reasons, like inhomogeneous electrical fields, the electrodes should not exceed a certain size. As DEAs are unidirectional acting devices, to gain well describable actuators, the parallel usage of several bundled, standardized stacked DEAs is good practice for adapting to different load scenarios.

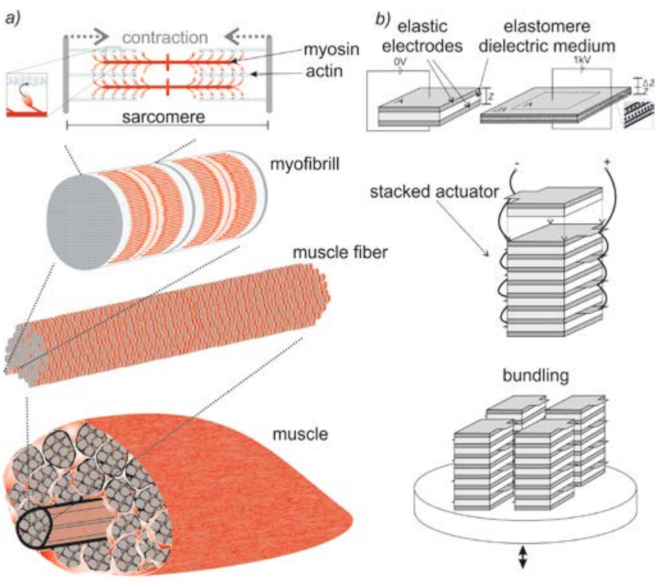

Figure 1. DEAs are biomimetic actuators due to the transfer of natural clustering principles.

As depicted in Fig. 1, DEAs can be described as biomimetic actuators not only because of their specific power and their inherent elasticity [7] but also because of their eligibility to adapt to the principles of hierarchical structures in natural muscle tissue. DEAs are promising actuators for the development of a new generation of robotic solutions with a broad spectrum of possible applications, which may vary from intrinsically safe service robots to highly dynamical energy-autonomous mobile kinematics or bionic prostheses. Hereinafter recent findings of a research project to facilitate the transition from fundamental research to the qualification of DEAs as regular control elements in complex and compliant robot kinematics and lightweight, silent prostheses are described.

II. Aerosol Jet Printing of Dielectric Elastomer Actuators

This section describes a new additive manufacturing process for stacked DEAs with very thin layers for reduced driving voltages and improved mechanical characteristics resulting from the additive manufacturing.

A. Framework Conditions for the Manufacturing of DEAs

Like mentioned before, the functional principle of a DEA is based on a simple plate capacitor. To describe the electromechanical characteristics of a DEA in detail, aside the Maxwell stress resulting from the electric field pressure from charges on the opposing electrodes [8], other effects like electrostriction have to be considered [9]. But for a first assessment of the framework conditions for the manufacturing of stacked DEAs the simplified equation presented in [7] is a good starting point:

$$p = \varepsilon_0 \varepsilon_r \frac{U^2}{z^2} \tag{1}$$

According to (1) the achievable pressure p resulting from a DEA depends on the permittivity ε_r of the dielectric medium, on the driving voltage U and finally on the thickness z of the dielectric layer between the electrodes. Within nearly two decades of research no suitable material for the dielectric medium with a significant higher permittivity other than the commonly used ones [10] [9] has been identified. The problem is that molecular material variations or fillers raising the permittivity of elastomers often also lower their breakthrough voltage. Using higher driving voltages to gain more pressure is also undesirable in terms of dimensioning the power electronics and for safety reasons. Therefore with the remaining parameter of the layer thickness z of the dielectric medium, depicted in Fig. 2, the reduction of the distance between the electrode structures of DEAs is a viable option to improve the performance of DEAs and to reach driving voltages below one kilo volt by shrinking the thickness of the dielectric medium to values below 100 microns as proposed in [11]. However, reducing the layer thickness of the structural elements of stacked DEAs increases the requirements for an automated manufacturing process, as it must be capable of stacking numerous layers on top of each other to gain an actuator usable on a macroscopic scale, even if the size of single DEA cells is for example reduced to ten microns or lower.

