Central Pattern Generators with Phase Regulation for the Control of Humanoid Locomotion

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***Abstract*— Central Pattern Generators have brought new and progressing results to bipedal walking, making it an interesting field of research with a dissimilar approach to typical ZMP implementations.**

Herein we present a CPG approach where the designer is able to build a basic motor repertoire that enables a biped robot to walk. The presented locomotor system includes a phase regulation feedback, which elicits or delays the transitions between swing and stance step phases according to load sensory information, adjusting the nominal walk to the exhibited walk in the environment.

The approach is tested on two simulated humanoid robots and in a DARwIn-OP robot, achieving a multitude of locomotor tasks, showing how general the proposed locomotor system can be. Simulations and experiments also demonstrate the role of phase regulation on addressing small external perturbations.

I. INTRODUCTION

Advancements in autonomous robots have increased the performance of humanoid robots, which in turn resulted in a growing interest in the tasks that potentially can achieve. Whichever autonomous task at hand of these humanoid robots, autonomous bipedal locomotion is an ubiquitous ability.

Several works have already established successful solutions for bipedal walking, most of which are model-based solutions. These approaches use inverse kinematics and kinetics in order to generate feet placement sequences, where the ZMP criterion are among the most popular, requiring a precise model of the robot dynamics and environment which may hamper the general application to different dynamic environments.

This is one of the arguments for advocating a biologically inspired approach based on Central Pattern Generators (CPGs). Key advantages and a review of works on CPGs are pointed in [1]. 1) CPGs produce stable rhythmic patterns in respect to their limit cycle behavior, returning to the normal stable state after transient perturbations. 2) Typically have a small number of control parameters, reducing the dimensionality of the control problem on higher level control. 3) Small changes in control parameters, even if abrupt, result in smooth modulations for the produced trajectories. 4) CPGs are well suited to integration of sensory feedback mechanisms. 5) Offer a good framework for learning and optimization algorithms. From our perspective, all these points make CPGs good candidates for legged robot control which can potentially generalize their ability in dynamic environments.

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CPG based controllers have been used in different kind of legged robots, even quadruped [2], [3] and biped robots. Most typical approaches when implementing CPGs for bipedal walking use phase oscillators that are fed into pattern generation layers [4]–[6] or using neural oscillators [7], [8]. Learning from demonstration using CPGs has also been studied in [9] and [10] with successful results, requiring however, already available and well defined walking patterns.

In this work we present a CPG approach based on phase oscillators to bipedal locomotion where the designer with little *a priori* knowledge is able to incrementally add basic motion primitives, reaching bipedal walking and other locomotor behaviors as a final result. This incremental construction of bipedal walking allows an easier parametrization and performance evaluation throughout the design process. The CPGs are also simpler to tune in contrast to other approaches, due to the relative reduced number of parameters, as well as their simple meaning and physical expression. Furthermore, the approach provides for a developmental mechanism, which enables progressively building a motor repertoire. We can easily benefit from evolutionary robotics and machine learning to explore this aspect.

The proposed CPG system also offers a good substrate for the inclusion of feedback mechanisms for modulation and adaptation. Others studies have explored mechanisms for phase resetting [5], [6], [10], phase coupling [4], and frequency adaptation [9], entraining the walking dynamics with the controller. In this work, we explore a phase regulation mechanisms using load sensory information observable in vertebrate legged animals [11]. While phase resetting only addresses the problem by resetting the phase on the onset of stance, phase regulation has advancing and delaying mechanisms for tackling the remaining conditional transitions. This kind of phase regulation using load information shares the same ideas as the feedback in other works on quadruped robots for system entrainment [2] and interlimb coordination [3]. However, the application of these ideas and the necessary adjustments to biped robots is new.

