Experimental Validation of a Template for Navigation of Miniature Legged Robots

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1 Introduction

Miniature legged robots involve highly-articulated transmission and actuation mechanisms, and are often made of materials with uncertain mechanical properties. As a result, it is particularly challenging to derive first-principle models that express the complex and inherently uncertain interactions between the system and its environment. In navigation tasks that involve quasi-static locomotion behaviors of miniature legged robots, movement is dominated by surface forces [1, 2]. Yet efforts for developing accurate descriptions of ground interactions suitable for inclusion into low-dimensional dynamical models amenable to planning control are still ongoing [**?**].

An alternative to first-principle models are ones that capture only selected, key, salient features of robot behavior. Such models are known as *templates* [3]. Research of the motion of sprawled arthropods on the horizontal plane [4, 5] has motivated various dynamic bio-inspired templates. For example, the Lateral Leg Spring (LLS) template [6] explains lateral stabilization [7] and helps to derive turning strategies [8, 9] for hexapedal runners. while the Sliding Spring Leg (SSL) model [10] extends LLS by incorporating the sliding effects of the leg-ground interaction. However, it is unclear how to map the parameters of such models to robot design and control parameters [11]. These challenges can be circumvented through kinematic templates.

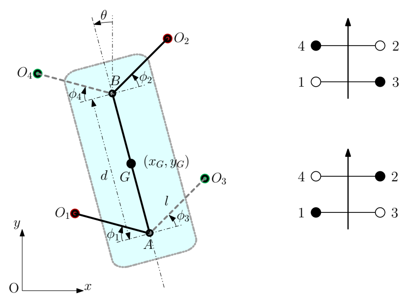
Although kinematic models tend to capture well robot behaviors in quasi-static operation regimes, no *general kinematic templates* for miniature legged robots are available. To be useful, such templates should be able to (i) capture salient behaviors of multiple robots, and (ii) facilitate analysis and control. To narrow this gap, the Switching Four-Bar Mechanism (SFM) model was introduced in [12], and was shown capable to capture the behavior of the miniature legged robot OctoRoACH [13] when crawling in low speeds. In the present work, we turn our attention to obtaining experimental evidence further supporting the hypothesis that the SFM may serve as a template for navigation of miniature robots operating in quasi-static regimes. Specifically, the paper uses data from three morphologically distinct miniature legged robots to show that the SFM can capture various atomic motion behaviors—i.e., motion primitives—on average, by employing only a small number of physically-intuitive parameters.

The work here also demonstrates the model's practical utility in performing navigation tasks with miniature legged robots. The constructed primitives are used by a Rapidly-exploring Random Tree (RRT) planner [14] to derive platform-compatible trajectories in environments populated with obstacles. These trajectories are subsequently realized on the robots in both open– and closed-loop navigation.

Developing the domain of navigation and control for miniature legged robots is important, given the potential of these robots. Legs support all-terrain mobility and high-maneuverability [15, 16], while low production cost and rapid manufacturing enable deployment in large numbers. Despite the growth in the area of design and manufacturing, the area of navigation and control—with a few exceptions [17, 18]—remains under-developed. The introduction of simple models such as the Switching Four-Bar Mechanism (SFM), which can both capture robot behaviors, and facilitate analysis and control, may accelerate progress.

2 Technical Approach

The SFM (Fig. 1(a)) is a horizontal-plane model comprising a rigid torso and four rigid legs [12] organized in two pairs, the right $\{AO_1, BO_2\}$ and left pair $\{AO_3, BO_4\}$, which turn active (take a step) with a 50% duty cycle (Fig. 1(b)). The torso and legs form two alternating (but symmetrical) four-bar linkages.

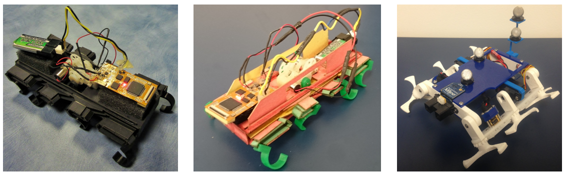


(a) (b)

Fig. 1. (a) The SFM. d is the length of the model, l the leg length, and G the geometric center of the model. (b) The model's foot-fall pattern.

