Role of feedback and local coupling in CNNs for locomotion control of a quadruped robot

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***Abstract*—This paper focuses on the role of sensory feedback in a network of neural oscillators used as CNN cells for locomotion control of a simulated quadruped robot. The oscillators are locally connected only through load feedback: each cell receives inputs from the neighbouring legs load signal allowing a phase synchronization that is at the basis of the emergence locomotion gait. Gait transition is then controlled by the oscillation frequency and the connectivity scheme among load signals and CNN neurons, resulting in a load dependent multi template controller.**

***Index Terms*—Neural oscillators, Central Pattern Generator, locomotion gait, dynamical simulation**

I. INTRODUCTION

Body-Brain and Environment can interact each other in different ways and one of the most important outcomes of this process is locomotion. The Central Pattern Generator (CPG) paradigm assumes that neural centers provide feedforward locomotion signals often without the presence of sensory feedback [1], however a different paradigm, relying primarily on sensory reflexes was proposed [2]. This solution, called decentralized approach, is evident in species like the stick insect where the locomotion emerges due to the presence of different sensorial inputs processed locally. The interaction with local processing units takes place at the leg level to generate coordination rules. In this case the emerging gaits are called free gaits and, in some conditions, can match the stereotyped gaits generated by the CPGs.

In this paper, the main attention is focalised to the extreme enhancement of the role of feedback (in particular load feedback) in the generation and transition among gaits in a modular CPG controlling locomotion in a simulated quadruped robot. To this aim, the basic oscillator unit, seen as a CNN cell will be presented, which takes inspiration by the Matsuoka neuron [3]. This neuron has been arranged to generate an half-center oscillator applied for the generation of locomotion gaits as used in [4]. A suitable modification of the such dynamics equations has been here performed eliminating the direct connections among the cells to enforce the feedback connections coming from the environment. In this way the overall structure will be much simpler than [4] and able to control motion in a basic two-leg module. For comparison with Fukuoka's work [4], application to quadrupedal locomotion will be dealt with in this paper. Some simulation results will be reported, where the suitability of the approach both in generating and in controlling gait transition will be analysed.

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II. QUADRUPEDAL LOCOMOTION

Animal locomotion is characterised by different gaits, i.e. adaptive sequences of limb motions which, even if in most cases pre-programmed, can be suitably shaped depending on the environment characteristics in order to reach a suitable compromise with energy constraints [5]–[7].

In this paper, particular attention will be devoted to the quadrupedal locomotion discussed by Fukuoka [4] and Owaki et al. [8], since these works aimed to study, through dynamic simulations, how the load feedback is able to contribute to the transition among different gaits. This is quite interesting in view of the interplay between the descending commands from the central nervous system and the local response of peripheral musculoscheletal structure. This is a typical example of embodiment, where adaptive behaviors emerge from the interaction among body and brain. Owaki et al. [8] designed and realised a neuron model consisting in a dynamical system where oscillation or convergence towards equilibrium points depends on local proprioceptive feedback. The approach was conceived for a very simple robot. Physiological studies reveal that somatosensory feedback is the main source of information for the stabilization of terrestial locomotion. Therefore, in [4], the authors introduced a quadruped robot controlled by a CPG network consisting of four motor neurons, each one arranged in a flexor-extensor couple with mutually inhibitory connections, each one in charge of controlling the dynamics of a single leg. Here feedback depended on local load and position. Following this approach, the authors were able to obtain a variety of different gaits, migrating from lateral sequence to trot to gallop as a function of some CPG speed parameters, maintaining the same hard wired CPG structure. The main drawbacks of the approach are the presence of side walls which prevented the structure from deviating from straight motion or stability loss, and the fact that the prismatic actuation of the knee joints (biologically unplausible) made the load sensor reading quite robust against typical disturbances in legged motion. In this paper, taking into account the basic novelties of the approaches just mentioned, we designed and implemented a modified version of the CPG with the aim to increase the role of load feedback by eliminating direct connections among all neurons and also adopting a more biologically plausible rotary joint in the robot knees, obtaining a number of different gaits and gait transitions as a function of intrinsic frequencies and load feedback spatial connection arrangement that acts as a Multi-template approach [9] with a large emphasis on environmental feedback. The robot was able to show a stable locomotion both in steady state conditions and while migrating through the different gaits during unconstrained walking. Another advantage of the proposed CPG network is that the elimination of direct links among ipsilateral legs allows the design of a basic CPG unit suitable for controlling a biped module, to be easily extended to multi legged structures, since intermodule information comes only through load signals.

III. Robot and CPG model

In this section, following a quadrupedal robot prototype already built in our laboratory, a computational quadruped model has been developed using the dynamic simulation environment V-REP [10].

