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Cost-Efficient Open Source Desktop Size Radial Stretching System With Force Sensor

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ABSTRACT The rapid and efficient development of soft active materials requires readily available, compact testing equipment. We propose a desktop-sized, cost-efficient, and open source radial stretching system as an alternative to commercially available biaxial and uniaxial stretching devices. It allows for doubling the diameter of an elastomer membrane while measuring the applied force. Our development enables significant cost reduction ($<$300 €) and increase the availability of equibiaxial deformation measurements for scientific material analysis. Construction plans, source code, and electronic circuit diagrams are freely available under a creative commons license.

INDEX TERMS Stretchable electronics, soft active materials, mechanics, arduino, material research, elastomers, creative commons, teaching, model.

I. INTRODUCTION

Mechanical material characterization is performed by a controlled deformation of a sample. Displacement and force sensors are used to measure the sample strain and stress. Simple test procedures comprising uniaxial, pure shear, and equibiaxial stretch experiments are usually performed for the multi-axial characterization of elastomers [1], [2]. The deceiving simplicity of this task is opposed by the high-priced laboratory equipment needed for standard measurement procedures [3]. Here we present a cost-efficient, desktop sized radial stretching system (RSS) for controlled uniaxial and equibiaxial deformation (Figure 1a) combined with a force sensor.

Applications of the stretching system arise in biological sensing [4], [5], hydrogel actuators [6], [7], stretchable electronics [8]–[10], soft machines [11]–[15] and robots [16], [17].

The RSS is simple to build with standard components, its open source nature makes it suitable for use in teaching and demonstrating material properties of rubbers and textiles. Its construction is a task appropriate for student labs to communicate the basic skills needed in electrical and mechanical engineering. We have made the experience that the device easily catches attention, this makes it interesting to be displayed at exhibitions by institutes or companies working with gels, rubbers or polymers. The RSS is a standalone measurement device because on the one hand the stretching mechanics works without any power supply and on the other hand operating the force probe requires only a common USB connection (5V DC).

To illustrate the usage of the radial stretching system in stretchable electronics research, we have employed the machine to extend the diameter of a stretchable electronic device by a factor of two. Figures 1b-d show a pliable LED-array stretched from 0% over 50% to 100% strain. Alternatively, our system easily allows for uniaxial stretching experiments. To achieve uniaxial stretch the sample is mounted on two opposite clamps, no modification of the RSS is needed. To keep costs low for replicating the RSS, we have only employed a laser cutter and a 3D printer together with common parts. The source code for the microchip (Arduino [18]), which transduces the inductance to a force value, is open source under a CC (creative commons) license and can be modified and improved by the community. Simple and quick manufacturing, compact size, cost efficiency and the usage of open source technology are summarized in the cover video published together with this article.

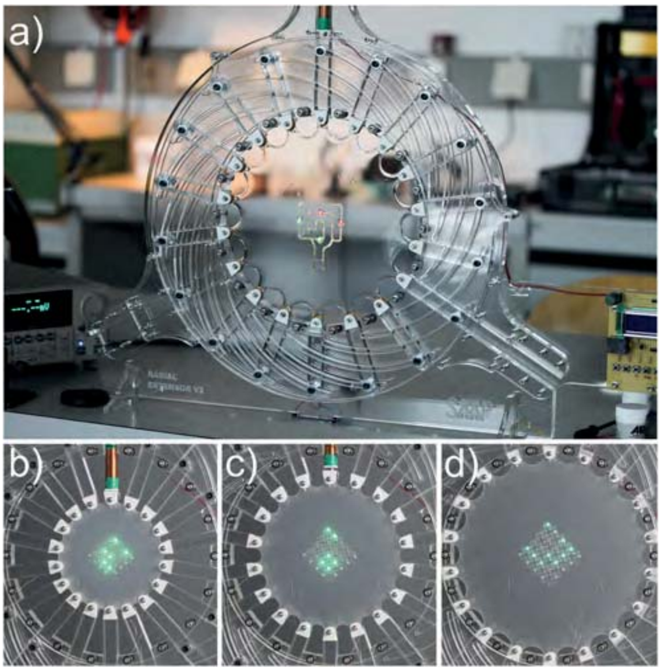

FIGURE 1. The radial stretching system (a) displays a stretchable SMD LED array [19]. It allows to investigate the transition of the circuit when stretched from (b) 0% to (c) 50% to (d) 100% strain. The RSS acts as a force gauge by displaying the applied force on a two line LCD.