The initial position of the legs is expressed by the leg *touchdown* angles (ϕ_1^{td} and ϕ_2^{td} for the left pair shown in Fig. 1(a)). The four-bar mechanism formed between the two pivot ground points O_1 and O_2 has one degree of freedom, taken here to be the angle of the hind leg of the corresponding leg pair, and thus ϕ_1 directly determines ϕ_2. At the end of the step all angles reach their *liftoff* configuration (denoted ϕ_1^{lo} and ϕ_2^{lo}). The touchdown and liftoff angles in the alternating pairs parameterize the model and determine how its output propagates spatially [12]. The state of the model is $q = (x_G, y_G, \theta) \in \mathbb{R}^2 \times \mathbb{S}$, while the equations that govern the model's state propagation are solved *analytically*. Using a least-squares constrained optimization we can identify model parameter values that enable the SFM to generate outputs that match the experimental paths of various robots, on average—see [12] for details on the procedure.

We use the three robots shown in Fig. 2. For each robot we consider three modes of operation (motion primitives): Straight Line (SL), Clockwise (CW), and Counter-Clockwise (CCW) turns. Robot state measurements are collected via a Vicon motion capture system, for a total of $N = 100$ trials for each case; each training path last for three seconds. Once the model is trained, it can be used for motion planning and control in support of navigation tasks of miniature legged robots in obstacle-cluttered environments.



(a) (b) (c)

Fig. 2. The robots studied here. (a) The OctoRoACH [13], designed at University of California, Berkeley. (b) A revamped OctoRoACH designed in-house, and (c) STAGBOT.

3 Results

The system identification approach described above has been applied to the two OctoRoACH robots. Table 1 contains the identified nominal parameter values, and errors in fit in the final states between the experimental averages and the output of the model. Figure 3 shows the experimentally collected paths and (trained) model outputs. The model outputs closely match the experimental averages in all cases. An additional benefit of this procedure is that it creates a look-up table to link model parameters—which will serve as control variables—to robot actuation inputs (motor velocities). This is important as it enables real-time feedback control that is guaranteed to be compatible with the platform at hand.

Table 1. Motion Primitives, Identified SFM Parameter Values, and Errors in Fit

Platform	Primitive Type	Model Parameters $\{\bar{\phi}^{\text{td}}, \bar{\phi}^{\text{lo}}, \theta^{\text{init}}\}$ [deg]	Error in Fit (in final state) $(\epsilon_x$ [cm], ϵ_y [cm], ϵ_θ [deg]$)$
OctoRoACH	SL	$\{65.57, 27.31, 0.00\}$	$(0.14, 0.57, 7.38)$
	CW	$\{38.78, 15.70, -15.00\}$	$(0.11, 0.21, 17.20)$
	CCW	$\{40.40, 11.65, 15.00\}$	$(0.35, 0.37, 19.55)$
Revamped OctoRoACH	SL	$\{0.06, -39.81, 0.00\}$	$(0.08, 0.64, 2.42)$
	CW	$\{23.96, 4.93, -15.00\}$	$(0.26, 0.47, 7.26)$
	CCW	$\{28.60, 11.30, 15.00\}$	$(0.21, 0.51, 7.91)$

Once the nominal model parameters are identified, the model can be used to solve motion planning problems. We have performed motion planning with the original OctoRoACH by implementing a primitives-based RRT planner in the obstacle-cluttered environment shown in Fig. 4(a). The resulting trajectory is sketched in Fig. 4(b). The sequence of primitives comprising the reference trajectory is then executed on the physical robot in open loop (Fig. 4(c)) in 15 trials. Because of the significant levels of noise and motion disturbances, evident in the experimental results of Fig. 4(c), the open loop approach has low probability of success (13.3%); closure of a control loop is mandated.

