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MULTIPHYSICS SIMULATION AND CONCEPT OF AN ELECTROMAGNETICALLY CONTROL VOLUMETRIC PIXEL AS A STEP TOWARDS A SHAPE MORPHING COMPOSITE

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Abstract: Constant development of robotics forces scientists and engineers to work on robots that are more visually and rigidly compatible with the environment around us. To make this possible, new flexible structures are necessary that enable programmatic shape change. To meet this need, in this work we present the concept and modelling methodology of a new structure enabling shape change using electromagnetic forces produced in liquid metal conductor and its stiffening using a granular jamming mechanism. This work presents the structure concept, the description of modelling methodology and empirical validation including the magnetitic field, scanned by magnetic field camera, and displacement distribution.

Key words: Soft robotics, Soft actuator, Shape morphing composite, Programmable structures, Multiphysics simulation

1. INTRODUCTION

As robotics becomes more and more popular, to a certain degree, it forced robot to become more compatible with the current environment. To meet these challenges an entire branch of science called soft robotics was created and is being developed. Main areas of research in the field of soft robotics relates to the development of new structures dedicated for specific tasks, such as swimming [1], flying or walking [2] and moving in the more natural manner. It is also possible to find many different soft robotics applications as a gripper [3] which can hold various objects with different shapes, sizes and weights. Examples of soft robotics being used not only in classical robotics applications but also in other fields of studies. Similar structure we can find in medical devices e.g. touchless human-computer interaction using magnetic skin [4] which has the potential of reducing the infections associated with check-ups and surgeries.

Soft robotics structures usually are built of common materials like silicone rubber compounds and other polymers. In this context, a lack of innovative solutions, which could increase application potential and guarantee better compatibility of a robot with its surroundings is observed. Development of alternative solutions, such as new classes of structures, i.e., new smart material or programmable structures, could accelerate development of the field. Authors from all over the world are trying to work on it. Soft robotics is an emerging field of science and technology with a lot of potential for its advancements.

Various types of actuators and stiffness changing mechanism are used in soft robotics. Previous works have suggested various actuators inputs like temperature [5], light [6], pressure [7, 8] or magnetic field [9]. Additionally, electroactive polymers (EAP) can be used as an actuator which can predict the whole bending behaviour of the EAP actuator dynamically [10]. Even though the above-mentioned solutions can be considered as good advancement in the field of soft robotics, they bring along some disadvantages, for example, pneumatic actuators have longer reaction time of approximately 0.5s [11]. Additionally, some of them require dangerous high activation voltage ranging between thousands of volts [12] which puts forward threat to humans.

To address the above-mentioned problems, we have proposed a structure that allows for rapid shape change with the low voltage using the Lorentz force generated in liquid metal conductor [13]. Additionally, the structure we have proposed can be stiffened after deformation using a granular jamming mechanism which increases its performance. The above-mentioned structure is an extension of our previous work [8] by adding a double layer of coils filled with liquid metal, which made it possible to increase the structure performance. We also proposed a different shape of the coils, thanks to which we can obtain more complex shapes. Additionally, we proposed the new modelling methods that includes the multiphysics simulations. In this work, we will focus on presenting the concept and characterization of a single volumetric pixel (voxel) structure, which, when combined in multi-voxel composite, can be morph into many different shapes [14, 15, 16, 17].

2. GENERAL CONCEPT

The proposed structure, which is shown in Fig. 1 and 2, takes advantage of a combination of two phenomena, development of the

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Lorentz force in a liquid metal conductor (like gallium or EGaIn) and granular jamming [23]. The structure consists of a granular core, made of coffee grains, and 4 hexagonal coils in pairs. The coils are fabricated by generating the microchannels in silicone rubber ecoflex 0020 (Smooth-On, Inc.) and then filling them with gallium. Since the silicone rubber has the Young Modulus of about 0.055 MPa, and the tension/ bending resistant of liquid metal is almost equal to 0, it allows the structure to be very flexible. It this solution, the coils are in series connection with each other so that the effect of the Lorentz force is doubled. Therefore, when the current carrying sample is placed in a magnetic field, a force is induced which allow the structure to bend. Furthermore, due to the presence of the granular core, filled with ground coffee, it is possible to freeze the shape by vacuum and granular jamming effect [18]. The mentioned phenomenon may also work with other granulates, but due to its very good mechanical properties, we chose coffee [19].