II. HISTORY

Modern desktop sized devices applying multiaxial stretch to elastic samples can be tracked back to Haas' work on the deformation of textile hulls of zeppelins in the early 20th century [20]. This marks the first documented use of a biaxial stretching system for material testing. In 1958 Treloar [21] publishes the use of a very similar stretching system to apply biaxial stress achieving an area increase of 800%. This system consists of a large number of ropes fixed to a square rubber sheet specimen using equidistant clamps. The ropes are guided through pulleys and their free ends are burdened with equal weights, thereby applying almost homogenous equibiaxial stress. Rivlin and Saunders replaced the weights with springs and thereby achieved dynamic control of the applied force and stress [22]. Most of these techniques do not allow for cyclic stretching. The rising importance of defined deformation in soft materials led to a revival of biaxial stretching systems. Examples include the OCAMAC [23] - applying uniaxial tension and torsion - and the device presented by Sturrock et al. [24] where the ropes in Treloar's 1958 stretcher are replaced with motorized screws to move the clamps holding the sample. Very good representations of experimental and theoretical aspects are given by Sacks [25] and Holzapfel and Ogden [26]. An extensive overview on stretching devices is available in Arenz et al. [27].

Current commercially available machines are large investments and provide automated measurement applying forces from 5N to 500kN [28], [29] or do not provide a means to measure force at all [30].

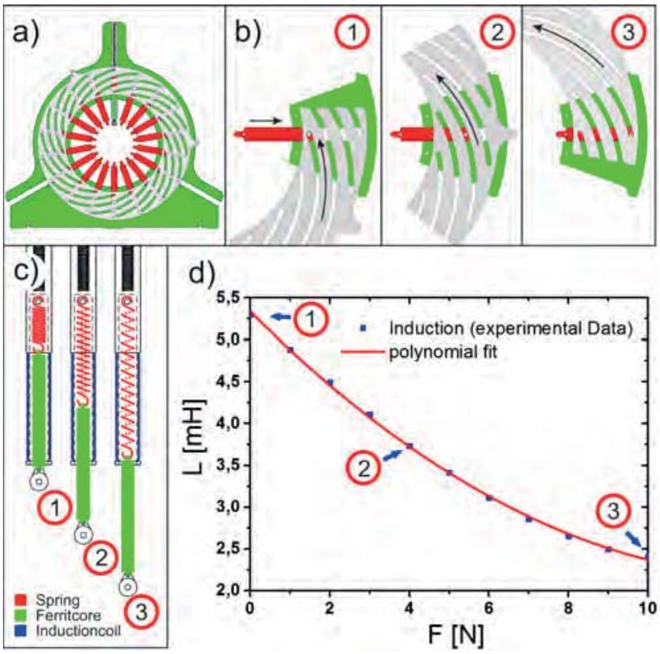

FIGURE 2. (a) Assembly of mechanical components of the RSS. Each arm is connected to the rotating frame with a peg inserted into a curved track (b). One of the arms is replaced by a inductive force sensor (c) calibrated with three defined force values (red encircled numbers) by a second order polynomial fit (d).

III. DEVICE ASSEMBLY

Often there is a need for a simple, compact stretching device, that nevertheless allows for fast and accurate measurements on elastically or plastically deformable materials. Our RSS stretching technique was inspired by the membrane stretcher developed at EPFL-LMTS [31] and is based on an aperture mechanism (Figure 2b).

