Active stabilization of a stiff quadruped robot using local feedback

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Abstract-Animal locomotion exhibits all the features of complex non linear systems such as multi-stability, critical fluctuation, limit cycle behavior and chaos. Studying these aspects on real robots has been proved difficult and therefore results mostly rely on the use of computer simulation. Simple control approaches - based on phase oscillators - have been proposed and exhibit several of these features. In this work, we compare two types of controllers: (a) an open loop control approach based on phase oscillators and (b) the Tegotae-based closed loop extension of this controller. The first controller has been shown to exhibit synchronization features between the body and the controller when applied to a quadruped robot with compliant leg structures. In this contribution, we apply both controllers to the locomotion of a stiff quadruped structure. We show that the Tegotae-controller exhibits self-organizing behavior, such as spontaneous gait transition and critical fluctuation. Moreover, it exhibits features such as the ability to stabilize both asymmetric and symmetric morphological changes, despite the lack of compliance in the leg.

Index Terms— Tegotae, Modularity, Morphological changes, Closed loop dynamical system, Phase oscillator, Bifurcation, Basin of attraction, Critical fluctuation

I. INTRODUCTION

The question of how animals coordinate their body to perform stable, robust and efficient locomotion in different environments and different morphological conditions (e.g. asymmetric weight distribution or asymmetric leg) can help us better understand how brain and body interact to induce behavior. In the long term, this has the potential to lead to a generic control architecture that can allow any generic legged structure to learn autonomously how to use its body to move efficiently, depending on the specific physiological and environmental conditions.

An interesting approach to body coordination of a quadruped robot with compliant legged structure has been proposed in [1]. The control is created by a Central Pattern Generator (CPG) modeled as an open loop network of coupled phase oscillators. The results showed that the leg compliance naturally favored the synchronization of the legs to the coordinated state imposed by the controller, despite the blindness of the controller. A closed loop extension of this type of controller - so-called Tegotae-based control - has been proposed in [2]. This approach uses external force information as feedback to close the control loop. The feedback

acts so as to favor behaviors that will counteract the external forces. In the context of legged robots, the external forces are the ground reaction forces and the intended behavior is to have the leg counteract gravity by favoring a state where the leg is in its stretched stance position. More precisely, each leg movement is generated by a phase like oscillatory structure, and the phase of the oscillator, in presence of ground reaction forces, is accelerated towards the stretched stance position of the leg and slowed down thereafter. The interesting aspects of this control architecture are that it is algorithmically completely decoupled. Coupling is only induced by the mechanical connection of the legs through the body. This control architecture already showed the ability to allow quadruped robots to autonomously converge to different gaits by simply changing the speed [2], [3] or modifying the center of mass position of the robot [4].

Both examples used a compliant leg structure and four legs of the same length. In this contribution, we want to study the behavior of those control paradigms in a more systematic framework where we can modify the weight distribution and leg lengths to study the adaptation of the controllers to different conditions. Moreover, we use a quadruped robot with stiff leg structures to better separate the effects of the control and compliance. For each configuration, we systematically compare two types of high level controllers: an open loop CPG-based controller, similar to the one presented in [1], and its closed loop Tegotae-based version similar to the one presented in [3].

We start by describing the experimental framework of a generic quadrupedal structure with stiff legs actuated by a total of eight motors. We then describe the foot trajectory generation method and the suggested high level controllers (open loop and closed loop). Then, experiments with different morphological modifications are then run and the two controllers are compared in terms of stability, symmetry and cycle to cycle correlation.

II. METHODS

A. Experimental framework

With a view on studying the topics introduced, a simple quadrupedal morphology was chosen. It is composed of four planar limbs symmetrically mounted on a main body. Each limb consists of 2 degrees of freedom (DoF) and can only move in the sagittal plane. A model with the same characteristics was developed using *Webots* robotics simulator (Fig. 1a), and the respective hardware platform was built (Fig. 1b and 1c).

