Analysis of Soft Robotic Bipedal Crawling

Benny Gamus[1], Lior Salem,[2] Amir D. Gat[1,2] and Yizhar Or[1,2]

***Abstract*— In nature many soft-bodied creatures are capable of complex locomotion in challenging conditions, inaccessible to skeletal animals, which has been inspiring the study of soft-robotic locomotion and manipulation. Focusing on walking soft robots, most of existing works are based on empirically tuned control sequences or kinematic models. Here we present an approach for simple modeling of a soft bipedal crawler as an equivalent 3-link rigid robot. Studying the quasistatic and dynamic locomotion of this model allows for better comprehension of the crawling mechanism and parametric optimization of the soft robot walking gait. Moreover, this models helps gaining insights into challenges in soft robotics, such as uncertainties in the contact friction, and may be exploited for designing gaits with improved robustness.**

INTRODUCTION

Innovative soft robots are developed to excel where traditional robots with rigid links struggle – mostly manipulation, grasping [1] and multigait walking [2]. To find a control sequence which leads to periodic walking gaits, most of the works employ kinematic or static modeling [3] or straightforward empirical approach [4]. Few studies [5], [6], which have considered the effect of contact friction on the locomotion, have shown how it can significantly influence the motion and performance.

3-LINK RIGID ROBOT

Consider a soft-robotic bipedal crawler with two embedded separately controlled fluidic networks on a frictional surface (see supplementary video at `https://goo.gl/NTBb1M`). We are presenting an approach for simple modeling of this robot by approximating it with an equivalent robot of three rigid links connected by two controlled joints, as illustrated in Fig. 1. The study of the contact transitions between stick and slip states, allows for planing and analytical optimization of the 3-link gait and consequently the soft walking gaits. Consider a symmetrical case where the left-most and right-most links are identical and have length l and mass m, and a center link has length $l_0 = \gamma l$ and mass $m_0 = \beta m$.

To the best of our knowledge, the frictional crawling of a 3-link rigid robot has not been properly studied, though being a very simple model of horizontal bipedal locomotion. A notable exception is [7] which have exploited a similar model to study the properties of dogs' walking-gaits, which further supports this approach.

[1] Benny Gamus, Amir D. Gat and Yizhar Or are with Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Technion City, Haifa, Israel 3200003. bennyg@campus.technion.ac.il

[2] Lior Salem, Amir D. Gat and Yizhar Or are also with the Technion Autonomous Systems Program, Technion – Israel Institute of Technology, Technion City, Haifa, Israel 3200003.

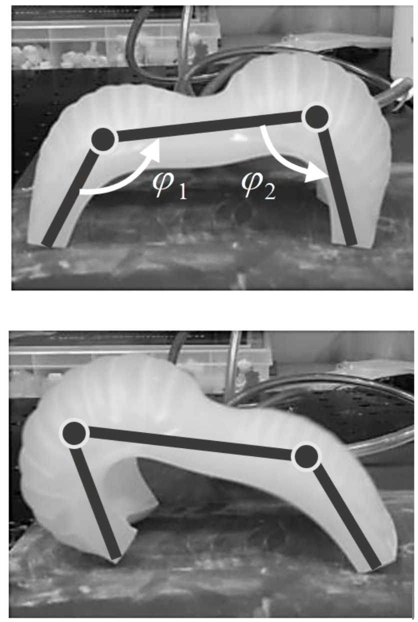

Fig. 1: 3-link robot approximation of a soft-robotic horizontal crawler

Focusing on fluid-driven soft actuators, in recent works [8] we have studied the deformation introduced by an embedded fluidic network (EFN) to the elastic structure. From these results we can model the influence of the EFN as external torques acting at the two joints $\varphi_1,\ \varphi_2$ of the 3-link robot, giving a lumped-parameter representation of the continuous deformation of a soft robot. After analyzing the gait and finding the required joint torques, we can translate them to control sequence of the pressure inlets to the EFN.

QUASISTATIC LOCOMOTION

To further simplify the gait analysis we assume that the trajectories of the two joints $\varphi_1,\ \varphi_2$ are fully prescribed by the controlled input. The torques required to enforce this motion are afterwards found from inverse dynamics. In the quasistatic case, when both of the joints are constrained by the EFN, the mechanism is kinematically over-constrained and one of the legs must slip. Analysis of the statics leads to the conclusion that the foot which is closer to the center-of-mass (in the horizontal direction) maintains stationary contact while the other leg slips.

Defining the center-of-mass horizontal distance from the left contact point $x_{cg}(t)$ and the horizontal distance between the contact points $d(t)$ we can find

$$\Delta(t) = x_{cg} - \frac{d}{2} = \frac{1+\beta}{2(2+\beta)} l \left[\cos(\varphi_2 + \theta) - \cos(\varphi_1 - \theta)\right],$$

where $\theta(t)$ is the absolute angle of the center link. The previous analysis indicates that when $\Delta = 0$ a switching occurs between right-leg-slippage ($\Delta < 0$) and left-leg-slippage ($\Delta > 0$).

Gait optimization and robustness

We now turn to investigate the 3-link model gaits' performances for various trajectories $\varphi_1(t)$, $\varphi_2(t)$. For concreteness consider harmonic periodic gaits of the form

$$\varphi_1(t) = \varphi_{1,0} + a_1 \sin(t + \psi/2)$$
$$\varphi_2(t) = \varphi_{2,0} + a_2 \sin(t - \psi/2).$$

A gait with *ideal switching* is a gait where one leg only slips during legs' extension while the other only slips during legs' retraction thus maximizing the net distance traveled per step S, which can be found from

$$S = \frac{1}{2} \int_T \dot{d} \ \mathrm{sgn}(\Delta) \mathrm{dt}$$

Investigating the above expression for Δ it can be analytically proven that ideal-switching gaits are only possible when the angles are symmetrical, i.e. $\varphi_{1,0} = \varphi_{2,0} = \varphi_0$ and $a_1 = a_2 = a$.