The basic working principle of the RSS is to extend the sample by manually rotating a frame mounted onto a base. Rotation of the frame results in radial motion of several arms holding the sample. The location of a force sensor is adjusted to the same radius as the sample by a crank allowing for reading of a valid force measure from a digital display.

In detail, the RSS has 18 arms to hold and extend the sample. A peg on each arm glides in a curved track excised from a rotating frame. Rotation of this frame synchronously pulls the arms apart (Figure 2b), increasing the sample diameter from initially 110 mm up to 220 mm. The arms are guided within a static frame sandwiched between two rotating frames (schematically depicted in Figure 2a). Ball bearings and silicone oil between the frames reduce friction and achieve smooth rotational gliding. Each arm has a 3 mm hole where 3D printed washers are anchored with a screw. The sample is fixed between the washers, which also avoid stress localization. A roughness in the range of 0.1 mm is produced on the washers by employing a low cost 3D printer with fused deposition modeling. The roughness prevents slipping of the specimen by increasing friction in

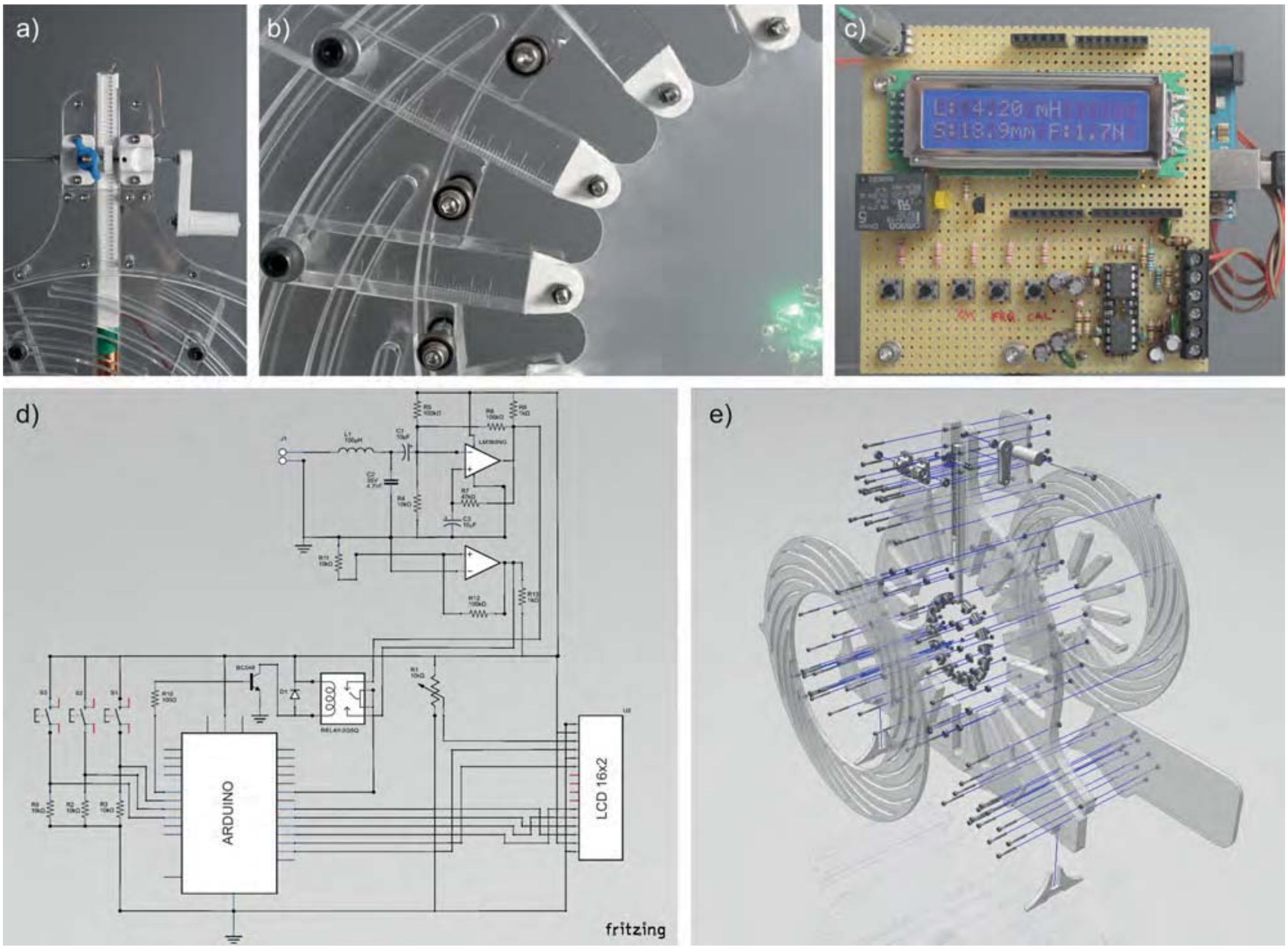

FIGURE 3. **RSS detail pictures for the replication: force sensor (a), composed of common small parts, 3D printed elements and a spring scale; the extensor arms (b); Arduino shield (c) with an electronic circuit (d) for measuring the inductance of the sensor and a LCD for visualizing the applied force; the explosion view (e) of the RSS for assembling.**

the mounting brackets. We designed the RSS so that one arm is easily replaced with a simple to manufacture force sensor, allowing for calculation of stress-strain curves under uni- or equibiaxial loading. The force sensor consists of a spring balance which is fixed within one 3D printed hollow arm. A ferrite core rod is mounted at the end of the spring. This rod freely glides within a coil fixed to the hollow arm (Figure 2c).