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Fig. 1. The robotic platform used in the experiments. (a) Model of the robot in simulation. The characteristics of the model are: $l_1 = l_2 = 104.5mm$ (limb segments), BH = 235mm (body height), BL = 390mm (body length), BWi = BH = 235mm (body width) and BWg = 1.4kg (body weight). Hardware implementation (b) isometric and (c) top views. The total weight of hardware platform is 2.2 kg.

The main components of the hardware platform are listed in Tab. I, according to the numbering of Fig. 1. All the functionalities of the robot are controlled by an *ODROID-XU4* computer, which collects a variety of information: ground reaction forces through four *Optoforce* sensors; DC current using an intermediary Arduino board for reading and sending the sensor data to the control computer; and inertial response by an IMU. The controller is also responsible for the trajectory following of each foot, for which it uses inverse kinematics and position control of every motor.

The 2 DoF of each limb are formed by Bioloid modules and custom parts, consisting two servo motors with a passive element attached in series. The design of the passive element is such that can easily be interchanged with elements of different dimensions and mechanical properties (e.g. spring stiffness). This allows the robot to quickly change its morphology and dynamics for both the whole body and single leg segment. In this work, we only used passive elements of different length while keeping the element as such stiff.

 TABLE I

 HARDWARE COMPONENTS IN THE ROBOTIC PLATFORM.

Number	Component
1	Dynamixel RX-28 servo motor
2	Interchangeable passive elements
3	Dynamixel AX-12 servo motor
4	Optoforce OMD-30-SE-100N 3D-force sensor
5	ODROID-XU4 embedded control pc
6	INA169 DC current sensor
7	Xsens MTi-3 AHRS IMU
8	USB2Dynamixel communication bus converter
9	LM2596S (12V) DC Voltage regulator

B. Foot trajectory

The two high level controllers further introduced in sections II-C and II-D output the phase of each limb (ϕ_i). Hence, their implementation requires a transformation between limb phase (ϕ_i) and motor actuations. As such, a trajectory is parametrized in cartesian space and then mapped to the limb phase ϕ_i , as shown in figure 4a. Fig. 2 describes how the trajectory is planned within the limb workspace, showing the



Fig. 2. Foot trajectory parametrization: end-effector trajectory shown in red for stance phase and in blue for swing phase, limb workspace represented in black, and limb postures during swing presented in gray. The end effector trajectory is parametrized by three parameters and follows the trajectory $p_1 - p_2 - p_3 - p_4$. h_{st} is the distance from position p_2 to the limit of the workspace (i.e. comparing to stretched limb) and h_{sw} , shown in the picture, is the distance from the workspace limit to position p_4 . A trajectory is defined by the maximum amplitude θ_{max} , medium height during swing phase h_{sw} , and medium height during stance phase h_{st} .

parameters that define swing phase (θ_{max} , h_{sw}). Stance phase is defined in the same fashion, by considering a parameter for height of stance h_{st} at the mid-point p_2 .

C. Open loop CPG-based control

Having all limbs represented as phase-oscillators, a first strategy is to use coupling terms between phase-oscillators to drive the system response towards a desired limit cycle [5], [6], [7], [1], [8]. Fig. 3a shows the network of phase-oscillators, where the time response of each limb i is described by the set of coupled differential equations given as

$$\dot{\phi}_i = 2\pi f + \sum_j w_{ij} \sin(\phi_j - \phi_i - \psi_{ij}) \tag{1}$$

where ϕ denotes the phase of oscillators and ψ is the desired phase difference between oscillators. The coupling terms



Fig. 3. Networks of phase-oscillators with couplings in the case of (a) open loop CPG and (b) no couplings in closed loop method based on Tegotae. During walking, limb 1 is the right-hind limb (RH), limb 2 is the left-hind limb (LH), 3 is the left-forelimb (LF) 4 is the right-forelimb (RF).

adjust the phase update of each oscillator, according to the phase of the neighbors ϕ_j , to the desired phase shift ψ_{ij} between limbs *i* and *j*, and to the weight of the coupling w_{ij} .

During a transient phase, the coupling between oscillators will have an important effect on driving the system from an arbitrary initial condition to steady state, where phase-locking occurs and all limbs oscillate at the same frequency $\omega = 2\pi f$, with phase differences equal to ψ_{ij} . A steady state gait can be performed, provided that the mechanical properties of the robot allow a stable transient and steady state phases.