The model, reported in motion in Fig.3, consists of four identical legs actuated through three revolute joints and a cylindrical foot attached to each leg through a prismatic passive joint that acts as a shock absorber, able to sense the leg loading. Also two appendages were applied at the extremes of the robot trunk, acting as head and tail and ready to be actuated for future experiments. On the contrary of the work proposed by Fukuoka, no side-walls where placed to limit the robot movement to a planar motion; so the reported simulations are related to unconstrained walking. Simulations were performed with a integration time $\Delta = 1ms$, the control system was developed in Matlab and the model realized in V-Rep was interfaced using remote API.

The CNN CPG structure controlling the robot locomotion is reported in Fig.1, whereas the dynamical model representing the single cell is reported in the following equations:

$$\begin{aligned} T_r\dot{u}_{ei} + u_{ei} &= \gamma[u_{fi}]^+ - bv_{ei} && \text{(1a)} \\ &+ s + feed1_{ei}, && \text{(1b)} \\ T_a\dot{v}_{ei} + v_{ei} &= y_{ei}, && \text{(1c)} \\ y_{ei} &= [u_{ei}]^+ = max(u_{ei}, 0) && \text{(1d)} \end{aligned}$$

$$\begin{aligned} T_r\dot{u}_{fi} + u_{fi} &= \gamma[u_{ei}]^+ - bv_{fi} && \text{(2a)} \\ &+ s + feed1_{fi} + \sum_{j=1}^{4}(feed2_{fj}), && \text{(2b)} \\ T_a\dot{v}_{fi} + v_{fi} &= y_{fi}, && \text{(2c)} \\ y_{fi} &= [u_{fi}]^+ = max(u_{fi}, 0) && \text{(2d)} \end{aligned}$$

$$\begin{aligned} feed1_{\{e,f\}i} &= \pm k_1 \times (\theta_i - \theta_0), && \text{(3a)} \\ feed2_{fj} &= \pm k_2 \times Leg\_load_{fj}, && \text{(3b)} \end{aligned}$$

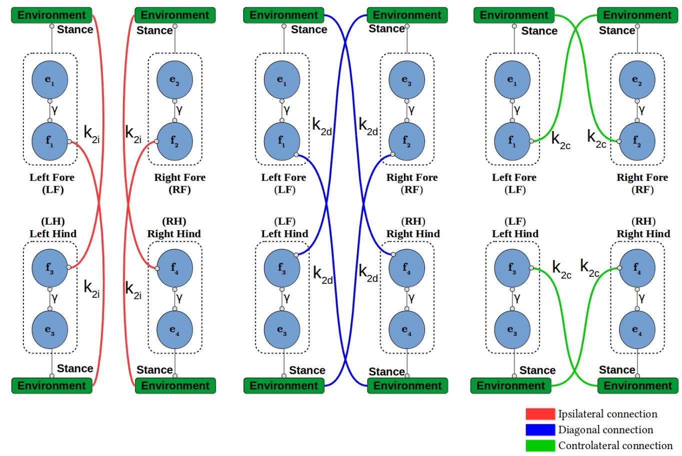


Fig. 1. Afferent load feedback connection types. Ipsilateral connections (left), diagonal connection (middle), contralateral connection (right). All links are bidirectional

This model exactly matches a CNN cell structure, where the terms in the second member of eq.(1a), (2a) represent the feedback and state template term, respectively; the terms in eq.(1b) and (2b) represent the bias terms and the control template entries, respectively, whose input are the feedback signals. Notably, the template structure is very simple: only the control template will have non diagonal entries different from zero (owing to $feed2_{fj}$).

Here we use the same parameter labels as in [4], to outline similarities and differences. As in [4], in these equations the suffix e, f and i denote the extensor, the flexor, and the leg number (i.e. 1: left front, 2: right front, 3: left hind, 4: right hind), respectively. Therefore each sub-unit of the CPG-CNN cell (Eqs. (1) and (2)) is made-up of two differential equations representing the extensor and flexor activity, respectively. The basic frequency of the CPG is determined by the time constants T_r and T_a. The variable s is a bias term which models the descending signal from the higher brain centres. The parameter γ weights the flexor- extensor interaction within each CPG-CNN cell. A first clear difference on [4] is the total absence of connection weights between the contralateral and ipsilateral neurons, that pre-determine interlimb coordination. In such a way, each leg will show a motion independent of the others. Coordination will be a result of feedback in a completely decentralised manner. The term $feed1_{\{e,f\}i}$ and $feed2_{fj}$ represent the sensory feedbacks, the latter standing for the connections among the leg oscillators and reporting load feedback from neighboring legs; θ_i is the actual hip joint angle; finally k_1 and k_2 will be positive (negative) in case of excitation (inhibition) of the target leg i. $y_{\{e,f\}i}$ are the outputs of the extensor and flexor neurons of the ith leg (Eqs

1d and 2d). All the above parameters are the same for each CNN-CPG cell controlling each leg. Fukuoka [4], reported a set of parameters useful for the generation of a trotting gait, assessing that other gaits or gait transitions are elicited by two type of variations: the *speed parameters* (s and T_r in equations above) contained in each CPG cell equations and a leg self-inhibition coming from load feedback.