As the core moves through the coil the induction varies. When a force is applied to the force probe, the spring balance lengthens and the ferrite rod moves out of the coil. This results in a lower inductance which is measured by an electrical circuit. The correlation algorithm is coded into a microchip. For calibration the induction is measured at three precise forces. The obtained points are fitted with a parabolic relation between induction and force. This parabola is used to relate inductance measurements to the applied mechanical force. The use of different spring balances (e.g. 1, 10, 100 N) is implemented in the source code. Figure 2d shows the relation between inductance and force for a 10 N spring balance.

The methodology used for deformation of the sample is named ‘strain-control’ because the quantity externally controlled by the system is the radial strain. This means that the RSS sets the radial extension of the sample, and the force changes accordingly until the sample reaches equilibrium in way such that during the equilibration the strain is constant. In contrast a setup using ‘stress-control’, e.g. Treloar’s dead loads, define the force. The extension of the sample in the latter case is not explicitly controlled, but rather changes to an equilibrium value while the force is kept constant.

Open source hardware (laser cutter [32], 3D printer [33]) and a workshop with basic equipment suffice to build a RSS. The supplementary information comprises the detailed construction plans, the PMMA cutting templates for the laser cutter in a DXF file format as well as the 3D files in an STL format required for 3D printing. Detailed pictures of the force probe (Figure 3a) and the arm mechanics (Figure 3b) for stretching are also included. Additionally the circuit diagram for the control, measurement and display unit of the RSS (Figure 3c, d), the source code for the Arduino and a detailed explosion view (Figure 3e) for the assembly