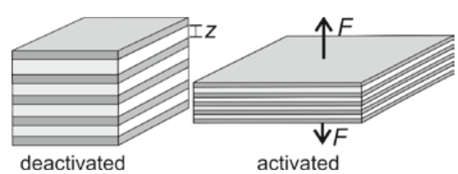

Figure 2. The contraction of an activated stacked DEA results in forces that have to be transmitted through the different layers.

Another requirement results from the contractive behavior of the unidirectional acting DEAs illustrated in Fig. 2. The generated forces have to be transmitted through the actuator. Therefore the adhesion between the different structural elements - dielectric medium and electrode - has to be good. Otherwise delamination between the electrode and the dielectric layer would occur rendering a DEA stack unusable. Aside the described adhesion there are other interdependencies between the structural elements of DEAs to be considered. As the most commonly used materials for DEAs are incompressible their contraction leads to a flow of the polymeric material and an increased area or diameter of the dielectric medium. The passive electrode structures should therefore be flexible and should show the same mechanical characteristics as the dielectric medium. Otherwise the electrodes would counteract the desired contraction and radial stress at the interface between electrode and the in-between layer would lead to a reduction of the long-term stability of a DEA. Regarding the fatigue resistance of DEAs a manufacturing process should also be capable of handling room-temperature vulcanizing two component (RTV-2) silicones as these have been proven to be more durable [12] than the likewise often used acrylic materials. Finally an automated manufacturing process for DEAs should allow for the generation of thinner electrode structures compared to the dielectric layers, as the electrodes do not contribute actively to the contraction of a DEA [13].

B. The Aerosol Jet Printing Process

The Aerosol Jet Printing Process is an additive, contactless production technique which was originally designed to print conducting paths on circuit boards. The process is based on the generation of an aerosol in a so called atomizer print-head by ultrasonic or pneumatic shearing. Afterwards the aerosol is aerodynamically focused in the printing-head nozzle into a concentrated beam. Through relative movements of a printing head, like depicted in Fig. 3, three-dimensional structures can be created on free-form substrates. The thickness of single layers can be very well fine-tuned from sub-micron to micron scales by the adjustment of the print-head velocity. Because of its pertinency to create homogeneous layers with a broad variety of materials [14] within the presented project the Aerosol Jet Printing process is investigated as a new method for the automated generation of stacked DEAs.

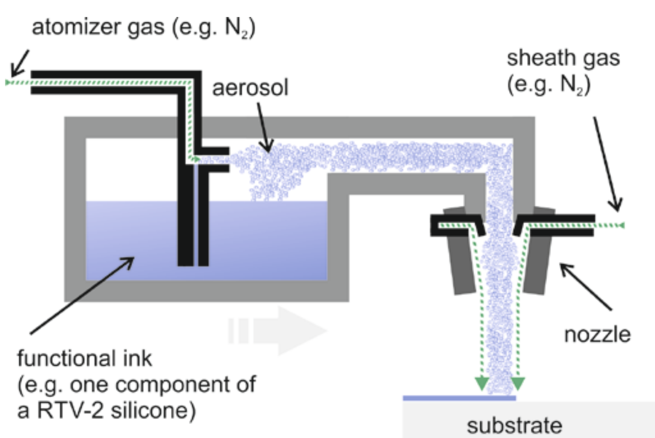

Figure 3. Simplified illustration of the Aerosol Jet Printing process.

One limitation of Aerosol Jet Printing is that it is only capable of processing inks with a viscosity up to 1000 mPas. We therefore use heated Elastosil P7670 RTV-2 silicone, which is described in many other research projects on DEAs, as it shows a viscosity of its both components A and B of 1800 mPas at room temperature. As mentioned earlier in this contribution the mechanical characteristics of DEAs in terms of inter-layer adhesion and flexibility of the electrodes are of importance. In our project we therefore investigate the printing of conductive elastomeric electrodes based on compounded RTV-2 silicones. To realize conductive RTV-2 silicones, the polymeric matrix can be filled with particles like carbon black or graphite. Those fillers need to be compounded at a weight percentage above ten percent to gain conductivity and hence significantly alter the mechanical properties of the base elastomer [15]. Different from carbon black or graphite, CNT-filled material can reach the percolation threshold only with one or two weight percent of CNTs [16]. This low ratio significantly limits the impact on the mechanical characteristics of the elastomeric base material. Within the presented project Baytubes C150P multi-wall carbon nano tubes (MWCNT) are Aerosol Jet printed between curing layers of RTV-2 silicones to realize flexible and conductive elastomer electrode layers. In the following section experimental results from the qualification of the Aerosol Jet Printing Process for the manufacturing of structural elements of DEAs are presented.