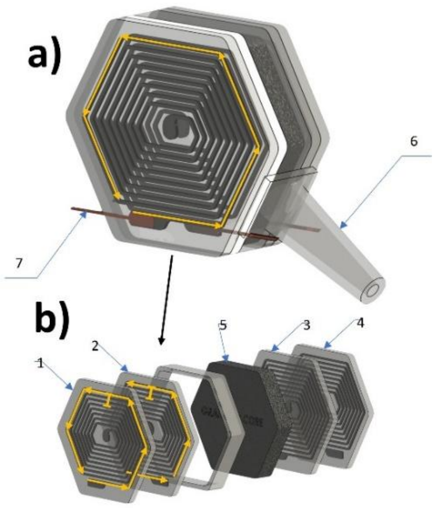

Fig. 1. A shape transforming actuator concept. As shown in the figure a and b, the structure consists of four coils, two on each side (1, 2 and 3, 4) connected in series comprising a granular core in between (5). Additionally, the sample is equipped with vacuum (6) and electrical (7) inputs

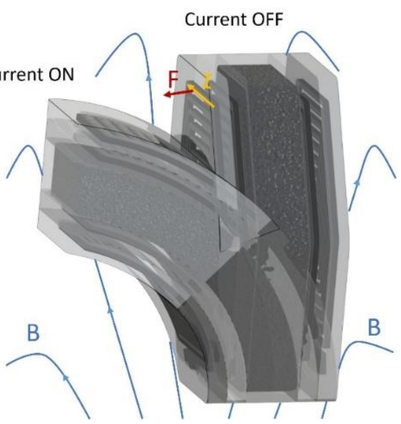

Fig. 2. This diagram shows the Lorentz force in action which causes the deformation of the sample. When the sample is placed in the magnetic field from a cylindrical permanent magnet, and current is supplied, the sample undergoes morphing due to the Lorentz force. This morphed shape can be frozen because of the presence of the granular core. B- magnetic field, I- current, F- resulting force

3. MULTIPHYSICS SIMULATION

The multiphysics simulations were performed in LS-DYNA environment using the coupling of mechanical and electromagnetic solvers (EM). Model, which is shown in Fig. 3, includes the cylindrical magnets (120 mm x 40 mm) modelled by solid elements that are roughly 5 mm in size and the constant coercive equal to 900 $\frac{kA}{m}$. The sample, which represents the single voxel, was modelled by solid elements with the size of about 1 mm. The silicone was modelled by linear elastic material model with Young Modulus 0.055 MPa. This is a certain simplification, but research shows that for small deformations, lower than 30%, silicone shows linear behaviour [20]. This approach was also used in the different papers [23]. The granular core was created using user-defined elasto-plastic material model described precisely in the work [21], which is an extension of the von Mises with a different plasticity radius for tension and compression. Model includes the influence of vacuum pressure on the mechanical behaviour. The material's constants for coffee grains were taken from the paper [21]. The boundary conditions are similar to the empirical tests, the lowest surface is constrained, and the current applied to the coils increases linearly from 0 to 5 A. The magnet poles are analogous to test conditions. Using the prepared model, the EM solver calculates the magnetic field distribution based on Maxwell's equations and then by the equation, $\vec{F} = \vec{j}\ x\ \vec{B}$ (F- Lorentz force, j-current density, B-magnetic field) the Lorentz force in gallium conductor. Since the integration timestep is the same for electromagnetic (EM) and mechanical solver after these calculations, the mechanical solver is able to calculate the sample deformation. We performed calculation and in the next chapters, we have compared the magnetic field distribution and sample displacement with empirical results.