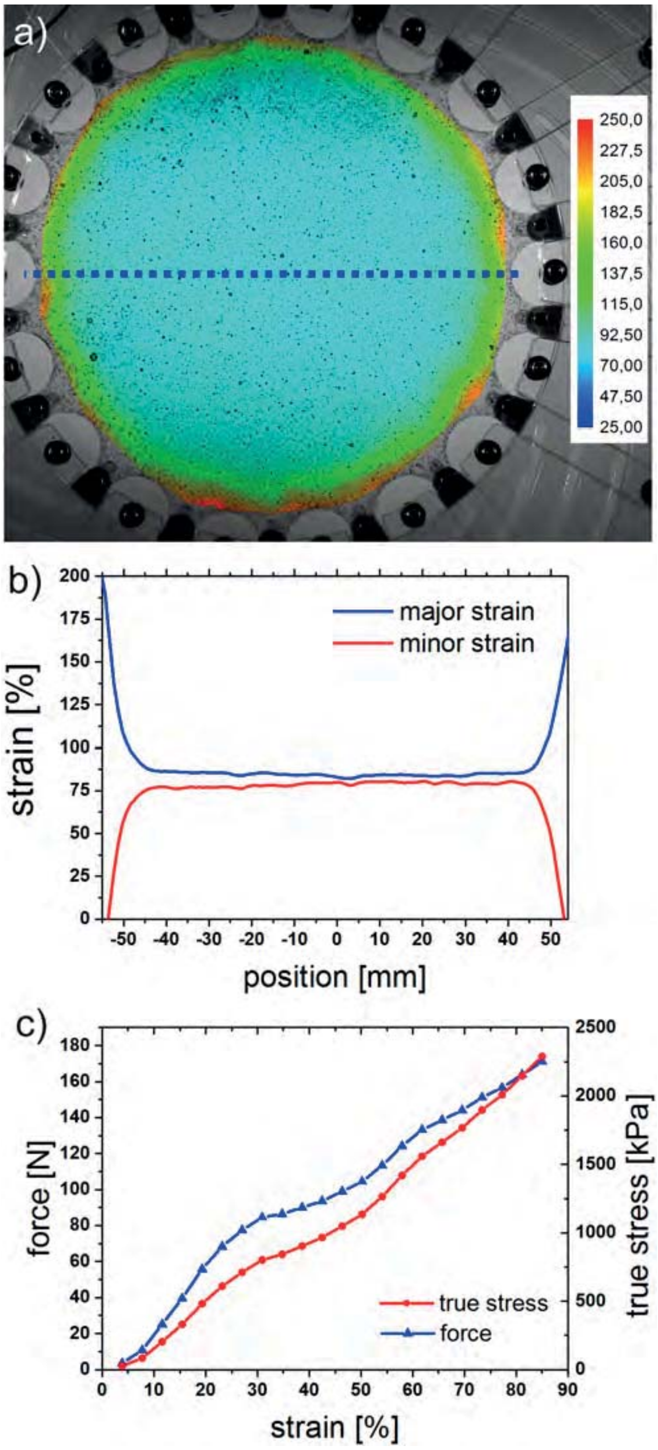

FIGURE 4. Deformation of a soft disc of VHB obtained through an optical deformation analysis device (Aramis). (a) Distribution of the major strain on an image of the stretched sample at maximum elongation. (b) Major and minor strain along the x axis depicted by the dotted blue line in (a). Demonstration of equal biaxial stretch by the coincidence of major and minor strain in the central region of the sample. (c) Force (blue squares) and nominal stress (red triangles) versus strain. The constant slope of the stress for low stretches is proportional to the small strain shear modulus.

is available as supplementary files. At the time of building the built-in components of the RSS amounted to less than €300.

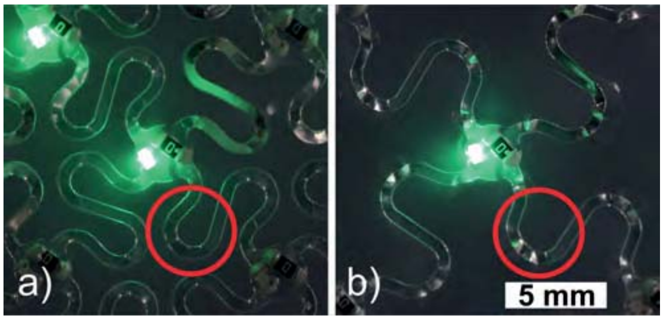

FIGURE 5. A detailed view of (a) relaxed and (b) stretched SMD LED matrix on a VHB substrate. The transition of deformation from (a) 2D to (b) 3D deformation of the conductor paths is visible in the highlighted area (red circle).