C. Experimental Results

As mentioned before both components A and B of the Elastosil P7670 silicone show a viscosity of 1800 mPas at room-temperature. By heating up the components A and B above 55 °C they get printable with the process parameters shown in Tab. I. First tests showed a stable process over two hours regarding the mass flow. The unequal parameters for both components are necessary as, despite their equal density (A: 1.01 g/cm3; B: 1.05 g/cm3), they obviously have different thermal conductivity coefficients and different mass flows when processed. With 0.13 mg/min component A showed twice the mass-flow as component B with 0.07 mg/min when both were printed with the same parameter set.

TABLE I. OVERVIEW OF CONDITIONS AND MODULATIONS FOR THE AEROSOL JET PRINTING PROCESS OF A RTV-2-SILICONE

	Temp.	**Gas flow**			**Mass flow rate**
		Sheath gas	**Exhaust gas**	**Atomizer gas**	
A	62 °C	100 cm^3/min	400 cm^3/min	1400 cm^3/min	0.13 mg/min
B	59 °C	100 cm^3/min	800 cm^3/min	2000 cm^3/min	0.14 mg/min

For the production of Elastosil P7670 both components have to be mixed at a 1:1 ratio. As the used elastomer has a curing-time of just a few minutes both components cannot be mixed in the ink reservoir of the print-head because the formation of silicone would destroy the aerosol generating parts of the print-head. Instead for a first evaluation of the process thin layers of component A and B are printed sequentially with the parameters shown above. An inspection of the printed layers with a 3D Laser-Scan-Microscope KEYENCE VK-9700 showed the topological profiles depicted in Fig. 4.

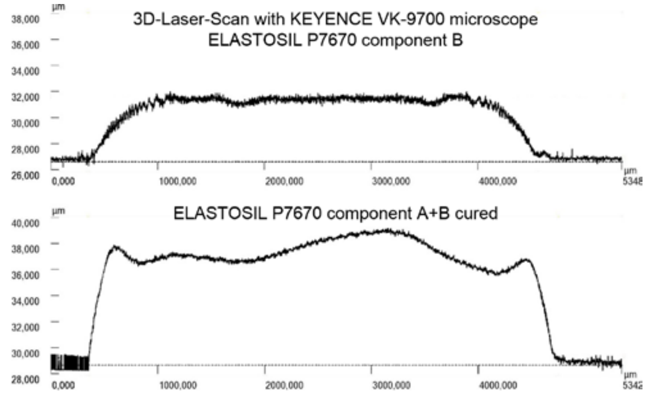

Figure 4. Topological profiles of Aerosol Jet printed layers of component B (top) and a cured elastomeric layer (bottom).

The profile of a printed layer of component B depicted in Fig. 4 (top) shows the eligibility of the Aerosol Jet Printing process for generating homogenous layers of silicone inks with a relatively high viscosity. The variance in layer thickness of four microns over the range of five millimeters in the second profile of the cured Elastosil results from the sequential printing of both components. The sheath gas of the second run deforms the uncured first layer. To gain stable geometric parameters, allowing the reproducible stacking of hundreds or even thousands of layers a deformation of yet uncured partial layers has to be ruled out. For the one-step processing of curing ready elastomer structures the printing systems is therefore actually being developed further to a system comparable to the one described in [17] where two aerosols are generated in two separate atomizers and are then combined in the printing nozzle. As the beam in the printing nozzle is coated in sheath gas the already mentioned premature curing of both components is no longer a problem as the materials do not get in contact with mechanical parts from the point where they first get in contact with each other. In parallel the printing system is enhanced by a PID-controlled heating system and an atomizer component with six aerosol generating cavities. With this improved system at 82 °C and a sheath gas flow of 300 cm3/min, an exhaust gas flow of 3900 cm3/min and an atomizer gas flow of 4400 cm3/min 0.26 mg/min of component A are printable in first tests in a stable process over five hours.

