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Soft Tactile Sensors with Variable Compliance

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Abstract— This paper reports the development of a soft tactile sensor with variable compliance. The concept is based on a magnetic Hall-Effect sensor coupled with a soft, pressure controlled pneumatic chamber. The sensor design is developed using computational Finite Element models. A physical prototype is then fabricated and evaluated in experimental tests, demonstrating that the sensor can be conveniently manufactured and exhibits the desired property of variable compliance which can be achieved through external control.

Keywords— Variable Compliance, Tactile Sensors, Hall Sensors, Pressure Sensor, Soft Robotics

I. Introduction

The integration of tactile sensors in robotic systems is an important element in aiding effective manipulation by helping to achieve the optimum contact force during interaction with objects [1-2]. Nevertheless, progress is required meet the performance of biological systems that interact with the environment with dexterity and precision. As a result, research into deformable or 'soft' tactile sensing systems has rapidly accelerated, spanning a broad range of target applications [3]. Sensors such as TakkTile [4] and Biotac [5] offer tactile sensing in compliant, easily integrated packages. BioTac now forms a key part of the commercially available dextrous Shadow Dextrous Hand (Shadow Robot Company Ltd.). These advances highlight the potential, and need, for commercial adoption of tactile sensing in robotics.

One drawback of soft tactile sensors is that the dynamic measurement range is typically limited by the mechanical compliance. Thus, highly deformable sensors have a reduced sensory range in comparison to those with a stiffer body [1]. The burgeoning field of soft robotics offers potential solutions to this limitation by actively controlling the soft structures of the sensor. To date, little research has been conducted in this area; work by Stanley et al has demonstrated the ability to achieve a variable stiffness tactile display using similar soft robotic principles [6] but this has not been extended to sensing elements.

In this paper, we present our proof-of-concept research to develop a soft tactile sensor with variable, controllable mechanical compliance. Our group has previously developed a soft magnetic-field based tactile sensor, MagOne [1]. This is constructed using a soft silicone body with embedded magnet coupled with a 3D Hall Effect sensor, enabling the measurement of both normal and shear forces. MagOne is readily fabricated to provide sensitive force measurements at a low cost, but it has a relatively small operating range. To adapt the sensor's range for different applications it can be fabricated from materials of different mechanical compliance. However, stiffer materials lead to a lower sensitivity of the overall sensor system. This is problematic for applications which involve both high sensitivity and the ability to measure large forces. Dynamically varying the sensor's mechanical compliance provides a convenient way to achieve this by, effectively changing the material properties of the sensor "on the fly" to adapt to a given situation. This will provide a sensor with controllable levels of sensitivity and dynamic range, enabling it to be used in a wider variety of applications and situations.

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II. Sensor Design

The MagOne sensor used a solid silicone elastomer dome to regulate movement of the magnetic element relative to the Hall-Effect sensor. In Mag1C (MagOne Compliant) this was adapted into a hollow dome with a cavity that can be pressurized through a pneumatic supply, thus enabling the compliance of the sensor to be altered dynamically.

Our proof-of-principle design for Mag1C is shown in Fig.1. Our prior work provides design guidelines for the magnetic sensing configuration stating that the maximum distance between the magnet and Hall Effect sensor should be approximately 1-2x the magnet diameter [1]. For this prototype the sensor was fabricated with a nominal 21mm diameter and using a constant wall thickness without additional reinforcement for ease of fabrication and assembly.

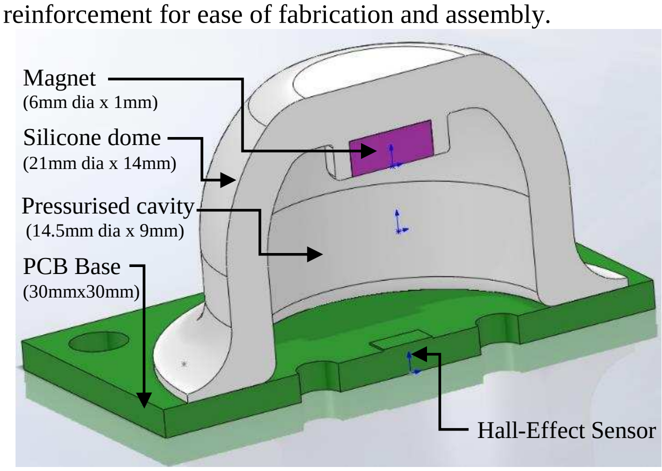

Fig.1. The Mag1C Conceptual Design

III. DESIGN OPTIMISATION

A series of computational models were developed to inform and optimize the design of the Mag1C sensor. The work reported here concerns investigations to determine an appropriate material and operating pressures for the sensor dome. The aim was to identify a configuration which enabled a significant change in mechanical compliance without the associated pressure causing excessive distortion of the 'dome' geometry'.

A. FEA Methodology

CAD models of the silicone dome and magnet were modelled in a Finite Element modelling package (Abaqus, Dassault Systèmes Simulia Corp). Application of normal loads on the sensor were simulated using a cylindrical body element. This was assigned a body force (to model an evenly distributed mass). An encastre boundary condition was applied to the base.