IV. DEMONSTRATION

Aiming for homogeneous equibiaxial strain on a maximal area, we use 18 mounting brackets. At large stretch ratios the sample region close to the brackets is increasingly inhomogeneously stretched causing the average strain to deviate from the strain in the center of the sample. To demonstrate the homogeneously stretching of a sample in the RSS an optical deformation analysis device (Aramis [34]) is used. Figure 4a presents results of such a measurement on a 1 mm thick VHB4910 (3M$^{\mathrm{TM}}$) specimen. The colored overlay represents the major strain within the sample. The major and minor strain along the blue dotted line in Figure 4a are displayed in Figure 4b. More than 80% of the inner sample disc is homogeneously stretched.

A force-strain relation is depicted in Figure 4c by measuring the expansion force at different strain values. Knowing the thickness and the force strain relation the stress-strain curve is obtained. For incompressible elastomers at low strains, a twelve-fold shear modulus of the strain compared to the slope of the true stress is presupposed. More detailed investigation of the stress-strain curve allows to inspect any hyperelastic model, like the Kuhn [35] or Gent model [36]. The hyperelastic models describe the deformation of both uniaxial and equibiaxial deformation with the same set of material parameters. By measuring uniaxial and equibiaxial deformation modes with one device, the RSS is a useful laboratory equipment testing this predictions and thus the suitability of each hyperelastic model.

Coming back to the usefulness of our device in the design of stretchable electronics we studied the out-of-plane deformation of conductor paths on a stretchable substrate. We use an approach based on meander like stretchable conductors [37]. The base of the conductors is a 12 micron thick polymer film, with a 100 nm thick evaporated Cr/Ag metal layer. The meander structure is carved out of the thin polymer substrate with a laser cutter. To allow for biaxial stretching, meanders with different orientation are used (Figure 1(b-d)). The meander paths continuously curve, avoiding straight lines which easily break upon elongation. A detailed comparison of the relaxed versus the stretched sample is depicted in Figure 5. In Li et al. [38] the mechanism for uniaxially stretching a meander-like structure is identified. Their model predicts that the film elongates by twisting out of plane, accommodated by the compliance of the substrate and the pattern of the film. In our experiment, the strips tilt out of the plane. The highlighted areas in Figure 5a and b show an example of how the meander deforms in a 3D manner upon stretching. The preparation of the Cr/Ag conductors on an elastic polymer support facilitates the large deformations of our stretchable interconnect lines. It is the stiffness of the PET-foil that protects the conductive film from ripping apart by avoiding large deformation but allowing for out-of-plane motion through its flexibility. Visiometric techniques allow for quantitatively measuring the deformation of the conductor paths and for comparing with predictions of existing models for meander deformation.

The RSS is a highly versatile tool to cyclically stress such composite samples revealing the durability, the onset of delamination and other lifetime parameters of stretchable electronic compounds.

V. CONCLUSION AND OUTLOOK

Soft active materials advancing the development of future smart systems, benefit from small and cost-efficient testing equipment [39], [40]. We believe that our low-budget, open source, desktop size radial stretching system with a force sensor will find widespread use in diverse areas in soft matter research, in education and as a representation tool in exhibitions.

Investigation of processes within biological tissues or single cells subject to stress profits from the small size of the RSS and quick mounting of samples. A down scaled version of the RSS can be created for tissue stretching within a cell culture incubator.

Further development will include a highly accurate and calibrated load cell in order to remove one of two manual steps for measuring a sample. We plan a subsequent version which measures a sample fully automatic by adding a stepper motor and a control system. With such improvements a complete stretch rate dependent automated hysteresis measurement or a fracture energy measurement become feasible. Having automated control over the applied strain allow for emulating a stress-controlled measurement. Straight forward ways to extend the system to higher temperatures or large work forces will be realized by employing durable materials for the frame (e.g. aluminum). The further evolution of the RSS design will be published on the website of SoMaP [41].

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