The above presented results show the eligibility of the Aerosol Jet Printing process to generate very thin dielectric layers. To form electrode structures for DEAs one option is to compound MWCNT into the polymer matrix as described above. Mixing CNTs into one component of the elastomer by commonly used milling processes unfortunately leads to materials with a viscosity far above suitable values for the Aerosol Jet process. Therefore an aqueous solvent of Baytubes P150C is produced in an ultrasonic bath and afterwards printed onto a curing silicone layer. With this method a conductive layer with a rather inhomogeneous resistance of several hundred kilo-ohms can be processed. To prevent the CNTs in the solvent from agglomeration, in a next step an ultrasonic sonotrode will be used to generate the aerosol in the atomizer. This should lead to electrode layers with better dispersed CNTs and therefore better conductivity. As the next printing system will be extended to mix two components of the Elastosil the parallel generation of a third CNT aerosol in a separate print-head would be one option for the dynamic switching between compounded and uncompounded layers. Several test showed that the application of new silicone layers on top of layers with an ongoing curing process do not reduce the tensile strength significantly. Therefore as another option CNTs could be printed on top of a curing elastomer layer sequentially previous to the processing of the next dielectric layer. This method would reduce the complexity of the printing system and would inherently result in very thin electrode layers.

III. Lightweight Power Electronics for Dielectric Elastomer Actuators

The presented findings regarding the new printing process indicate that there is a good chance for the automated manufacturing of stacked DEAs with very low layer thicknesses of ten microns and below. But even then, with breakthrough voltages of 30 to 46 V/µm for Elastosil P7670 [12] a DEA with a thickness of its dielectric medium of ten microns will be operated at maximum voltages of 300 to 460 volts. This results in the necessity of using high voltage power electronics. Nowadays DC converters are used to drive DEAs. These converters are built up of toroidal transformers or at least a high number of electronic components. The weight of available high voltage power sources, for instance for ten watts, ranges between 45 g and 140 g [18–20]. As indicated above one advantage of DEAs is their low weight due to the low density of the used elastomeric materials. With the good suitability of DEAs for partitioning, the composition of complex kinematics with independently working actuators realizing advanced functionality seems possible. However each actuator needs its own individual control voltage to cause an individual contraction. Thinking for instance of a complex hand prosthesis with dozens of DEAs incorporating the same amount of heavy high power sources illustrates the problem of negative influence of actual power electronics on the good specific power of DEAs. Therefore aside manufacturing the presented project also focuses on the development of a new set of lightweight power electronics aiming at the improvement of the overall specific power of DEA driven kinematic systems.

A. Controlling Dielectric Elastomer Actuators by Pulse Width Modulation

As DEAs are electromechanical systems with inertia, derived from principles to control classical electric drives, pulse width modulation (PWM) can be an alternative option for controlling the contraction of artificial muscles. Using PWM permits the substitution of high-mass DC converters for each actuator by single lightweight semiconductor elements. In such a setup one single high voltage source can supply many DEAs by providing one system wide central high voltage. The semiconductive elements for the individual DEAs alter this fixed high voltage by changing the ratio of switching over a fixed period at high frequencies and thereby change the effective voltage and the resulting contraction of the capacitive DEA. Aside the advantages in terms of weight per DEA this approach allows better dimensioning of the power supply for a complex kinematic system. As in most cases not all actuators or artificial muscles contract at the same time, the central high voltage source can be smaller in terms of power than the sum of the power consumption of all actuators. PWM may also allow sensory analysis of active DEAs as in future works the PWM signal could be used as a reference for measuring the actual capacity and thereby deformation of a DEA. In contrast to electrical motors DEAs need high voltage for actuation. So a new lightweight power electronic configuration for switching high voltage has to be developed. The feasibility of using PWM for controlling DEAs is already shown in [21] by using the optocoupler OC100HG for switching high voltage. In the presented project different controlling configurations are investigated for generating a pulse width modulated high voltage signal. Aside the described optocoupler insulated-gate bipolar transistors (IGBT) and metal-oxide-semiconductor field-effect transistors (MOSFET) are tested regarding their accuracy in following rectangular signals at varying frequencies and are compared by their dynamic switching characteristics and weight. As a framework for investigations on first DEA demonstrators, the PWM controlling circuits are designed for a maximum switching voltage of four kilo volts. All tests are conducted at 3.5 kilo volts.