On the contrary, this work proposes a different approach, in which, starting from a CPG configuration with a predefined set of parameters (Table I), gait generation and/or transition are achieved only by changing the a subset of parameters as reported in Table II and the load feedback connection among the legs: each leg does not receive its own load signal but from the other ones, following an appropriate connection scheme. Moreover another fundamental difference is that in our model there is no direct connection among motor neurons controlling neither ipsilateral nor contralateral legs. In fact these connections, which were present in the original system [4], were discovered to heavily constrain leg motion, preventing a flexible migration among certain gaits which requires particular phase arrangement. Moreover this leads to the formulation of a CPG module comprising only one leg controller and feedback from the body through a neighbouring leg; this can be easily extended to two (in case of quadrupeds) or several leg couples (for example hexapods). It has to be emphasised that this situation does not impose any phase constraint among legs and so there is no pre-determined gait. Initial gait is a function of initial conditions which are subsequently overcome by load feedback.

Parameter	T_a	b	γ	θ_0	k_1
Value	0.6	3	2	0	3

TABLE I
PARAMETERS ADOPTED IN THE CPG. THIS CONFIGURATION IS COMPLETED BY SETTINGS THE OTHER PARAMETERS THAT DEPEND ON THE SELECTED LOCOMOTION GAIT.

Anderson et al. [11] reported that a sinusoidal hip movement entrains the rhythm of the CPG during fictive locomotion, and that feedback from the hip joint can exert the central network in generating fictive locomotion. Many modeling studies have demonstrated that it is very important to adjust the CPG through this hip joint feedback if successful steady locomotion is to be achieved [12], [13]. For this model, as in [4], each hip joint angle was multiplied by the constant gain k_1 and simply provided in input to the CPG of each leg, as in Eq.3. Without this feedback, the model, as in [4], would gradually drift away from the CPG rhythm during stepping, no longer being able to walk. Another difference from [4] lies in the different approach used when dealing with load feedback. Specifically, this sensory feedback of each leg does not affect its CPG but the neighbouring ones, according to the three specific connection types shown in Fig.1. Afferent signals from each leg i are inputted into the CPG (flexor side) of the contralateral/ipsilateral/diagonal leg j and may be excitatory or inhibitory, according to the needs. What reported above is used to generate the CPG phases, whose signals are used to define the specific state (stance or swing) of each leg. While in each phase, the corresponding leg will move towards a specific reference angle under the control of classical position PID controller, as reported in [4].

Gait	s	T_r	$k2_i$	$k2_c$	$k2_d$
Lateral Sequence	2	0.16	-0.04	0.08	0
Trot	2.6	0.12	0	0.04	-0.08
Canter	3	0.6	0.12	-0.04	0
Gallop	3	0.6	0.08	-0.08	0

TABLE II
PARAMETERS ADOPTED FOR DIFFERENT GAITS.

IV. GAIT GENERATION AND TRANSITION

The simulation starts imposing initial conditions on the state variable for each neuron, and fixing a set of parameters from Table II, useful to elicit a particular gait. The transient to the gait imposed resulted quite short.

Following this strategy, a number of stable distinct gaits were obtained, like lateral sequence, trot, canter and gallop. As discussed above, the strategy here introduced for obtaining a completely decentralised controller can be viewed as a Multi-Template approach to locomotion based on a number of parameters that can be downloaded into the structure to obtain a specific gait. The parameter set is reported in Table II, where s and T_r are the speed parameters in eq. (1) and (2), whereas $k2_i$, $k2_c$ and $k2_d$ refer to the connections reported in Fig.1 to represent the gains $k2$ in eq. (3) in ipsilateral, contralateral or diagonal connections respectively.

For space reasons, from the number of different simulations performed, here one result about the transition between two different gaits, namely Lateral sequence to trot, is reported to show the suitability of this kind of decentralised approach to locomotion control.

Lateral sequence is a four beat-gait, typically at low speed: the quadruped will alternate between having three or two feet on the ground. In the proposed network, this gait was obtained with a negative ipsilateral load feedback and a positive contrataleral one, as depicted in TableII.

The phase drivers of the legs, i.e. the flexors output, display how the legs are shifted among them (Fig. 2 from $8s$ to $10s$). The canonical lateral sequence footfall sequence observed in quadruped was obtained.