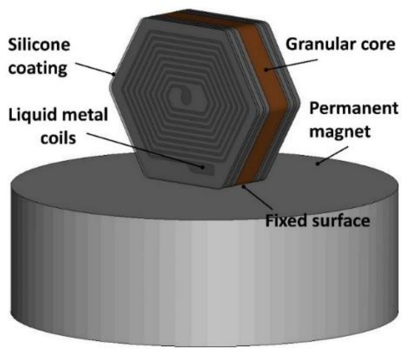

Fig. 3. Rendering LS-DYNA numerical model for multiphysics simulations containing general description of major functional parts of the system under study

4. SAMPLE FABRICATION

To check the proposed modelling methodology, it was necessary to prepare a test sample. The initial step in manufacturing it was to design in Solidworks CAD various parts which were later fabricated using Reise 3D pro2 plus printer. For the molds fabrication the Polylactic acid (PLA) was used. The next step was to fill the molds with silicone rubber ecoflex 00-20 (smooth-on) [22]. Each of the silicone molds was cured in classical laboratory dryer with 50^oC, and the curing time was ≈ 25 min. Later, the layers were separated from the molds and attached with one electrode per

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layer. To complete the circuit, two layers were sticked together such that current carrying coils are in series with each other. Samples from negative molds were glued together thanks to a thin layer created with a spin-coater. The next step was to fill the coils with liquid gallium by injecting a syringe to one end of the coil and pushing the preheated liquid metal through both the layers of voxels. Towards the end of synthesis of the sample, a granular core was incorporated in the assembly which was filled with fine coffee grains. In the final step the housing and pneumatic input were added. The manufacturing process is depicted in Fig. 4.

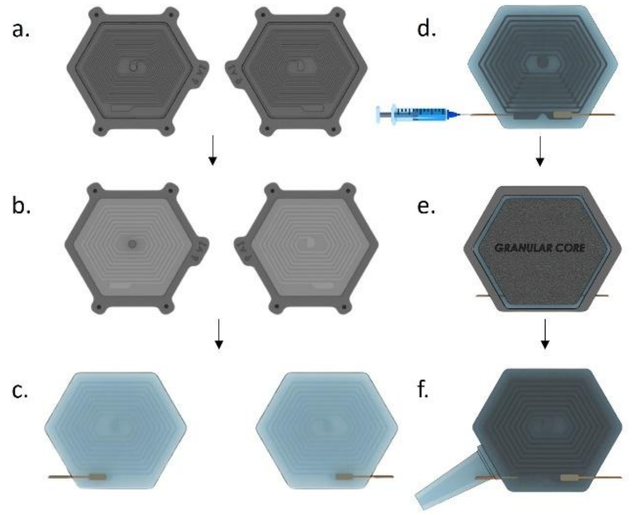

Fig. 4. Composite preparation scheme: a) FDM printed coil moulds, b) coil moulds were poured in with silicone rubber, c) silicone rubber mouldings with elastic coils were inserted with electrodes, d) elastic coil moulding comprised of two glued together layers of silicon rubber, injected with liquid gallium, e) integration of the elastic liquid metal coil with granular core pocket, f) complete sample