Since the use of optocouplers for PWM controlling of DEAs was shown in [21], the first switching element which is investigated is an optocoupler OC100HG. This type of switching element has the main advantage of an already existing galvanic isolation between the low voltage controlling signal and the high voltage source. With a weight of about seven grams it is a lightweight device allowing a simple integration into controlling circuits and therefore permits a compact system setup. The optocoupler OC100HG consists of two LEDs and one photodiode. It can withstand high voltages up to ten kilo volts DC. For the supplied voltage of 3.5 kilo volts a maximum frequency of about 415 hertz is identified. At this frequency the voltage is fully switched on and off, however the rectangular signal transforms to the shape of a saw tooth signal. Above this frequency the signal degenerates and the maximum of the supplied voltage signal is not reached anymore. To realize a switching of above 3.5 kilo volts either the frequency has to be lowered or the control signal for the LEDs has to be amplified. This would lead to an operation of the optocouplers' LEDs outside their technical specification. The main disadvantage of the OC100HG is the low current it can withstand. Given a stacked DEA with 1000 single cells, with some simplifications it can be estimated that such actuator with an electrode area of one square centimeter and a layer thickness of 50 microns will show a capacity in the range of 50 nano farads. Therefore higher charging currents are expected than the specified 300 micro ampere. Optocouplers like OC100HG are therefore not well suited to drive stacked DEAs with PWM. Alternatives for higher currents at high voltage switching with high frequencies are IGBTs and MOSFETs.

With the IXGF30N400 of IXYS an IGBT is investigated. With a weight of five grams this IGBT is a lightweight device slightly lighter than the mentioned optocoupler. Its integration is simple and the maximum voltage of this bipolar transistor is four kilo volts. For switching the IGBT a voltage of 15 volts between gate and emitter has to be applied. Thus an external power supply for a gate driver is necessary. Additionally a load of one mega ohm is implemented to allow higher currents, which results in a faster rising of the high voltage signal. With this setup a maximum frequency of 630 hertz can be reached, where the rising time of the rectangular high voltage signal is 20 percent of one cycle. The third configuration that is investigated in the first phase of the project uses MOSFETs of the type BUZ50A provided by Siemens with a weight of 1.9 grams. Because one single MOSFET of this type only can withstand one kilo volts, in a first test setup four MOSFETs are used to achieve the specified four kilo volts. As in the configuration with the IGBT a gate driver with an external power supply of 15 volts and a gate resistor for each transistor are needed. Also a load of one mega ohm is used. Compared to the other options the MOSFET configuration is the most complex circuit. However a maximum switching frequency in the range of kilo hertz can be realized, while the rectangular structure of the PWM signal is still almost conserved. For example at a frequency of 2.49 kilo hertz 90 percent of the full supplied high voltage is reached after 15 percent of one cycle as depicted in Fig. 5. The noisy signal appearing at the gate of the MOSFETs is expected to be an unintended feedback of the power source because this source is not designed to be able to switch in the range of kilo hertz. However in this experiment the noise did not have any negative effects.

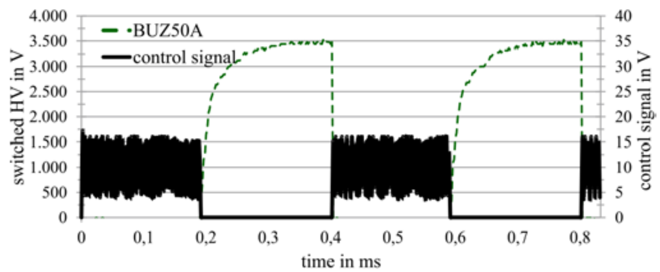

Figure 5. Control signal and switched high voltage signal with a frequency of 2.49 kHz by using a complex circuit of MOSFETs of type BUZ50A.