Trot is a two beat gait, characterised by high stability: here legs are diagonally zero-phase synchronized. In our simulations, the emergence of this gait was observed through the application of a negative leg load diagonal feedback i.e. between LF-RH and RF-LH, $k2_d = -0.08$, at the aim to make diagonal legs to move in synchrony, elimination of ipsilateral connections, and a weak positive contralateral connection, as reported in Table II. The other two parameters s and T_r acted to speed-up the neuron intrinsic frequency. The transition from lateral sequence to trot can be appreciated in Fig.2 from $10s$ to $13s$.

In details, the structure was initialised with the proper parameters able to elicit lateral sequence. Then, after $10s$ of

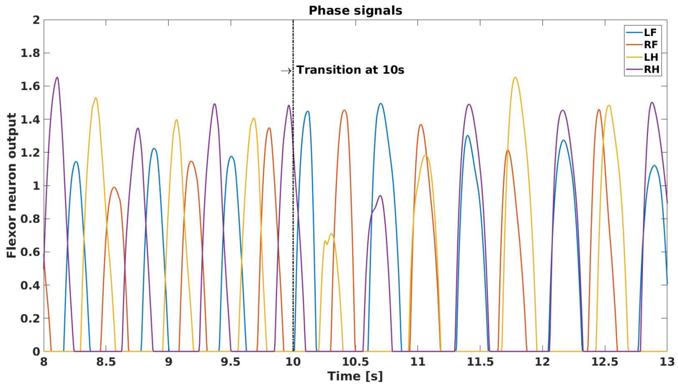
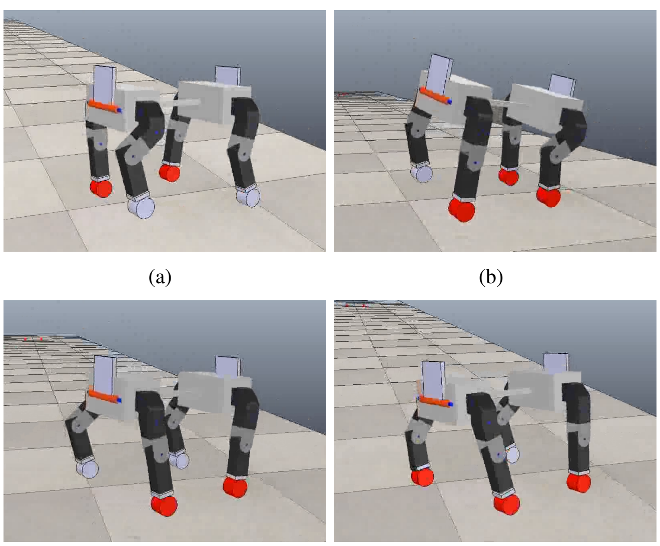


Fig. 2. Flexor output of the networks neurons: The plot displays that after 10sec of simulation the flexor phase changes according to the desired gait after a small transient. A temporal sequence of 5s of simulation is displayed.

simulation, parameters were switched to those ones for the trot gait. After about $0.5s$ the synchronization among the diagonal legs can be appreciated, as typical of the trot gait, depicted in Fig4. Notably that the gait is not strictly stereotyped, due to unavoidable balance fluctuations taking place in a realistic dynamical simulation environment, where leg loading feedback plays a primary role in this purely decentralised approach.

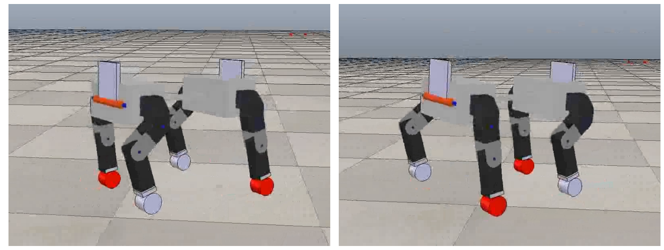


(a) (b) (c) (d)

Fig. 3. Snapshots showing lateral sequence: supporting feet are depicted in red. During the phase (a) right ipsilateral legs are in stance while the others are finishing the swing phase in order to be ready for the (b) phase in which three legs are touching the ground. Subsequently in (c) the right hindleg goes in swing and the robot is only supported by the two left ipsilateral legs but since the right foreleg in finishing its swing phase, in (d) a three support arrangement is re-established.

V. Conclusion

The aim of this work was to investigate the design and implementation of a minimalistic CPG network, possessing a minimal number of fixed connections and in which control of



(a) (b)

Fig. 4. Snapshots showing trot simulation.

interlimb coordination is mainly obtained using load feedback from environment. This is particularly outlined in the results reported, since a completely decentralised CNN-based CPG controller was implemented, where each neuron leg controller is completely independent on the others, receiving control signals only from load feedback. This is a successful result of an entrainment among body and neural controller. This work opens the possibility to realize a very simple network with simpler computational neural models joined to a completely decentralized approach. The present experiments can represent a fundamental starting point towards the emergence of highly adaptive locomotion strategies in front, for instance, of leg accidents.

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