5. EMPERICAL TESTS AND MODEL VALIDATION

5.1. Magnetic field

The distribution of the magnetic field produced by a cylindrical magnet was measured with the MagCam magnetic field scanner equipped with minicube 3D camera. This sensor, thanks to the matrix of more than 16000 hall sensors, allows to measure the magnetic field with the high resolution about 0.1 mm. All individual sensor allows to measure the 3 components of magnetic field (Bx, By, Bz) and present a graph which magnetic field distribution of the entire specified range. We scanned the magnetic field in volume 80 mm x 80 mm x 56 mm what is visualized in Fig. 5c, d. The measurement with the Magcam was performed 3 times to get the most accurate data and compatible data. The magnetic field distribution recorded by Magcam scanning and simulation is shown in Fig. 5. Despite the fact that we scanned the entire volume, the results were compared for two surfaces 50.5 and 20.5 mm above the magnet surface which is visualized in Fig. 5a and Fig. 5b respectively. As we can see the general distribution is similar for both test and simulation. The magnetic field is greater at the lower position in the centre of the sample, at point A, and is equal to 0.23 T for both test and simulation. At point B and C the values are 0.19 T. In line with theoretical predictions, the magnetic field decreases with distance from the source. At the higher position (55.5 mm above the magnet surface) magnetic field is equal 0.113 T, 0.087 T and 0.084 in point A, B and C respectively. In this case the simulation returns slightly different results. In the centre we can see 0.112 T and on the sides 0.085 T. The overall distribution at this position is comparable, and the maximum error does not exceed 3%.

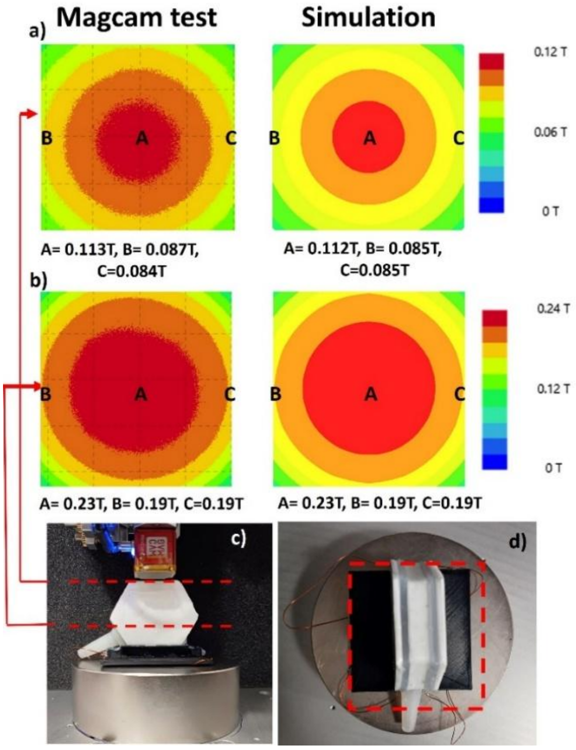

Fig. 5. Empirical tests and simulation of magnetic field distribution: a) and b) corresponding the area presented in c) and d) respectively

5.2. Deformation distribution

Deformation distribution, which is shown in Fig. 6a, was recorded by a camera with 50MPixels and a laser sensor OMRON ZX 1-LD300A81 which was able to measure the sample displacement. The measurement point was placed in the sample's centre line, 45 mm above the magnet area. The tests were performed for 5 vacuum pressure values (0, 0.02, 0.04, 0.06, 0.08, 0.1MPa). Each test was repeated 3 times. Fig. 6a presents the sample deformations for the different values of current for the atmospheric pressure (upper row) and the vacuum pressure 0.1MPa (lower row). Fig. 6b presents the displacement in function of current for the highest and lowest vacuum pressure for empirical research as well as for simulations. Additionally, Fig. 6c shows the maximum sample deflection in function of vacuum pressure. It can be seen that the maximum deflection for the current 5A is equal to 10.4 mm for the atmospheric pressure. It can be seen that the sample deformation for the maximum vacuum pressure is almost 10 times lower. Generally, we can find the strongly nonlinear characteristic between maximum deflection and vacuum pressure. Fig. 6b shows really good correlation between the simulation and experiments, usually lower than 5% in the whole current range.