We thus study the analytic kinematic expressions of the 3-link model trajectories to optimize of gaits' performances (as discussed further) by varying the nominal angle φ_0, the amplitude a and the phase difference ψ.

It can be shown that the distance traveled per step S monotonically increases with the amplitude a and monotonically decreases with the phase difference ψ, while having an optimum nominal angle of $\varphi_0 = \pi/2$. We also define the cost of transport (CoT),

$$CoT = \frac{W^+}{Mg\ S}$$

where W^+ is the positive mechanical work expended by the torques (assuming that negative power cannot be stored and regenerated) and $Mg = (2m + m_0)g$ is the robot's total weight, and a criterion of robustness to uncertainty in the friction $R_\sigma = (S - \bar{S}_\sigma)/S$, where $\bar{S}_\sigma$ is the mean distance traveled when the friction coefficients at the contacts are normally distributed with standard deviation σ. The later parameter is calculated numerically via a stochastic Monte Carlo simulation.

Analysis of these criteria in the parametric-space (as shown in Fig. 2 and Fig. 3) allows for choosing gaits with same nominal distance per step but better robustness to friction and smaller cost of transport, which shall lead to better performances of both the rigid and soft robots from practical considerations.

Briefly discussing the limitations of the presented approach, one shall consider the possible inaccuracies from applying the torques-sequence calculated by this method in open-loop. Also, since the approximated model analytically shows mostly monotonical performance improvement with the parameters, similar behavior of the soft robot can be expected, but shall be the subject of further investigation.

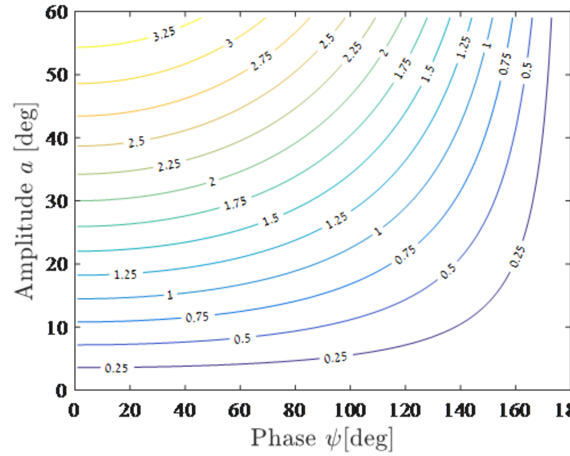

Fig. 2: Distance traveled per step S in parametric-space

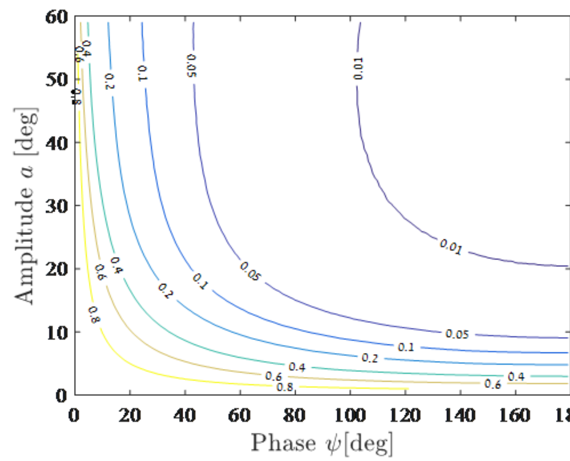

Fig. 3: Robustness to friction R_σ in parametric-space

References

[1] K. Suzumori, S. Iikura, and H. Tanaka, "Development of flexible microactuator and its applications to robotic mechanisms," in *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, pp. 1622–1627, IEEE, 1991.

[2] R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, and G. M. Whitesides, "Multigait soft robot," *Proceedings of the National Academy of Sciences*, vol. 108, no. 51, pp. 20400–20403, 2011.

[3] A. D. Marchese and D. Rus, "Design, kinematics, and control of a soft spatial fluidic elastomer manipulator," *The International Journal of Robotics Research*, p. 0278364915587925, 2015.

[4] M. Calisti, F. Corucci, A. Arienti, and C. Laschi, "Bipedal walking of an octopus-inspired robot," in *Conference on Biomimetic and Biohybrid Systems*, pp. 35–46, Springer, 2014.

[5] C. Majidi, R. F. Shepherd, R. K. Kramer, G. M. Whitesides, and R. J. Wood, "Influence of surface traction on soft robot undulation," *The International Journal of Robotics Research*, vol. 32, no. 13, pp. 1577–1584, 2013.

[6] X. Zhou, C. Majidi, *et al.*, "Flexing into motion: A locomotion mechanism for soft robots," *International Journal of Non-Linear Mechanics*, vol. 74, pp. 7–17, 2015.

[7] J. R. Usherwood, S. B. Williams, and A. M. Wilson, "Mechanics of dog walking compared with a passive, stiff-limbed, 4-bar linkage model, and their collisional implications," *Journal of Experimental Biology*, vol. 210, no. 3, pp. 533–540, 2007.

[8] B. Gamus, L. Salem, E. Ben-Haim, A. D. Gat, and Y. Or, "Interaction between inertia, viscosity, and elasticity in soft robotic actuator with fluidic network," *IEEE Transactions on Robotics*, vol. 34, no. 1, pp. 81–90, 2018.