We present results from simulations on HOAP and DARwIn-OP models in Webots software, showing the adequacy of the locomotor system to generate bipedal walk on different robots. We also perform experiments on a DARwIn-OP, where we demonstrate how we can accomplish locomotion on a real robot. Further, we achieve several distinct locomotor behaviors, such as forward, backward, and turning walking thus illustrating that the proposed methodology is

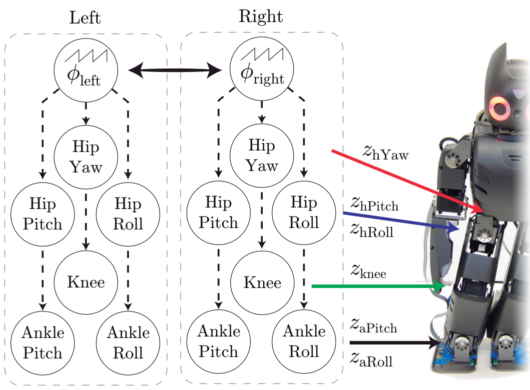


Fig. 1. CPGs and corresponding phase oscillators, motion generators and corresponding joints. Bilateral coupling is represented by the bilateral arrow.

easy to generalize. Phase regulation was also evaluated on both models in simulation and in the robot, demonstrating the adaptation of the nominal walk to environment changes, such as slight slopes, and not requiring ideal parameterizations, granting a broader range of parameter values to be used. The proposed work is relevant since comparatively to previous bio-inspired works [4]–[6] it provides for real world robustness to slight slopes. Further, the generalization of the proposed work both in different platforms and towards different behaviors is another innovative aspect of the proposed work.

II. LOCOMOTION SYSTEM OVERVIEW

Central Pattern Generators are neural circuits responsible for generating rhythmic patterns of activation for several rhythmic motor actions, including locomotion. Locomotor CPGs generate the rhythmic activation for the walking motor patterns and are suggested to be organized as coupled unit-burst elements, with at least one unit per articulation [12]. Interacting closely with these central generators, feedback pathways play an important role on influencing locomotion. Experiments have shown that several important reflexes and feedback pathways adapt locomotory motions and even modulate phase dependent feedback pathways [11].

The proposed locomotion system is based on the concept of CPGs, where each CPG addresses the motions of a single leg, implemented as organized unit generators from non-linear differential equations. Each unit generator is responsible for the activation of one joint, composed by a motion pattern generator driven by a global rhythmic generator [13] (fig. 1).

The rhythmic generator uses a phase oscillator to generate the base rhythm of locomotion, presenting appealing properties, as straightforward maintenance of phase relationships and entrainment, which we use to achieve interlimb coordination among the unit generators, and to serve as a substrate to feedback pathways, such as the proposed phase regulation.

The motion pattern generator receives a rhythmic signal and generates joint trajectories through the sum of motion primitives. Similar to [9], [14], [15], motion primitives are encoded as a set of non-linear dynamical equations with well-defined attractor dynamics. Motion primitives are smoothly and easily modulated regarding their amplitudes, frequencies, and pattern offsets. Using dynamical equations we are also able to deal with external perturbations that interrupt the nominal motions.

Motion generation in our approach is flexible in the sense that it allows for easy addition and change of motion primitives, and provides for an easy integration with autonomous mechanisms as for learning, optimization or evolution and exploration of locomotor behaviors. These developmental mechanisms that enable to progressively build motion primitives and improve locomotor abilities address a current challenge in robotics research. This can be achieved through tuning of parameters for motions; creating new motion primitives; from experience, trial and error or even evolutionary methods; creation and reorganization of feedback pathways and its effects in motor patterns.

Regardless, we consider that as a starting point in the life of the robot we should have a basic motor repertoire of motion primitives that achieve basic, but capable, walking behavior. We propose a method for achieving basic walking through a progressive increment of motion primitives, using sinusoidal and bell-shaped trajectories to describe general motions observable from biped walking. Note that we do not explicitly include the robot physics or the task dynamics onto the controller design, but rather we want that the control structure reflects the robot own process of understanding through interactions with the environment [16].