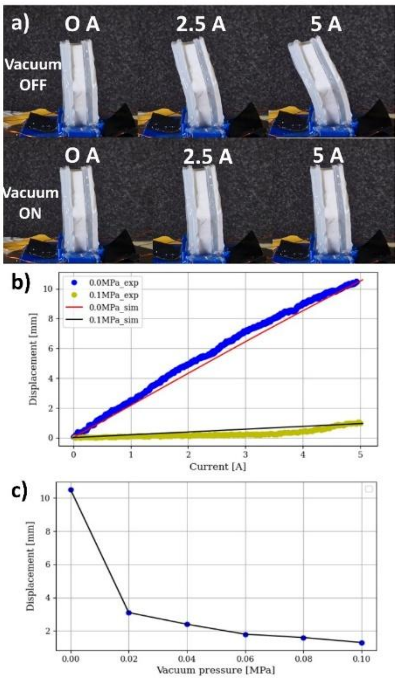

Fig. 6. Sample deformation modes a), composite displacement in function of charge current b), maximum displacement in function of vacuum pressure c)

5.3. Future morphing composite

Proposed voxel which showed its good properties by being combined into multi-voxel structure could create the deformable composite which could be able to deform in multiple shapes. It is shown as a concept in Fig. 7 where initially flat structure (Fig. 7a) can deform in shape 1 (Fig. 7b) or shape 2 (Fig. 7c). Thanks to granular jamming effect structure could be also frozen after the deformation and therefore would have the ability to bear loads.

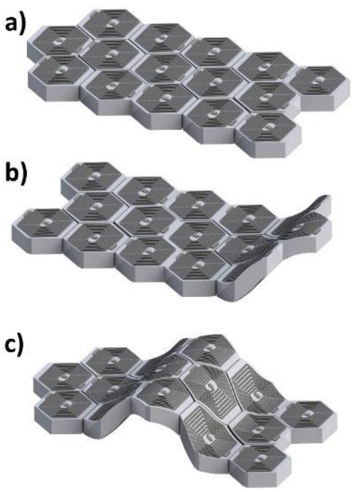

Fig. 7. Concept of a morphable composite material comprised of electromagnetically controlled volumetric pixels (voxels). a) a flat plate comprised of voxel with independent control b), c) deformation modes of the composite induced by the Lorentz force arising when charge current is applied selectively to the one most outer rows of voxels and to the center voxels respectively, while the whole structure is placed in the vicinity of external magnetic field

6. CONCLUSION

This work shows the concept of the new volumetric pixel (voxel) structure able of changing its shape under Lorentz force generated in liquid metal conductor and retaining it by employing a granular jamming mechanism. This concept is an extension of our previous work presented in paper [23] where we proposed the e-morph actuator. The structure presented in this work consists of double-layered coils, which increase the number of turns and thus the value of the Lorenz force by the factor of two, while ensuring much better compactness of the structure because both electrical current leads are located at the bottom of the structure. This is an undoubted advantage of this structure. Compared to our previous works, here we proposed a hexagonal shape of the coils, not a rectangular one, thanks to which we can obtain more complex deformation shapes. The work showed that the maximum deformation of the structure is 10.4 mm and the stiffness of the structure after applying negative pressure can increase almost tenfold.

In this work we also presented innovative methods for modeling and empirical measurement for the proposed structure. Usually for similar structures, Scientists calculate the Lorentz forces in separate solvers or by analytical methods and then just applied them as a point or linear forces in mechanical solvers. Thanks to our approach and the use of multiphysics simulations, we can obtain a very good correlation with the experiment even in a strongly non-homogeneous magnetic field. The general error in magnetic field distribution in comparison with Magcam measurement was lower that 3%, but the maximum error for deformation was lower than 5%. This proves that our method works correctly, and we can use it to further develop the structure.

The proposed voxel structure can be used in the future e.g., as a building block for a morphable composite material in which its shape can be controlled by selectively generating the Lorenz force locally, for particular set of pixels, as shown in Fig. 7, enabling different modes of the structure. Such a structure would require an extensive development process, but we see huge potential for it.

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