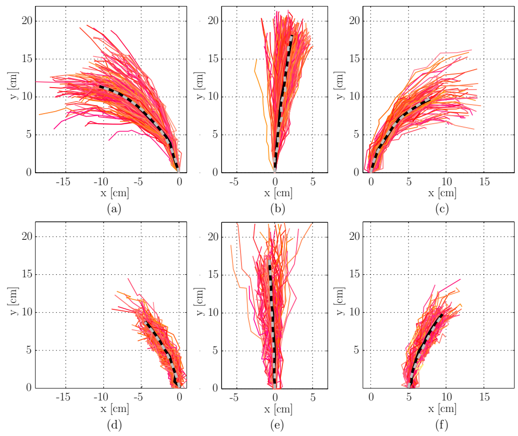


Fig. 3. Experimental data for the motion primitives of Table 1. Individual paths, experimental averages, and SFM outputs are shown with thin, dark thick, and lightly-shaded dashed curves, respectively. (a)-(c) CCW, SL, and CW primitives for the OctoRoACH. Similarly (d)-(f) for the revamped OctoRoACH. The model captures well all data sets.

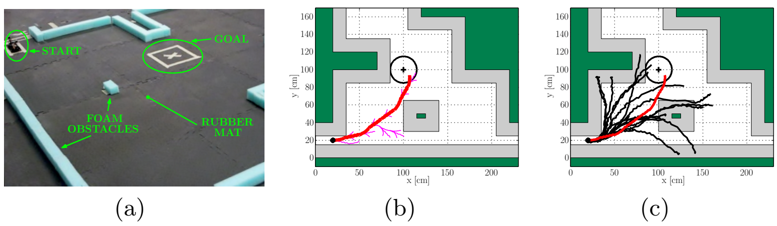


Fig. 4. (a) Physical realization of the test environment. (b) The RRT planner is combined with the primitives of Table 1 to generate desired trajectories (thick curves). Darker areas mark actual obstacles, while lightly-shaded areas indicate the augmented obstacle regions. (c) Application using OctoRoACH primitives in open loop.

4 Scheduled Experiments

The results obtained herein will be extended in three ways. First, we will test the efficacy of the SFM in capturing the behavior of a morphologically different palm-sized robot built in house, STAGBOT (see Fig. 2(c)). Similar to the OctoRoACH cases, we will consider three motion primitives (SL, CCW, and CW) and collect $N = 100$ sample paths for each case. We will then identify nominal model parameters that best capture the experimentally-observed paths, on average. Showing that the model captures the behavior of such a different robot will further support the hypothesis that the SFM may serve as a template for miniature legged robots in quasi-static operation regimes.

Next, we will develop a low-level controller based on the structure of the SFM that can be applied to both the OctoRoACH and STAGBOT. Apart from creating a means to mitigate the effect of noise and motion disturbances, this procedure will effectively open the way to *template-based* motion planning and control strategies for miniature legged robot that are required to perform navigation tasks. Last but not least, the proposed control and navigation strategy will be thoroughly evaluated in both open– and closed-loop configuration and for both the OctoRoACH and STAGBOT platforms when tasked to navigate to obstacle-cluttered environments similar to the one depicted in Fig. 4(a)

5 Main Experimental Insights

Experimental evidence from morphologically distinct robots may suggest that the Switching Four-bar Mechanism (SFM) can indeed serve as a template for miniature legged robots when performing navigation tasks in quasi-static operation regimes. Robot motion capabilities can be encoded in the form of motion primitives, and then a constrained optimization scheme can link robot control inputs to template parameters realizing these primitives. The SFM can integrate well with planners such as RRT, enabling motion planning at the miniature scale. It also affords closed-form expressions for state propagation, a feature which can be exploited to develop a low-level model-based trajectory tracking controller. This is crucial as the model itself in fact facilitates control by allowing for real-time optimization to be performed.

Desired primitives-based trajectories can be evaluated experimentally both in open and closed-loop, demonstrating the efficacy of the SFM in template-based navigation. Developing the domain of navigation and control for miniature legged robots is important, given the potential of these robots in a variety of interesting real-world applications such as building and pipe inspection, search and rescue, unobtrusive wildlife monitoring, as well as Intelligence, Surveillance, and Reconnaissance (ISR). Critical to successfully addressing the challenges in navigation and control at small scales is the availability of simple models that can both capture the behavior of the robotic platforms, and facilitate analysis and control. This work shows that the Switching Four-Bar Mechanism (SFM) template can be a useful tool along this direction.

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