A. Rhythm generator

The proposed CPG has a phase oscillator to produce the rhythmicity for the motion generators:

$$\dot{\phi}_i = \omega + k \sin\left(\phi_i - \phi_o + \pi\right), \qquad (1)$$

where $\phi_i \in [-\pi, \pi]$ (rad.s^{-1}) is the phase of the oscillator, increasing monotonically and linearly with rate ω. This oscillator can be considered as a time keeping clock for the generation of the rhythmic motions of the joints of given leg i (left and right). It provides for coordination of all rhythmic motions on the several joints through bilateral coupling between left and right legs, specifying and maintaining a phase difference of π, with k coupling strength.

B. Motion generator

Joint position $z_{i,j}(t)$ is generated according to the current phase of the CPG, as follows:

$$\dot{z}_{i,j} = \sum f_j(z_{i,j}, \phi_i) - \alpha(z_{i,j} - O_{i,j}). \qquad (2)$$

$O_{i,j}$ specifies the offset, or baseline, of the final generated rhythmic motion and α is the relaxation parameter for the offset. A single motion primitive is defined by a function $f_j(z, \phi_i)$ and the final generated trajectory results from the summation of all motion primitives for that joint. j specifies the joint: hip roll (hRoll), hip yaw (hYaw), hip pitch (hPitch), knee (kPitch), ankle roll (aRoll) and ankle pitch (aPitch); and i specifies the left or right leg.

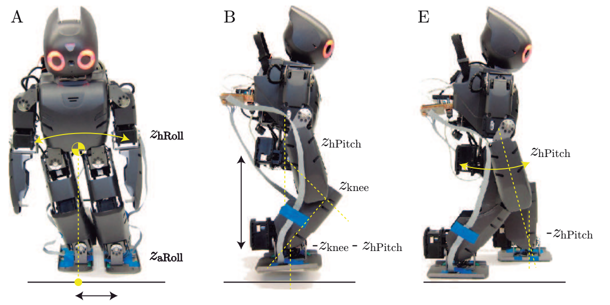


Fig. 2. 3 motion primitives. A) Balancing motion; B) Flexion motion; E) Compass motion.

Every joint may have a different set of motion primitives, sets that are dependent on the final desired locomotor behavior, making locomotion a problem of modular motor behaviors and modular motor programs.

III. WALKING MOTIONS

The proposed motions for basic bipedal walking considered in this work are herein presented in such an order, that by sequentially adding them, one can easily tune to achieve walking. From own familiarity with human walking, observations and kinematic descriptions like [17], one can put together a set of coarse motions that compose a basic locomotion.

In this work we resort to sinusoidal and bell-shaped motion primitives. For maintaining the feet parallel to the ground at all times, we assign symmetric motions to the ankle from those performed in the hip and knee.

A. Balancing motion

The first motion considered is the balancing motion, one of the crucial motions for bipedal walking. As the robot steps alternately, it must displace the body over the supporting leg during the step cycle, allowing the contralateral leg to execute the swing phase of the step. Failing to achieve a correct displacement over the supporting foot at the correct timing for the next swinging leg, will lead to a fall.

In the robot we achieve this motion by acting on the hip roll and ankle roll joints, as a sinusoidal trajectory that makes the robot oscillate laterally (fig. 2:A).

$$f_{\mathrm{hRoll}}^{\mathrm{balancing}} = -A_{\mathrm{balancing}}\omega \sin(\phi_i) \tag{3}$$
$$f_{\mathrm{aRoll}}^{\mathrm{balancing}} = -f_{\mathrm{hRoll}}^{\mathrm{balancing}} \tag{4}$$

In eqs. (3,4) i specifies the left or right leg, ϕ_i is the phase of left or right CPG, and parameter $A_{\mathrm{balancing}}$ specifies the amplitude of the lateral displacement motion.

B. Flexion motion

Leg flexion motion is performed by the unloaded leg so the foot achieves vertical clearance during the swing phase of the step, executed in strict alternation between the two legs. Vertical clearance is achieved when changing leg height, by actuating on the three pitch joints: hip, knee and ankle (fig. 2:B).