By treating each limb as a phase oscillator with parametrized trajectory following, and therefore coupled motor actuation within each limb, this technique results in a big reduction of the search space. In the presented case, this allows a fast optimization of the trajectory parameters θ_{max} , h_{st} and h_{sw} alongside with the desired phase difference Ψ_{ij} and the transition phase ϕ_t .



Fig. 4. Transformation from limb phase ϕ_i to trajectory position in cartesian space. (a) Open loop CPG: phase-trajectory transformation dependent on transition phase ϕ_i allowing different duty factors. (b) Tegotae: Attraction to point p_2 proportional to feedback N_i and to $\cos \phi_i$.

D. Tegotae-based control

Whereas in the previous case coupling terms impose the gait to be performed in open loop, Tegotae relies on force feedback from the ground. Instead of enforcing a specific pattern as the open loop controller, it lets the coupling emerge as a dynamic interaction between the brain, body and the environment [4], [2], [3]. A set of separate non coupled phase-oscillators (Fig. 3b) is affected by the reflexes of ground contact in a decentralized fashion, and interact only through the dynamical behavior of the robot. It is important to mention that the ground contact forces are felt by each limb separately and the feedback is used locally by affecting only the movement of the corresponding leg. Implemented in a similarly as in [3], the local reflex mechanism results in an attraction to a stable point p_2 (Fig. 4b). The time evolution of each limb's phase (ϕ_i) is in this case given by the differential equation

$$\dot{\phi}_i = 2\pi f + \sigma N_i \cos(\phi_i) \tag{2}$$

where N_i is the normal ground reaction force and σ the attraction coefficient.

During transient, whenever force feedback is felt during a swing phase, the attraction created by the second term of Eq. 2 will drive the limb position to the mid-point of stance. All these independent corrections interact through the body dynamics of the robot and drive the system towards a steady state limit cycle where force feedback is experienced only during stance phase, given that the dynamics allow a steady state behavior.

III. EXPERIMENTS

This chapter starts by presenting the preliminary experiments and results that lead to the parameter selection needed for the subsequent research. After Sec. III-A the most relevant procedures of this work are mentioned as a guide to the results given later on.

A. Parameter selection

The first approach introduced based on open loop CPG results in a search space reduction and allows an effective gait optimization. In [9], the trajectory parameters θ_{max} , h_{st} and h_{sw} were optimized in simulation alongside with the intrinsic frequency f and the three desired phase shifts ψ_{12} , ψ_{23} and ψ_{34} using Particle Swarm Optimization (PSO). As a result of the optimization process, convergence to walking-trot was observed for speeds up to 1.3 $BL \cdot s^{-1}$ (Fig. 1a), showing the characteristic of stretched knee during stance phase ($h_{st} \approx 0$).

To validate the convergence results, trot was compared in hardware to other walking gaits observed in nature, namely diagonal-sequence (D-S) walk and lateral-sequence (L-S) walk. These experiments were performed at a low frequency (f = 0.25 Hz), with a trajectory defined by $\theta_{max} = 0.3rad$, $h_{st} = 0mm$ and $h_{sw} = 15mm$, and allowed the measurement of average speed of the center of mass ($\overline{v_{CM}}$) and energy efficiency (ε_t). These measurements were collected over 5 one meter runs, where energy efficiency (ε_t) is computed as the distance traveled over the electric consumed by all motors, the latter being extracted from the current sensor. The results can be seen in Tab. II, and indicated that both the average speed ($\overline{v_{CM}}$) and the energy efficiency (ε_t) are significantly better during trot.

Hence, the initial focus of this work was driven towards trot gait, where the influence of the trajectory was studied in order to fix its parameters. The desired phase shifts ψ_{ij} were removed from the search space by fixing them according to trot ($\psi_{12} = -\psi_{23} = \psi_{34} = \pi$). Likewise, a stance height of $h_{st} = 0$ was beneficial on hardware in terms of energy energy efficiency. At last, a set of 25 experiments was conducted at a low frequency (f = 0.25 Hz) to evaluate the grid of the parameters for (h_{sw} , θ_{max}), with $h_{sw} \in \{5, 10, 15, 20, 25\}mm$ and $\theta_{max} \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$.