Based on the comparison which in detail is described in [22] the MOSFET setup shows the best results. To reduce the complexity for further setups like depicted in Fig. 6 the newly commercially available n-channel MOSFET of type IXTA-T02N450HV is used. It can be used as a single semiconductor switching device of voltages up to four kilo volts and has a weight of 2.5 grams.

B. *Demonstrating Pulse Width Modulation of Dielectric Elastomer Actuators*

To demonstrate the feasibility of the pulse width modulation concept a test setup is realized. On one circuit board all components for PWM controlling multiple DEAs are combined.

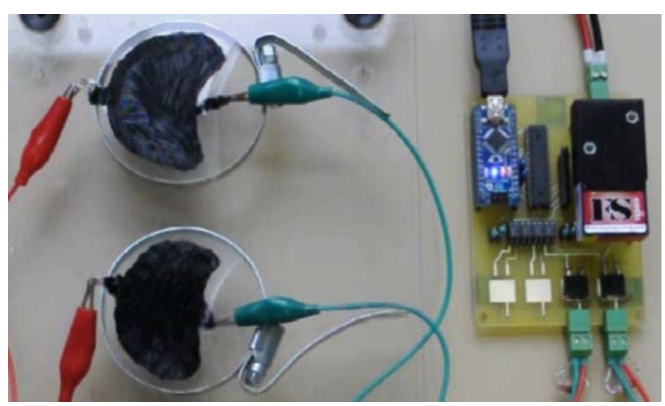

Figure 6. Test setup to control two DEAs with one central DC converter by pulse width modulation and MOSFETs.

As power source a DC converter of the type EMCO FS-40-15 with ten watts output and a maximum voltage of four kilo volts is used. The PWM signals are generated by a Texas Instruments TLC5940 chip. To interface the power electronics with the used software infrastructure - the Robot Operating System (ROS) - an Arduino Nano board is used. As high voltage switching elements the above mentioned MOSFETs of the type IXTA-T02N450HV are applied. In the presented setup a maximum of 16 individual DEAs can be controlled. In the setup depicted in Fig. 6 two MOSFETs are installed to control two DEAs. With the test system the two DEAs show their normal very fast and responsive contraction behavior. With the test system the two DEAs show their normal very fast and responsive contraction behavior. Up to our knowledge this setup is the first described working demonstrator for driving and controlling multiple DEAs with one high voltage source by PWM based on MOSFETs.

IV. Conclusion

The presented paper outlines the necessity for a new energy efficient, lightweight and flexible type of actuation technology for robotics and prostheses. DEAs are a promising technology that needs to be transferred from fundamental material science to the application as regular control elements in complex and compliant robot kinematics or new generation of biomimetic prostheses. Recent findings of two of the main research tasks of the presented ongoing five-year project indicate that enhancements regarding automated manufacturing of DEAs and lightweight power electronics are possible. The Aerosol Jet Printing has a great potential for the automated printing of stacked DEAs with unprecedented mechanical and structural features. Further work has to be conducted to build up Aerosol Jet Printing systems for the parallel generation of all components needed to create functional DEAs continuously. The PWM driving principle is a feasible approach to control DEAs with lightweight semiconductor elements. Here the next step is an extensive review on the implications of this approach in terms of efficiency in energy transmission.

References

[1] S. Seok, A. Wang, D. Otten, and S. Kim, “Actuator design for high force proprioceptive control in fast legged locomotion,” in 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2012), pp. 1970–1975.

[2] D. G. Caldwell, G. A. Medrano-Cerda, and M. Goodwin, “Control of pneumatic muscle actuators,” IEEE Control Syst. Mag, vol. 15, no. 1, pp. 40–48, 1995.

[3] Raibert, M, Blankespoor, K, Nelson, G, Playter, R, “Bigdog, the rough-terrain quadruped robot,” in Proceedings of the 17th World Congress of the International Federation of Automatic Control, 2008.

[4] E. Asmussen and F. Bonde-Petersen, “Apparent Efficiency and Storage of Elastic Energy in Human Muscles during Exercise,” Acta Physiologica Scandinavica, vol. 92, no. 4, pp. 537–545, 1974.