We describe this motion at joint level as having a bell shaped curve, resulting in a smooth profile for the trajectory of flexion. This is shown in eq. (5) for hip, eq. (6) for knee, and eq. (7) for ankle.

$$f_{\mathrm{hPitch}}^{\mathrm{flex}} = \frac{A_{\mathrm{hip}}\omega\phi_i}{\sigma^2} exp\left(-\frac{\phi_i^2}{2\sigma^2}\right) \tag{5}$$
$$f_{\mathrm{kPitch}}^{\mathrm{flex}} = -\frac{A_{\mathrm{knee}}\omega\phi_i}{\sigma^2} exp\left(-\frac{\phi_i^2}{2\sigma^2}\right) \tag{6}$$
$$f_{\mathrm{aPitch}}^{\mathrm{flex}} = -\left(f_{\mathrm{hPitch}}^{\mathrm{flex}} + f_{\mathrm{kPitch}}^{\mathrm{flex}}\right) \tag{7}$$

The amplitude of the bell trajectory is specified by parameter A_{hip} for the hip and A_{knee} for the knee. The trajectory described by the ankle is the sum of the hip and knee so the feet remains parallel at all times. This flexion motion is centered at $\phi_i = 0$, comprising the range from $\phi_i \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ by setting $\sigma = \frac{\pi}{6}$, performing an overall swing phase of about 50% of the step cycle.

C. Knee yielding motion

A characteristic of legged locomotion is the yield that occurs in the knee joint when the leg starts the stance phase and body weight is passed onto it. As mentioned in [17] as the third determinant of walking, this flexion happens when the Center of Gravity (COG) is passing its peak. By adding a small flexion on the knee joint during the stance phase we flatten the vertical trajectory of the COG of the walking robot.

This motion is added to the knee and ankle joints and is described by a sinusoidal profile of amplitude A_{yield} with π phase shift for the flexion to occur at middle of stance phase:

$$f_{\mathrm{kPitch}}^{\mathrm{yield}} = -A_{\mathrm{yield}}\omega \sin(\phi_i + \pi) \tag{8}$$
$$f_{\mathrm{aPitch}}^{\mathrm{yield}} = -f_{\mathrm{kPitch}}^{\mathrm{yield}} \tag{9}$$

D. Pelvis rotation motion

In level human walking the pelvis rotates alternately. In [17] this is mentioned as the first determinant of locomotion, flattening the vertical COG trajectory, as well as smoothing the inflections when changing the vertical direction of the COG.

We add this motion not just with performance in mind, but also to add some natural resemblance to human walking. This pelvic rotation is performed at the hip yaw joints, described as a sinusoidal trajectory with amplitude A_{rotation} and $\frac{\pi}{2}$ phase shift:

$$f_{\mathrm{hYaw}}^{\mathrm{rotation}} = -A_{\mathrm{rotation}}\omega \sin\left(\phi_i + \frac{\pi}{2}\right) \tag{10}$$

E. Compass motion

The final motion we consider is responsible for producing the propulsion of the body during locomotion. This motion moves the legs in the sagittal plane, alternately moving the contralateral legs forward and backward, like a compass (fig. 2:E). It generates the forward steps in coordination with all the other motions, resulting in forward walking.

This motion is described as sinusoidal profiles at the hip and ankle pitch joints, with amplitude A_{compass} and $\frac{\pi}{2}$ phase shift:

$$f^{\text{compass}}_{\text{hPitch}} = -A_{\text{compass}}\omega \sin\left(\phi_i + \frac{\pi}{2}\right) \quad (11)$$
$$f^{\text{compass}}_{\text{aPitch}} = -f^{\text{compass}}_{\text{hPitch}} \quad (12)$$

