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A Pressure Controlled Membrane Mechanism for Optimising Haptic Sensing

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Abstract. Active-passive robotic sensors adjust their stiffness ad-hoc as is appropriate for a task. In situations where the sensor is to operate in an unpredictable environment, or where the sensor is required to work with high sensitivity over a large stiffness range, it is beneficial for the sensor to maintain a high level of sensitivity over its entire operational range. This paper presents the theoretical model for a pneumatically controlled haptic sensor which maintains optimal sensitivity over a large range of force input values.

1 Introduction

Haptic sensors generally involve a trade off between high sensitivity over a small measurement range and the capability to work over a larger measurement range with lower sensitivity [1]. When their structure involves soft materials, this trade off often relates to the material's deformation. Softer materials are highly sensitive to a small range of stimulus values and stiffer materials are less sensitive, but work over a larger range [2, 3]. For many applications, the soft material's properties and elasticity can be chosen or tuned for the specific purpose [2]. Some applications, however, require sensor sensitivity to be adjusted ad-hoc, such as distinguishing between a range of objects of similar material properties, or working in unpredictable environments or with unknown objects [4]. For these cases, the sensor's material properties cannot be pre-selected for all operational requirements.

Variable stiffness materials and mechanisms have become an active area of research within robotics, where an actuator that can change stiffness between soft and hard states is considered advantageous, as it can selectively have the benefits of both soft and rigid structures [5]. It is, therefore, possible to actively alter the stiffness or shape of a soft haptic sensor, in order to more appropriately probe its stimulus, by combining it with soft actuation and variable stiffness mechanisms [2, 4, 5]. However, the literature lacks studies that review how the changes to a sensor's stiffness affect its sensitivity, and how to mitigate potential sensitivity loss.

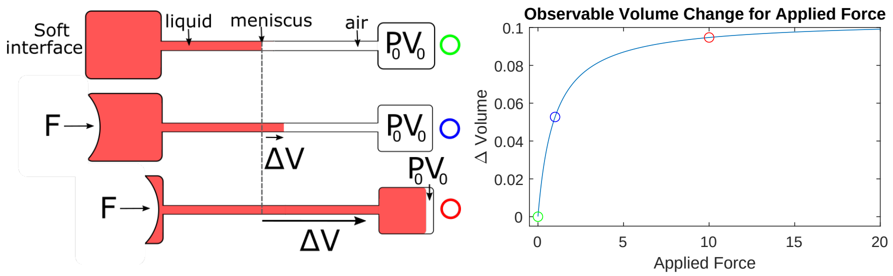
This paper considers a soft robotic haptic sensor that exploits a combined actuator-sensor configuration for active-passive modalities and presents a theoretical basis to optimise its sensitivity. The design is based on a soft sensor concept similar to those proposed in [2, 6]. In this concept, an external force from the environment is applied to a soft interface (membrane) and the mechanical information is captured by the system via the translocation of an internal fluid. The external force can be measured by monitoring the movement of the fluid through a pipe (Figure 1a). The movement of the fluid can be measured in several ways, such as using a camera [6], a soft encoder [7], or measuring the flow [8]. This paper focuses on the data available to such a sensor, independent of its measurement mechanism, and, in particular, models an actuator-sensor system whose air-filled cavity can be pressurised by a controllable pump. An increasing air pressure effectively stiffens the soft interface's membrane; the suggested model shows that it is possible to enhance the sensitivity of the sensor over its working range of applied forces via this method.

2 Method

The sensor system (Figure 1) relies on the transmission of mechanical stimuli into the lateral movement of liquid through a pipe. By tracking this movement, the lateral distance travelled by the liquid can be correlated to the applied force and the transmission ratio between the force and distance quantified i.e. the sensor's sensitivity (in mN^{-1}). As the air is compressed within the sensor (due to the deformation of the sensor's membrane when a force is applied), this ratio becomes smaller, meaning that a larger stimulus (force) is needed to give the same response (fluid displacement) (Figure 1b). This implies that having a more highly pressurised cavity reduces the sensor's sensitivity, but increases its measurement range, since a more highly pressurised cavity will require more force to reach maximum compression. Similarly, reducing the air pressure increases sensitivity over a smaller measurement range. The ability to dynamically vary sensitivity and measurement range during operation can enable improved haptic sensing performance, particularly when the stimulus exhibits non-linear stiffness properties e.g. human tissue.