TABLE II Comparative Gait Analysis on Hardware

Imposed Gait	$\overline{v_{CM}}[cm \cdot s^{-1}]$	$\varepsilon_t[m \cdot kJ^{-1}]$
Trot	5.9	4.042
D-S walk	3.5	1.583
L-S walk	3.2	1.87

By collecting current measurements during each of the performed gaits, it was possible to compare the different energy efficiencies $\varepsilon_t[m \cdot kJ^{-1}]$, which corresponded to the possible traveling distance per kJ of energy spent. The first step was to extract the base current consumption, drawn by motor controller boards of the Dynamixel servo motors when the actuators are disabled. The base was then subtracted from the total measurements to obtain the energy efficiency curve shown in Fig. 5. The figure illustrates that the selected value of h_{sw} should be just enough to allow good ground clearance, but not higher, as lifting the foot higher increases energetic costs. Moreover, h_{sw} should not be smaller than the optimal value since the foot can touch the ground sooner than anticipated due to noisy body oscillations which would result in energy loss such as unintended friction. Regarding θ_{max} , it has a linear effect on speed and appears to affect energy efficiency positively. However, too big steps increase the body oscillations, which may cause divergence from the limit cycle behavior, especially at higher speeds. Our aim was to pick a safe trajectory which could result in stable limit cycle in the range of speeds tested. Thus, we proceeded the experiments by fixing $\theta_{max} = 0.3$ rad, $h_{st} = 0$ mm and $h_{sw} = 15$ mm. Due to hardware limitations that resulted in large tracking errors (bandwidth saturation of the servo motors), we did not perform experiments on imposed frequencies f larger than 0.75 Hz.

B. Emergence of gaits

Considering now the closed loop decentralized control of each limb, the first series of experiments was intended to examine the capacity of the control to drive the system to steady state limit cycle locomotion from any initial condition. Three sets of experiments were performed on hardware, starting from the initial conditions described in Tab. III. For each of these sets, the transient response was recorded for $\sigma \in [0.05, 0.1, 0.15, 0.2, 0.25]$, until steady state was reached, where phase differences remained constant.



Fig. 5. Energy efficiency (ε_t) of trot gaits dependent of trajectory parameters h_{sw} and θ_{max} after extraction of base current.

TABLE III	
CONVERGENCE ANALYSIS - INITIAL CONDITIONS	s

Initial Gait	ϕ_0
In-phase limbs Lateral-Sequence walk Diagonal-Sequence walk	$ \begin{bmatrix} 0, 0, 0, 0 \\ [3\pi/2, \pi/2, 0, \pi] \\ [\pi/2, 3\pi/2, 0, \pi] \end{bmatrix} $

C. Steady state limit cycle gaits

Once the effect of local feedback during transient phase was evaluated, the obtained steady state behavior was studied. Using the trajectory parameters explained in section III-A, gaits with different attraction coefficients σ were analyzed. The experiments made are described in Tab. IV, where for different frequencies a range of σ values was tested. $\sigma = \sigma_{min} = 0$ corresponds to imposing open loop walking-trot. Throughout these experiments, the following variables are measured: the orientation of the robot, average speed ($\overline{v_{CM}}$), the DC current used by all the motors, feet contact forces and joint angles. This allows the tracking of a rich set of sensor data that reflects the robot's locomotion characteristics.

TABLE IV Steady State Limit Cycle Analysis

f [Hz]	σ_{min}	σ_{max}	nr. of experiments
0.25	0	0.25	6
0.5	0	0.3	7
0.75	0	0.5	9

D. Gait adaptation experiments

Taking advantage of the versatility of the robotic platform, a final series of experiments was performed, applying certain morphological changes. Two types of morphologic adjustments were made: (i) variation of mass distribution by a 10% body weight increase (225g) distinctly positioned and (ii) modification of limb length (l_1 , l_2 or both). The set of experiments performed is described in Tab. V and can be divided into two groups of changes: symmetrical or asymmetrical in terms of left-right body symmetry. Experiment



Fig. 6. Force measurements of each limb *i* (F_{ix} in red, F_{iy} in green and F_{iz} in blue) showing convergence to limit cycle behavior correspondent to trot - in-phase initial condition and $\sigma = 0.1$.

