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ABSTRACT
The aim of this paper is an investigation of the additive manufacturing for the realization of a low-cost sensor and its application for force measurements. The proposed sensor consists of an inductor, an elastic spacer and a smooth ferrite plate. The inductor is fabricated by 3D printing technology. The spacer is realized in the form of an elastic mesh which was realized by employing 3D printing technology for mold fabrication in which is poured liquid silicone elastomer Ecoflex. The commercially available ferrite material is used as a magnetic part of the sensor. The dimensions of the developed sensor with casing are 25.2 x 29.3 x 7.7 mm

I. INTRODUCTION
Different kinds of sensors, technologies and sensing mechanism for monitoring and measuring the force in various applications are realised: fiber-optic sensor for biomechanical measurement,\textsuperscript{1} the 3D printed force sensor fabricated by a digital light processing and high temperature resin, and an inkjet-printed strain gauge made from poly(3,4-ethylenedioxythiophene) polystyrene sulfonate ink,\textsuperscript{2} a flexible polymer tactile sensor with embedded multiple capacitors for normal and shear force measurement.\textsuperscript{3}

Ferrite materials have been used for the realization of different kind of magnetic sensors. Numerous sensors consist of various types and forms of smooth ferrites which are fabricated for specific sensing applications. In Ref. 4 sensors for displacement measurements are developed using the heterogeneous integration process of traditional PCB (Printed circuit board) and LTCC (Low temperature co-fired) technology with a flexible polyimide foil as membrane and a ferrite disk attached to it. The self-resonant frequency modulation of an integrated coil caused by the relative displacement of a ferrite core is used for the fabrication of passive force sensor.\textsuperscript{4}

Recent advances in additive manufacturing are very promising for the fabrication of innovative and high-performance sensors. Additive technology opens new possibilities for the realization of different kinds of sensors with enhanced features: force sensor based on capacitive sensing mechanism\textsuperscript{5} or flexible piezoresistive force sensor based on micro-pyramid arrays.\textsuperscript{6}

A large number of innovative sensors demonstrated very good performances of silicone rubber Ecoflex for realization of various sensors: skin-mountable and super-stretchable strain sensors,\textsuperscript{7} flexible piezocapacitive sensors with wrinkled microstructures produced by a flexible Ecoflex film,\textsuperscript{8} a highly deformable soft three-axis load cell,\textsuperscript{9} inductive sensor for displacement measurements with ferrite flaky fillers embedded in a stretchable membrane.\textsuperscript{10}

In this paper, a new simple inductive sensor for force measurement is presented. Design, the manufacturing process and experimental characterization of the force sensor prototype are presented. The working principle of the sensor is based on the variation of the inductance caused by distance changes of smooth ferrite close to the inductor. After a brief introduction, in Section II design of the sensor is described. In Section III the process of sensor’s fabrication is presented. Section IV shows the experimental setup for the characterization of the fabricated sensor and obtained measurement results. Finally, Section V presents the conclusion of the paper and obtained results.
II. DESIGN AND FABRICATION OF THE SENSOR

The proposed sensor consists of a casing, an inductor, a smooth plate of ferrite and a layer of elastomer, as it is presented in Fig. 1a.

A. Fabrication of the inductor and used ferrite

The coil of the inductor is designed in the form of a rectangular spiral. The top view and cross section view of the designed inductor are presented in Fig. 1b. The substrate of the inductor is designed in the form of a flat plate (outer dimension of 25 x 21 x 1.2 mm$^3$) with a channel in the shape of a spiral with 8 turns. The width of the designed channel is 600 μm and the depth is 600 μm. The spacing between the turns of the channel is 600 μm. The substrate is fabricated using a 3D printer nano3Dprint$^{12}$ and PLA (polylactic acid) filament.$^{13}$ After the fabrication of the substrate, the channel is filled with a silver paste and wire contacts are added.

Commercially available smooth ferrite used in Ref. 14 completely covers the surface of a designed inductor, so its outer dimensions are 21 x 25 mm$^2$. The thickness of the used ferrite is 3.8 mm.

B. Fabrication of the spacer

Silicone rubber Ecoflex$^{15}$ is used for the fabrication of the sensor’s elastomer. A model of the mold is designed and printed using a 3D printer and PLA filament to obtain the desired shape of the elastomer. The mold is in the rectangular shape of external
FIG. 4. The photograph of the measurement setup.

FIG. 5. a) The frequency dependence of the inductance for different applied forces, b) the inductance change versus applied force.
dimensions of 21 x 25 mm² and a thickness of 1.5 mm. In the mold are designed columns of 16 square-shaped bars with dimensions of 3.25 x 3.25 mm² (Fig. 2). Two equal liquid parts of Ecoflex (vol. 1+1 ml) are mixed and poured into the 3D printed mold. The liquid silicone in the mold is cured under room temperature for 4 hours. After that, the silicone elastomer in the shape of a matrix is taken out of the mold.

C. Fabrication of the housing and packing of the sensor

The casing of the sensor is made to hold all parts of the sensor together. The model of the casing is a rectangular plate (dimensions of 25.2 x 29.3 x 1.2 mm³), with 4 guiding in the corners (inner height of 6.5 mm), Fig. 3a. The casing is fabricated using a 3D printer of PLA filament. All fabricated parts of the sensor (the inductor, the elastomer, and the ferrite) are stacked together and inserted into the casing (Fig. 3b,c). The pins in the corners fix and hold all the sensor’s components together and prevent the sensor’s parts from moving in the x-y plane.

III. CHARACTERIZATION OF THE SENSOR

The characterization of the developed sensor is done by employing Impedance Analyser HP4194A and in house developed force con in the mold is cured under room temperature for 4 hours. After that, the silicone elastomer is taken out of the mold. The pin in the corners fix and hold all the sensor’s components together and prevent the sensor’s parts from moving in the x-y plane.

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The measurements are done in the frequency range from 19 MHz to 20 MHz for the forces up to 2 N in the steps of 0.5 N. When no force is applied on the sensor the inductance of the sensor is 615.50 nH at the frequency of 19.5 MHz. The measured inductance of the sensor is 619.13 nH when the force of 2 N is applied. The calculated sensitivity of the proposed sensor is 1.82 nH/N, Fig. 5b.

IV. CONCLUSION

This work aims to investigate the possibilities of integration of new technology with novel material for the realization of a simple sensor suitable for force measurement. The main objectives of this paper are design, development and characterisation of force sensor fabricated by additive manufacturing technology.

The force sensor is realized by combining the fused filament fabrication technology with new materials such as PLA and Ecoflex which have good mechanical properties. The developed sensor has a simple structure and an inexpensive process of fabrication. Using the additive technology for the fabrication, the sensor and its casing are fabricated with simple and easily interchangeable patternning capability, at low costs with the elimination of the waste that accrues in traditional manufacturing. The Ecoflex is used in order to achieve sensitivity of the sensor to the applied force. The usage of silicone rubber opens the possibilities to develop the sensor of the desired shapes and features. Sensor’s elastic layer is in the form of a matrix in order to achieve a good elasticity of Ecoflex and a sensitivity of the sensor. The obtained sensitivity of the proposed sensor is 1.82 nH/N.

Future work will be focused on the development of the sensor fully fabricated by 3D printing technology using a conductive polymer (such as conductive PLA) for printing the inductor and ferro magnetic filament for printing the magnetic part of sensor.

The performances of the filmed inductor can be improved by creating grooved gratings on the surface of the ferrite film. Based on that investigation, the performances of the proposed sensor can be improved using the grooved gratings on the ferrite surface instead of smooth ferrite which will be the topic of our future research.

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