To derive the the relationship between the force applied to the sensor's interface (F), and the change to internal cavity pressure (P), it is assumed that the liquid experiences negligible compression, and that the change is adiabatic

$$\Delta F = \Delta P A \tag{1}$$


(a)

(b)

Fig. 1: a) Schematic of the actuator-sensor device in three states of no force, small force, and a large force applied. In adiabatic conditions, PV remains constant. b) Information available to a sensory device for a range of stimuli, calculated by substituting equation (1) into (2). The three states are marked with a corresponding 'o'. Units are arbitrary.

where A is the cross-sectional area of the pipe. The decrease in volume (V) of the inner cavity due to an applied pressure can be calculated using the pipe's cross-sectional area and the observed distance (L) travelled by the liquid's meniscus:

$$\varDelta V = -A\varDelta L$$

so that Boyle's law captures the compression of the air in adiabatic conditions

$$\varDelta P = \frac{V_0 P_0}{V_0 - A\varDelta L} - P_0 \tag{2}$$

where subscript 0 indicates initial values. We can obtain a relation for the change in the position of the meniscus at the liquid/air boundary as a function of the applied force. As $\varDelta L \to 0$:

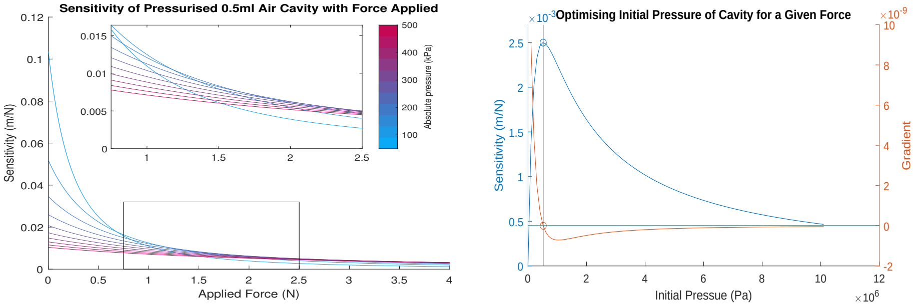
$$\frac{dL}{dF} = \alpha = \frac{V_0 P_0}{A^2(\frac{F}{A} + P_0)^2} \tag{3}$$

where the ratio α relates to the sensitivity of the sensor. Now, it is useful to calculate how α changes for a fixed force as a function of the initial pressure, whilst keeping V_0 constant (Figure 2a)

$$\frac{d\alpha}{dP_0} = \frac{V_0(\frac{F^2}{P_0^2} - A^2)}{(\frac{F^2}{P_0} + P_0 A^2 + 2FA)^2} \tag{4}$$

A larger ratio corresponds to a higher sensitivity and hence, we can find the extrema of equation (3) using equation (4) (Figure 2b), setting

$$V_0(\frac{F^2}{P_0^2} - A^2) = 0; V_0 \neq 0 \implies P_{opt}^2 = \frac{F^2}{A^2} \tag{5}$$


(a)

(b)

Fig. 2: a) The sensitivity is higher for a low pressure (blue) cavity than for higher pressures (red), but it reduces in a non-linear manner. The inset shows that the more highly pressurised cavities become more sensitive than those with a low pressure as the force increases above 2N. The colour bar correlates the colour of the line to the pressure used to calculate the data. b) Sensitivity for P_0 values (blue) and its gradient (orange) according to equations (3) and (4) respectively for a fixed applied force of 5N. The optimal initial pressure for this force corresponds to the vertical black line.

which gives us the linear relation for finding optimal pressure at a given applied force. We can dismiss the negative solution as being non-physical, although its existence usefully confirms that the positive solution is a maximum, and so solving equation (5) gives the pressure that is needed to give the highest sensitivity for a given force and cross-sectional pipe area.

3 Discussion

While equation (5) is identical, in appearance, to the standard definition of pressure, it does not represent the relationship between two physical quantities, but is, instead, intended to inform the control system for a sensor where the compression of air leads to a non-linear deterioration of the sensor's sensitivity. The solution lends itself to a simple interpretation: the pressure of the cavity should be such that it returns the meniscus of the liquid to its rest position.

The model presented in this paper considers only the pneumatic property of the sensor. For a full analysis, the material properties of the soft interface and other parts of the structure would also have to be considered. However, these factors are likely to complement the phenomenon of reduced sensitivity as the system is moved from its resting configuration and the material is stretched or deformed, which could be recovered by applying a back-pressure to the system. These preliminary calculations support the development of a device that follows the concept of Figure 1. In future work, the presented mechanism will be realised with a pressure controller attached to the air cavity in order to validate that sensitivity can be enhanced.

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