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Design improvement by a simulative investigation of the locomotion of a snake-like soft robot

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This work aims to improve the design of a snake-like soft robot in terms of its velocity of locomotion by a geometric model. Therefore, we determine the locomotion of the snake-like soft robot as the result of a given excitation curvature and a given friction anisotropy between the robot and the ground.

Varying the design parameters of the robot in the model allows to identify important parameters to increase the velocity of locomotion of the snake-like soft robot. Whereas its body design is sufficient, the transverse friction of its artificial skin is the main parameter to be improved. The transverse friction can be adjusted by turning the scales of the artificial skin. The velocity of locomotion of the robot increases significantly by this simple trick.

1 Introduction

The design of new soft robots is often based on experience and trial-and-error. The same is for a proposed snake-like soft robot of the authors. The robot consists of universal soft bending actuators connected in series and has an artificial skin oriented on the belly of real snakes. The artificial skin consists of overlapping scales and provides anisotropic friction in forward-backward direction. A comprehensive method to evaluate the design of the robot and to improve it is a simulative investigation.

Due to large deformations and non-linear material models, the dynamic simulation of soft robots typically involves high computational cost. Hence, reduced models, which fit exactly to the aim of an investigation, are of special interest. In this work, we use a simple geometric model, presented in a preliminary work of the authors [1], to improve a snake-like soft robot's velocity of locomotion. Therefore, we vary the design parameters of the robot in the model in order to identify those with the highest sensitivity on the velocity of locomotion.

2 Methods

The snake-like robot, as well as real snakes propel themselves by a transversal wave traveling through the body, a so called serpentine locomotion. The shape of the body of both is fully described by its curvature which is assumed to be sinusoidal [1,2] $\kappa(s,t) = \hat{\kappa}\cos\left(p\pi\left(\frac{s}{L}+\frac{t}{T}\right)\right)$, where $\hat{\kappa}$ is the maximum curvature, p is the periodicity, L is the length of the body, T is the period of undulation, $s \in [0, L]$ is the arc-length parameter and t is the time. In the case of a real snake the body bends continuously, whereas the snake-like robot approximates this motion with constant-curvature bending actuators connected in series. Numerical integration allows to calculate a plane curve $\mathbf{r}(s,t) = (x(s,t), y(s,t))$, which represents the body, based on an initial position and an initial orientation of the body in a global coordinate system (x, y).

In addition to the motion of the body, an anisotropic friction between the body and the ground is necessary such that it is capable to move forward. In this model, we assume anisotropic Coulomb friction by geometrically weighting the friction in transverse μ_t, forward μ_f and backward direction μ_b for each point of the arc-length s depending on its current velocity direction. By applying the consideration that the robot's or snake's excitation forces compensate themselves throughout the body length, locomotion can be determined. A more detailed description of the model is given by [1,2].

Varying one parameter after the other in the model ("one-factor-at-a-time method") and comparing the traveled distance after one period of undulation, identifies significant parameters on the velocity of serpentine locomotion. Although we aim to improve the design of the snake-like robot, the original parameters combination of the variation represents a real snakes. This is beneficial, because the locomotion of animals is typically well adapted and the results derived from a real snake can be taken over to the design of a snake-like robot. The coefficients of friction μ_t, μ_f and μ_b are related to the design of the skin, whereas the maximum dimensionless curvature $\hat{\kappa}L$ and the number of bending actuators are related to the bending of the body. The periodicity p from $\kappa(s,t)$ typically is $p = 2$ and the period of undulation T has little influence as long as the motion is relatively slow.

