Influence of friction on the locomotion of soft robots

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The recent interest in soft robots results from their adaptability, versatility and flexibility, which is very advantageous for new applications in human-robot interaction, health care or field exploration. Many feasibility studies have already demonstrated the versatility of soft robots to grip irregular objects, walk on uneven surfaces, or interact with humans. Further research on mathematical models of these continuously deformable robots is ongoing to predict their performance in real life and operational situations. In particular, the models should be able to describe nonlinear material properties, contact situations and the dynamic behavior of the soft robot in action, which is a major challenge.

In this paper, basic measurements of the friction behavior of a fabricated pneu-net bending actuator are performed in different actuation phases. In order to analyze the dependence on the momentary actuation, the coefficient of friction is related to the applied pressure, which shows a nonlinear characteristic. The results are used in the Euler’s Elastica model of the soft bending actuator to describe the overall deformation according to the contact conditions more precisely.

1 Introduction

Soft Robots are a new kind of soft material structures, which are pneumatically actuated or tendon driven. Due to their special properties when gripping complex shaped objects without extensive sensor technology and when changing the gait by simply adjusting the control, they show high potential for new applications, such as in close human-robot interaction, health care or field exploration. However, modeling the soft robots is challenging, since due to the soft materials used, non-linear material properties arise and large, continuous deformations have to be taken into account because of the missing support structure.

At the Institute of Applied Structural Mechanics soft robots are investigated numerically and experimentally. In order to investigate the locomotion and interactions between the soft robot and its environment, a pneumatically driven bending actuator was manufactured and analyzed. In addition, its deformation is described by Euler’s rod model, as reported in earlier works [1–3]. Due to the simplified representation of the structure of the soft robot as a material line in space, some model parameters, such as the pressure-induced driving curvature and the bending stiffness, have to be identified experimentally. Additionally, the interaction with the environment, as the frictional characteristic between walking soft robot and contacting surface, need to be known in order to describe the locomotion precisely, cf. [4]. Hence, in this work, the measurements of the friction behavior for the bending actuator on different surfaces (glas, steel and sand paper) are determined and used to calculate its overall deformation during activation.

2 Test Setup and Results

To measure the coefficient of friction, a test setup was developed in which one end of the bending actuator is clamped and the other end can slide on different surfaces, see Fig.1b. The coefficient of friction is investigated on steel, glass and sand paper of grain 150, which are mounted on a force sensor (Kistler 3-component measuring system 9119A). In each test sequence, the actuator is pressurized three times with a constant value between 10 kPa and 50 kPa, and the forces are measured in the direction of the basic coordinate system, cf. Fig.1a.

When activated, the tangential force $F_2$ increases drastically and then decreases slowly to an almost constant value, as visible in Fig.1a within the areas marked grey. The variation of the tangential force results from local engagements of the bending actuator, in particular with the rough abrasive paper, so that the deformation process extends over a longer period of time. However, from these values the course of the coefficient of friction $\mu$ over time is calculated, which is very uniform after the local deformations have subsided.

Fig.2a and 2b display the mean values of the coefficient of friction on the different surfaces and for different clamping conditions of the bending actuator. It is clearly visible that even for the same surface and same actuating pressure, the coefficient of friction highly depends on the clamping condition, and with this, on the local contact behavior of the bending actuator. For the simple supported case, the coefficient of friction shows an almost constant behavior relative to the applied pressure with values for sand paper and glass of $0.7 < \mu_{\text{glass}}, \mu_{\text{sand paper}} < 0.8$ and values for steel of $\mu_{\text{steel}} \approx 1.1$. In contrast, the coefficient of friction for the bending actuator fixed one end shows a totally different behavior. Here the values for steel and sandpaper are close together and increase with applied pressure up to 25 kPa after which they remain constant at a lower level of $\mu_{\text{steel}} = \mu_{\text{sand paper}} \approx 0.8$. The coefficient of friction on glass are independent on the actuated pressure and takes on values of $\mu_{\text{glass}} \approx 0.3$. Even if the friction behavior on sand paper appears to be the same for both clamping conditions

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Section 5: Nonlinear oscillations

**Fig. 1:** Sequence of measured forces and calculated coefficient of friction (evaluable area marked in blue) during one experiment a), setup to evaluate the coefficient of friction of a soft bending actuator b) and photos of the soft bending actuator and the investigated surfaces c) and higher pressure values, this does not apply to the behavior for steel and glass. Possible explanations are the influence of adhesive effects or local deformations which cannot be completely degraded and which depend on the respective overall deformation.

**Fig. 2:** Coefficient of friction with respect to applied pressure on the soft bending actuator for a fixed support a) and a simple support b), and results of Euler’s elastica for the overall deformation of the bending actuator with considered friction behavior compared to experiments c)

### 3 Conclusion

The coefficient of friction of a pneumatically driven soft bending actuator on steel, sand paper and glass was experimentally investigated and found to be highly nonlinear with respect to the applied pressure and the clamping situation of the actuator. However, using the measured values in the theory of Euler’s elastica to predict the deformation of the actuator, very good agreements can be found, cf. Fig. 2c. Hence, an experimental parameterization of the rod model by the explained routine is possible, which strengthen the numerical modeling of soft robots.

### References

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