Investigations were undertaken to explore the effect of pressure on a range of sensor bodies. Preliminary work had informed the use of a maximum pressure of 8kPa. Three levels of pressure were then simulated; 0kPa, 4kPa and 8kPa to explore their effect on sensor compliance when the body was fabricated from different silicon materials. These silicones are nonlinear, hyper-elastic elements that can be represented using the Yeoh model [7]. The Yeoh coefficients for our three candidate materials (Table 1) were taken from published experimental studies and assigned to the models [8].

TABLE I. YEOH HYPERELASTIC COEFFICIENTS [8]

Material	Constant C10 (Pa)	Constant C20 (Pa)	Constant C30 (Pa)
EcoFlex 0050	14622.45	638.4237	-0.1381282
DragonSkin 20	43783.04	5472.995	-19.9947
DragonSkin 30	40017.26	11617.76	-84.7407

B. Results of FEA

a) Effect of operating pressure

Fig.2. shows the effect of the different operating pressures on three sensor bodies using different silicones. The sensor using E50 deforms the most when pressurised, the top surface moves vertically by almost 1mm at 8kPa with some "ballooning" evident. The D20 and D30 materials are stiffer and retain their shape, although D30 dome deforms marginally more than D20 due to its greater compliance.

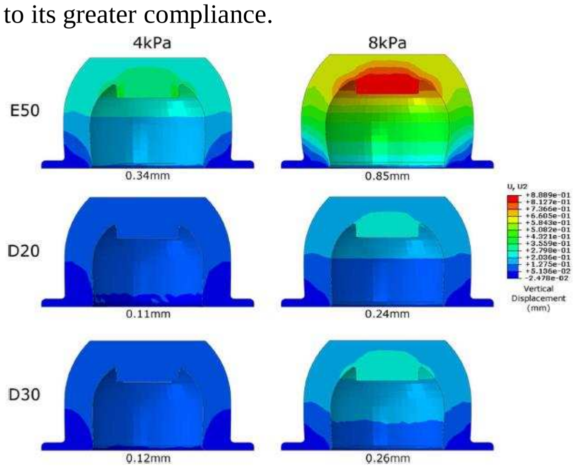

Fig.2. Unloaded deformation of Mag1C at different pressures

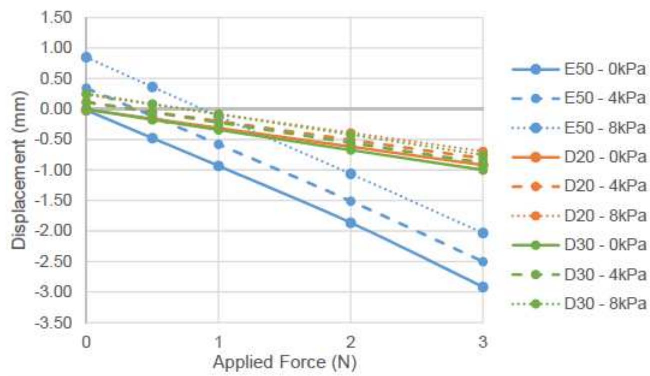

Fig.3. Change in displacement with loads at different pressures

b) Effect of Pressure with Applied Load

Each material was loaded with 0.5N, 1N, 2N and 3N, at each of the 3 pressure values. Fig.3 shows the resultant vertical displacement of the magnet's lower surface. It is evident that E50 shows the greatest sensitivity to both applied load and internal pressure in comparison to D20 and D30.

c) Design Outcomes

The FE analyses show that the mechanical behaviour of the sensor body will be affected significantly by both the internal operating pressure and the material of the compliant dome. Since our primary goal was to achieve a sensor with variable compliance, E50 was selected since it provides a significant change with pressure, in contrast to D20 and D30.

IV. SENSOR FABRICATION

The sensor dome was fabricated using a casting process through a 3-D printed two-part mould following the same method as described for our MagOne sensor[1]. The resultant dome was then placed directly over the Hall Effect sensor (MLX 90393) with the embedded magnet aligning in the centre. An exploded view of the assembly is depicted in Fig.4.

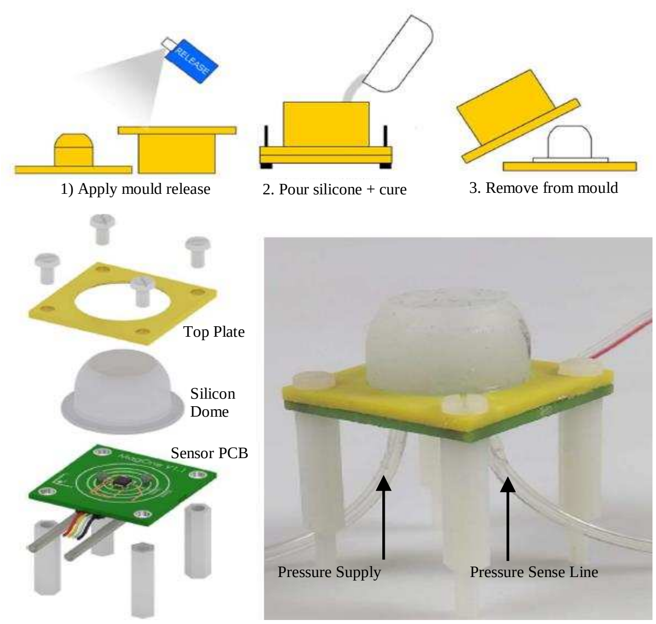

Fig.4. Fabrication process (top), Assembly (left) and Final prototype (right) of the Mag1C Sensor.