0 refers to the initial state presented above, experiments 1 to 3 are induced asymmetries to the robot, whereas the last two represent morphological changes of having shorter hind limbs (Exp. 4) and shorted fore limbs (Exp. 5). All the experiments of this section were performed with f = 0.75Hz. For the open loop cases, trot is imposed, while in the closed loop case $\sigma = 0.3$.

TABLE V Gait Adaptation Analysis

Exp.	Type of perturbation	location
0	none	
1	+ 5 <i>mm</i> in l_2	limb 4
2 3	10% of added weight	between limbs 1 and 4 above limb 3
4 5	- 25 mm in l_1 and l_2	hind limbs (3 and 4) forelimbs (1 and 2)

IV. RESULTS AND DISCUSSION

A. Convergence to walking-trot

The gait convergence can be seen in various parameters such as oscillator phases or ground contact forces. In this first part, ground contact forces are reported to show the convergence of the gait cycles since they are directly measured with sensors. Fig. 6 shows the 3-dimensional ground reaction forces of each foot. In this experiment, the limbs start in-phase ($\phi_i(0) = 0, 1 < i <= 4$)) and, with $\sigma = 0.1$, the relatively fast adaptation of the limb phases by physical communication towards a stable periodic trot is visible. Referring to the experiments described in Sec. III-B, starting from any of the initial conditions given in Tab. III, the resulting steady state behavior is a walking-trot.

The speed of convergence from in-phase initial condition was found to decrease with increasing σ , as shown in Fig. 7a.



Fig. 7. Convergence characteristics. (a) Convergence time (CT) of the gait, from in-phase oscillations to steady state trot oscillations, with respect to the attraction coefficient σ . (b) Phase evolution of the first limb in presence of the high attraction coefficient ($\sigma = 0.5$) and low frequency (f = 0.25 Hz).

The attraction coefficient σ should therefore be high enough to allow a fast convergence to the stable limit cycle. However, if this attraction is too high, the phase evolution right after the convergence will be slowed down (Fig. 7b) resulting in highly reduced locomotion speed. This is caused by the second term of Eq. 2 counteracting the progressive movement of the first term such that $\dot{\phi}_i$ goes towards zero which results in the phase getting stuck in the attraction point.

B. Steady state limit cycle behavior

After observing the convergence of the system to trot gait, the steady state behavior of the initial morphology was studied according to section III-C. By comparing open loop cases ($\sigma = 0$) and closed loop ones with increasing σ , it is possible to see certain advantages of the latter. The limit cycle response is imposed in open loop control by the oscillatory couplings. However, the closed loop control method with Tegotae modifies the gait depending on the real-time force feedback, even though the emerging gait was almost always trot. Fig. 8 highlights some advantages by comparing the open loop case and a closed loop one with $\sigma =$ 0.3 and f = 0.75 Hz. After performing both experiments, 5 consecutive cycles were selected and their inertial responses presented first in terms of roll versus pitch. This represents an inverted pendulum behavior of the robot's body. Each cycle is colored from blue in the cycle beginning to yellow in the end. Then, the time evolution of the yaw angles is shown. In this representation, two main advantages are observable. First, in the open loop case, the orientation suffers from rough changes as can be seen in the peaks of roll×pitch which derive from certain foot collisions with the ground which generate slippage. This is correlated with the drift seen in yaw for the open loop case (Fig. 8c). Second, the decentralized closed loop approach makes the limit cycle more smooth, reducing limping and allowing therefore a more straight locomotion pattern.