[5] Yoshihito Osada, Ed, HANDBOOK ON BIOMIMETICS. Tokyo: NTS Inc, 2000.

[6] R. Shankar, T. K. Ghosh, and R. J. Spontak, “Dielectric elastomers as next-generation polymeric actuators,” Soft Matter, vol. 3, no. 9, p. 1116, 2007.

[7] R. E. Pelrine, R. D. Kornbluh, and J. P. Joseph, “Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation,” Sensors and Actuators A: Physical, vol. 64, no. 1, pp. 77–85, 1998.

[8] R. Pelrine, “High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%,” Science, vol. 287, no. 5454, pp. 836–839, 2000.

[9] P. Brochu and Q. Pei, Advances in Dielectric Elastomers for Actuators and Artificial Muscles. Available: http://onlinelibrary.wiley.com/store/10.1002/marc.200900425/asset/10_ftp.pdf?v=1&t=h9icjbgo&s=70c076f7333f96b9a197ac0cb2d71bbb06c9b569 (2012, Nov. 14).

[10] R. Pelrine, R. Kornbluh, J. Joseph, R. Heydt, Q. Pei, and S. Chiba, “High-field deformation of elastomeric dielectrics for actuators,” Materials Science and Engineering: C, vol. 11, no. 2, pp. 89–100, 2000.

[11] F. Carpi, S. Bauer, and D. d. Rossi, “Stretching Dielectric Elastomer Performance,” Science, vol. 330, no. 6012, pp. 1759–1761, 2010.

[12] P. Lotz, “Dielektrische Elastomerstapelaktoren für ein peristaltisches Fluidfördersystem,” Dissertation, TU Darmstadt, Darmstadt, 2010.

[13] M. Matysek, “Dielektrische Elastomeraktoren in Multilayer-Technologie für taktile Displays,” Dissertation, TU Darmstadt, 2010.

[14] C. Goth, S. Putzo, and J. Franke, “Aerosol Jet Printing on Rapid Prototyping Materials for Fine Pitch Electronic Applications,” in IEEE 61st Electronic Components and Technology Conference (ECTC), 2011: May 31, 2011 - June 3, 2011, Lake Buena Vista, Florida, USA; 2011 proceedings, Piscataway, NJ: IEEE, 2011, pp. 1211–1216, 2011.

[15] L. Bokobza, “Multiwall carbon nanotube elastomeric composites: A review,” Polymer, vol. 48, no. 17, pp. 4907–4920, 2007.

[16] J. Fritzsche, H. Lorenz, and M. Klüppel, “CNT Based Elastomer-Hybrid-Nanocomposites with Promising Mechanical and Electrical Properties,” Macromol. Mater. Eng, vol. 294, no. 9, pp. 551–560, 2009.

[17] A. M. Sukeshini, T. Jenkins, P. Gardner, R. M. Miller, and T. L. Reitz, “Investigation of Aerosol Jet Deposition Parameters for Printing SOFC Layers,” in Proceedings of the ASME 2010 Eighth International Fuel Cell Science, Engineering and Technology Conference: FuelCell2010: ASME, 2010.

[18] EMCO High Voltage Corporation, Datasheet FS SERIES. Available: www.emcohighvoltage.com/pdfs/fsseries.pdf.

[19] Spellmann HIGH VOLTAGE ELECTRONICS CORPORATION, Instruction Manual - UM SERIES: 118097-001 Rev A.

[20] UltraVolt Inc, Datasheet: D Series high voltage power supplies. Available: http://www.ultravolt.com/uv_docs/DSeries.pdf.

[21] T. A. Gisby, E. P. Calius, S. Xie, and I. A. Anderson, “An adaptive control method for dielectric elastomer devices,” in Proceedings of SPIE: SPIE 2008, pp. 6927 - 69271C, 2008.

[22] M. Landgraf, M. Hedges, S. Reitelshöfer, and J. Franke, “Aerosol Jet Printing and Lightweight Power Electronics for Dielectric Elastomer Actuators,” in 3rd International Electric Drives Production Conference: Proceedings, Piscataway, NJ: IEEE Service Center, 2013.