3 Results

Referring to 1a, the velocity of a snake clearly depends on its maximum curvature. With a maximum dimensionless curvature of $\hat{\kappa}L = 7$ the velocity of real snakes is already close to the optimum at $\hat{\kappa}L \approx 9$. The maximum curvature of the snake-like

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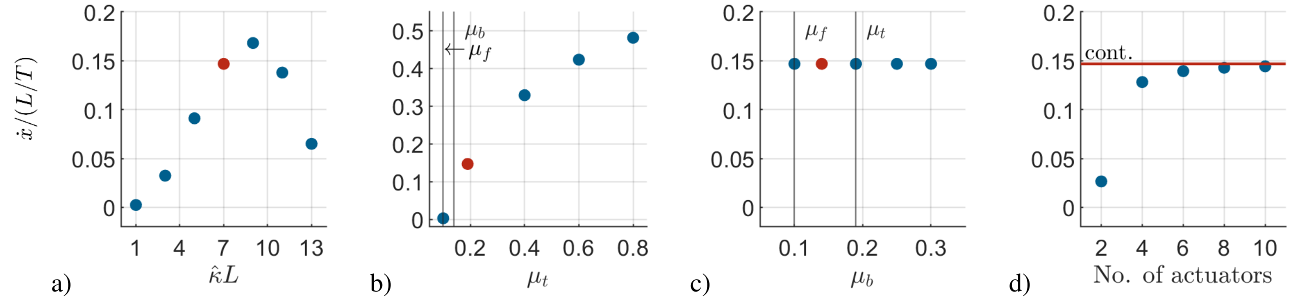

Fig. 1: The snake's velocity $\dot{x}/(L/T)$ for a variation of a) the maximum dimensionless curvature $\hat{\kappa}L$, b) transverse friction μ_t, c) backward friction μ_b, and d) a changing number of hypothetical bending actuators approximating a continuous curvature. Red color indicates the original value of a real snake.

robot is $\hat{\kappa}L = 7.5$ and is predetermined by the universal bending actuator which initiates its bending. However, an optimized maximum curvature would slightly increase the velocity of locomotion.

The variation of the transverse friction μ_t in 1b shows significant influence of the friction μ_t on the velocity, whereas the backward friction μ_b in 1c has a negligible influence. Note that only the friction ratio μ_t/μ_f determines the velocity, whereas the friction level, which would change by a variation of μ_f, determines the excitation forces needed for locomotion. The overlapping scales of the proposed snake-like robot are contrary to that finding, because they provide backward-forward frictional anisotropy, while $\mu_t \approx \mu_f$. However, by turning the scales of the artificial skin such that the direction of highest friction changes, a beneficial order of friction $\mu_f \leq \mu_b < \mu_t$ can be achieved. Turning the scales by an angle of 90 degrees will lead to the theoretically best result $\mu_f = \mu_b < \mu_t$. In a practical application, the angle should be chosen smaller in order to remain the possibility of another gait than serpentine locomotion. Further improvements could be achieved by an improved skin design leading to a higher friction ratio μ_t/μ_f.

While real snakes bend with a continuous curvature, 1d shows the hypothetical case of a snake consisting of several constant-curvature bending actuators in series, related to the snake-like robot. The result is an increase of velocity for an increasing number of actuators, converging to the velocity of a continuous bending snake. When building a robot, it is desirable to reduce the number of actuators because the complexity of the design and of the control reduces likewise. For example, using only 4 - 6 actuators reduces complexity with an acceptable reduction of velocity. This is an important finding for the snake-like robot, because the proposed robot consists of 9 actuators.

4 Conclusion

To sum up the results, the maximum curvature of the current robot allows little improvements, while the number of constant-curvature bending actuators to approximate a continuous bending can be reduced from 9 to 4 - 6. The simplest way to improve the artificial skin of the robot is to change the direction of highest friction by turning the scales.

With the originally proposed design, the snake-like robot will reach a velocity close to zero $\dot{x}/(L/T) = 0.009$ due to a lack of transverse friction. A design with scales turned by 60 degrees and 6 bending actuators significantly increases the velocity to $\dot{x}/(L/T) = 0.07$ although the complexity of the robot is reduced. The complexity can be further reduced to 4 actuators without loss of velocity, if the maximum dimensionless curvature of the robot is $\hat{\kappa}L = 8.5$ instead of $\hat{\kappa}L = 7.5$. The previously discussed examples demonstrate, that the model used in this work is sufficient to identify significant improvements on the velocity of a snake-like soft robot by applying only minor changes to the design.

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