V. EXPERIMENTAL EVALUATION

The prototype Mag1C sensor was evaluated in a series of experimental tests. Here, we focus on the ability to dynamically alter mechanical compliance by varying the operating pressure.

A. EXPERIMENTAL SETUP

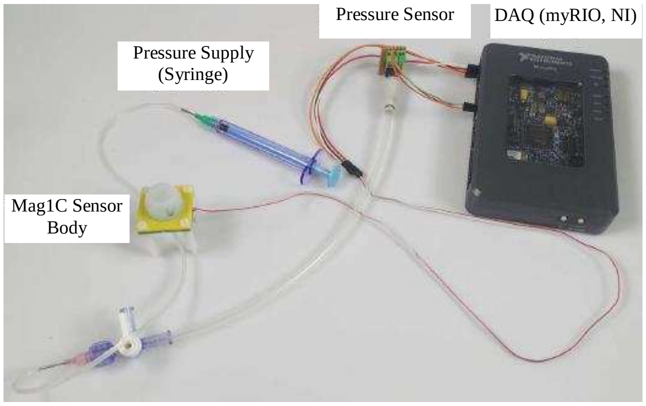

Fig.5.The variable compliance tactile sensor system

Fig.5 shows the full experimental system used to operate and evaluate Mag1C. The operating pressure, and thus compliance, is controlled manually using a syringe and the pressure monitored using an analogue pressure sensor (Honeywell SSCDANN030PAAA5). The Hall-Effect and pressure sensors are monitored using a bespoke data acquisition system (myRIO hardware and LabVIEW software, National Instruments). This system was connected to a load testing machine which was used to apply repeated controlled loading to the sensor across the range of operating pressures.

B. EXPERIMENTAL RESULTS

Fig. 6 shows results from repeat loading of the Mag1C prototype. The sensor shows a near linear force-displacement response across this load range for each operating pressure. It can also be seen that increasing the operating pressure has a clear effect on sensor compliance, manifested by an increased 'bias displacement' coupled with a small increase in gradient. In addition, Table 2 illustrates the maximum load range of the sensor at each operating pressure (obtained by comparing the sensor response when unloaded and when the dome was maximally compressed). This shows a clear increase in the sensor's dynamic range with pressure and only a slight change in the minimum force level.

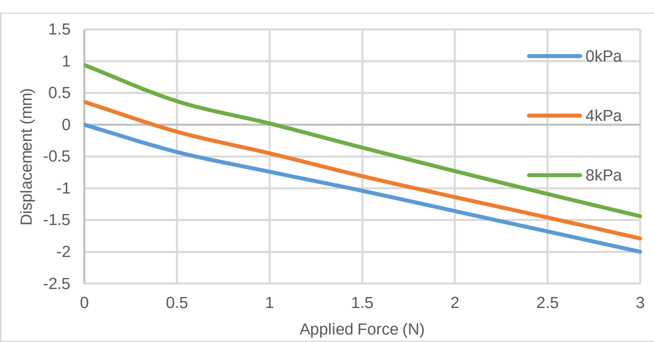

Fig.6. Effect of pressure on the compliance of the Mag1C sensor

TABLE II. LOAD RANGE OF MAG1C AT DIFFERENT PRESSURES

Load Range	**Pressure Ranges**		
	0 kPa	***4 kPa***	***8 kPa***
Minimum force (N)	0.035	0.059	0.093
Maximum force (N)	4.500	6.300	8.000
Dynamic Range (N)	4.465	6.241	7.907

VI. DISCUSSION

The combined use of FE modelling and physical testing was crucial; FE informed the sensor design while the physical prototype demonstrated that the concept was practical and will enable more detailed characterisation in the future.

A simple design was used here in which the dome used a single casting without external reinforcement layers. This can result in 'ballooning' of the dome when using softer silicones, but could be easily prevented by modifying the design to include a reinforcement layer to constrain expansion of the dome.

VII. CONCLUSIONS AND FUTUREWORK

The aim of this work was to produce a sensor in which the physical compliance could be conveniently, and dynamically, controlled. The Mag1C sensor presented in this paper represents initial advances toward this goal. We demonstrated a conceptual compliant sensor design, informed by FE modelling which was then fabricated and physically tested. This demonstrated that altering the operating pressure of the sensor resulted in a significant change in the sensor's compliance and dynamic load range of over 20%.

Our future work will focus on further optimisation of the sensor design, Integrating an automated pressure control system and investigating the use of computational methods for dynamic calibration of the sensor output.

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