In order to support the visual observation drawn in previous parts, quantitative analysis were performed for some findings. A set of metrics was defined and computed over



Fig. 8. Initial Morphology (Symmetric): (a) Open and (b) closed loop pendular behaviors observed in roll (Φ) *versus* pitch (Θ). (c) Yaw angle drift in time for both control methods.

a group of 5 consecutive cycles for each experiment. The procedure defined here is used for the results of section IV-C. In order to show the periodicity of gait cycles, three (5×5) correlation coefficient matrices $(\rho_{\Phi}, \rho_{\Theta}, \rho_{\Psi})$ over the gait cycles of an experiment are computed for each roll(Φ), pitch(Θ) and yaw(ψ) angles during the locomotion. The upper triangle of each correlation matrix is then averaged independently for all individual experiments to obtain the average correlation coefficients ($\overline{\rho}_{\Phi}, \overline{\rho}_{\Theta}, \overline{\rho}_{\Psi}$). The average drift of yaw in these 5 cycles (in degrees) is denoted as Ψ_{trend} .

In Tab. VI, these metrics computed for each experiment are presented. Regarding the results for this set of experiments, the improvement in Ψ_{trend} is observed, however the closed loop seems to have a slightly worse periodicity over gait cycles. This almost negligible effect could be due to the realtime corrections stemming from Tegotae (e.g. a premature touchdown modifies the phases of gait oscillators, thus affecting periodicity), as well as force sensor noise which does not occur in the open loop case.

TABLE VI GAIT ADAPTATION RESULTS

Exp.	Controller	$\overline{ ho}_{\Phi}$	$\overline{ ho}_{\Theta}$	$\overline{ ho}_{\Psi}$	Ψ_{trend}
0	OL	0.979	0.963	0.912	1.9
0	CL	0.977	0.955	0.904	-0.1
1	OL	0.989	0.989	0.962	-1.6
1	CL	0.989	0.981	0.961	-1.3
2	OL	0.944	0.958	0.784	-5.5
2	CL	0.858	0.836	0.699	-2.0
3	OL	0.526	0.517	0.837	5.7
3	CL	0.747	0.675	0.803	2.6
4	OL	0.992	0.986	0.937	-0.3
4	CL	0.982	0.959	0.979	-1.0
5	OL	0.998	0.997	0.977	-1.8
5	CL	0.995	0.994	0.870	-0.7



Fig. 9. **Experiment 1 (small asymmetry):** (a) Open and (b) closed loop pendular behaviors observed in roll (Φ) *versus* pitch (Θ) .



Fig. 10. **Experiment 2 (distinct asymmetry):** (a) Open and (b) closed loop pendular behaviors observed in roll (Φ) *versus* pitch (Θ). (c) Yaw angle drift in time for both control methods.

C. Gait adaptation

Following now the experiments described in section III-D, a small perturbation was initially introduced by increasing the length of the second segment (l_2) of limb 4 by 5mm (Exp. 1). The pendular behavior for this case is shown in Fig. 9. Comparing again the open loop and local feedback cases, and having seen the respective ones for the symmetric case (Fig. 8), it can be inferred that the closed loop technique approximates the dynamical response towards the non-perturbed system. By looking at Tab. VI, a slight improvement of Ψ_{trend} is observed, and the periodicity of the limit cycle remains nearly the same.

Moving further in the experiments, more pronounced asymmetries were created by adding extra weight in specific regions. The result of experiment 2 is presented in Fig. 10, where it is seen that the closed loop limit cycle is in this case much less periodic (also visible in Tab. VI). This effect is due to the hard corrections being constantly performed to counter the effect of the asymmetric weight distribution, and the turning caused by the additional weight is considerably removed. In fact, 64% of the negative Ψ_{trend} is removed with the closed loop approach showing active correction properties. In addition, the limit cycle of the closed loop control is resembling the limit cycles of the symmetric structure (Fig. 8).

The third experiment where the extra weight is placed on the left forelimb results in a significantly different gait. All of the other experiments exhibited periodicity of body oscillations over consecutive gait cycles. However, this experiment results in a gait which has periodicity over two cycles. Odd numbered gait cycles are quasi periodic among the other odd numbered cycles and the even numbered gait cycles are periodic among the even ones (i.e. cycles 1, 3, 5... are similar to each other and cycles 2, 4, 6... are also similar among each other but cycles 1 and 2 are significantly different). The main reason is the mass concentrated in the corner of the robot. The momentum of the extra mass during one cycle affects the second one, yet, that effect is reversed in the third cycle. Thus, the proposed metrics might not be suited to catch the specifics of this experiment to compare it with the others; a more elaborate metric could be implemented in future work.

The last discussion is about the effects of having smaller hind or fore limbs, respectively experiments 4 and 5. The results of the first case are presented in Fig. 11 where a new type of limit cycle (D-S) appears. Now, instead of treating the morphological change as a perturbation and pushing the locomotion pattern in the direction of trot, a different symmetrical behavior emerges. In the case of open loop, despite the left-right symmetry of the new configuration, the imposed trot gait results in a periodic but asymmetric limit cycle. On the other hand, the local feedback actively adjusts the phases to allow a symmetrically oscillating body motion. The limb phase oscillations are shown in Fig. 11c, where the limbs are reordered into $[\phi_3, \phi_1, \phi_2, \phi_4]$ to favor the comparison between diagonal limbs. While in the first diagonal $(\phi_1 - \phi_3)$ hardly any change occurs from the initial trot condition to the steady state one, in the second one $(\phi_2 - \phi_4)$ a dephasing occurs during transient and is kept throughout the steady state oscillation. The phase shift between diagonals is also adapted, pushing the footfold pattern towards a diagonalsequence walk. This gait interestingly is observed in primates [10] [11] where the walking posture includes a positively tilted torso, alike our morphology. Ground contact forces are also more evenly distributed through all the limbs in the case of closed loop. Regarding limit cycle periodicity (Tab. VI), closed loop with a gait different than trot reaches a similar performance to the open loop trot, strengthening the idea of an adapted gait.

In the final case of having shorter forelimbs (Exp. 5), gait adaptation was also observed, however without significant drifts from the trot gait.

V. CONCLUSION

In this work, a simple local feedback rule for legged locomotion is compared to standard open loop phase oscillators. A quadruped robot with planar limbs and force sensors as the end effectors was modeled in simulation and built in hardware. First, a suitable leg trajectory has been chosen according to experiments performed in simulation and hardware evolving around the cost of transport. Then, a chosen trajectory was used to compare the two control approaches in different morphological conditions.



Fig. 11. **Experiment 4 (small hind limbs):** (a) Open and (b) closed loop pendular behaviors observed in roll (Φ) *versus* pitch (Θ). (c) Limb phase oscillations during closed loop gait - convergence towards diagonal-sequence (D-S) walk - oscillations from top to bottom are ϕ_3 , ϕ_1 , ϕ_2 and ϕ_4 .

These morphologies include asymmetric modifications such as off-centered mass distribution and single-leg elongation and symmetric modifications such as the shortening of hind or fore limbs. The roll, pitch and yaw angles as well as ground reaction forces were recorded.

The results show several interesting properties of the controller. First, regarding the open-loop controller, the results suggest that the lack of compliance in the leg does not prevent the body from synchronizing with the controller, although the observed gait is less dynamic and less stable. Second and more interestingly, the Tegotae-based control not only increases the symmetry of the generated gait when compared to the open loop controller but also exhibits autonomous gait transition induced by morphological changes. Another remarkable feature is its ability to stabilize (symmetric) gaits in case of asymmetric morphological changes. This shows that a simple mechanism can be used to generate and therefore study the interesting dynamic features of animal locomotion that are their robustness (limit cycle behavior) and their adaptability (critical fluctuation [12] and multistability [13]).

Locomotion is a complex interaction between three systems: the brain, the body and the environment. This paper is one more step towards the discovery of a "as simple as possible but not simpler" generic paradigm for the control of legged robots. "Simple" to facilitate the understanding of the system but "not simpler" to have enough complexity to exhibit the dynamic features of interest.

The follow up research interests appearing from this study that will form our future work are two-fold: exploring the effects of (i) the surface parameters (friction, texture, stiffness, roughness) in Tegotae-based control since the oscillators are only coupled through physical interactions of the robot and the environment, (ii) the structural stiffness when the morphology of the robot is subjected to the changes addressed in this paper.

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