F. Motion summary

The overall result of all the motions is straight bipedal walking. Here we summarize all the motions assigned to each joint:

$$\dot{z}_{\text{hRoll}} = -\alpha(z_{\text{hRoll}} - O_{\text{hRoll}}) + f^{\text{balancing}}_{\text{hRoll}}, \quad (13)$$
$$\dot{z}_{\text{aRoll}} = -\alpha(z_{\text{aRoll}} - O_{\text{aRoll}}) + f^{\text{balancing}}_{\text{aRoll}}, \quad (14)$$
$$\dot{z}_{\text{hYaw}} = -\alpha(z_{\text{hYaw}} - O_{\text{hYaw}}) + f^{\text{rotation}}_{\text{hYaw}} \quad (15)$$
$$\dot{z}_{\text{hPitch}} = -\alpha(z_{\text{hPitch}} - O_{\text{hPitch}}) + f^{\text{flex}}_{\text{hPitch}} + f^{\text{compass}}_{\text{hPitch}} \quad (16)$$
$$\dot{z}_{\text{kPitch}} = -\alpha(z_{\text{kPitch}} - O_{\text{kPitch}}) + f^{\text{flex}}_{\text{kPitch}} + f^{\text{yield}}_{\text{kPitch}} \quad (17)$$
$$\dot{z}_{\text{aPitch}} = -\alpha(z_{\text{aPitch}} - O_{\text{aPitch}}) + f^{\text{flex}}_{\text{aPitch}} + f^{\text{yield}}_{\text{aPitch}} + f^{\text{compass}}_{\text{aPitch}} \quad (18)$$

A correct tuning of parameters is necessary for achieving bipedal walking in the robot. We perform this parametrization by incrementally tuning and adding each motion in sequence by trial and error. Optimization works are currently being developed to determine these parameters based on some criteria.

IV. PHASE REGULATION MECHANISM

Feedback pathways play an important role in the generation of legged locomotion. Sensory information originating from tactile information; from muscle position, velocity and strain; as well as other more complex senses like vestibular and vision; are used to dynamically adapt the centrally generated pattern of locomotion to the requirements of the environment.

In this work we apply a low level feedback mechanism that regulates the transitions between step phases (swing and stance phases), relying in load information in a phase dependent manner [11]. This regulation is useful to adequate the generated walking motions to the robot and the environment dynamics, and resultant dynamic interactions.

Phase transition is regulated through four mechanisms:

a) Advance from swing to stance: $a_{i,\text{adv}}, \delta_{i,\text{l}}$: When the swinging leg is loaded before reaching stance phase, we elicit a transition in the CPG from swing to stance, matching the physical state of the foot gaining ground contact.

b) Delay from stance to swing: $a_{i,\text{del}}, \delta_{i,\text{l}}$: At the end of the stance phase we delay the execution of swing if the leg is yet supporting weight. In case the swing phase is performed while the leg is still load, the body may become unsupported and lead to a fall.

c) Advance from stance to swing: $b_{i,\text{adv}}, \delta_{i,\text{u}}$: We elicit a transition from stance to swing when the leg is unloaded before the end of stance phase. This transition matches the performed motion with the physical manifestation of the walking pattern.

d) Delay from swing to stance: $a_{i,\text{del}}, \delta_{i,\text{u}}$: We slow down the transition from the swing phase to stance phase, until the swinging leg touches the ground.

A. Implementation of phase regulation

To achieve phase regulation we influence the dynamic states of the leg CPG: phase ϕ_i and the motion trajectories $z_{i,j}$. Phase regulation mechanisms are enabled at well defined intervals of the step phase, defined using gaussian and sigmoid functions as boolean multipliers to specify the range for each transition mechanism.

From descriptions a), c) we consider that advancing mechanisms are enabled during the later half of the step phase, defining $a_{i,\text{adv}}$ from swing to stance and $b_{i,\text{adv}}$ from stance to swing.

$$a_{i,\text{adv}} = \begin{cases} 1, & 0 \le \phi_i \le \frac{\pi}{2} \\ 0, & \text{otherwise} \end{cases}, \quad b_{i,\text{adv}} = \begin{cases} 1, & -\pi \le \phi_i \le -\frac{\pi}{2} \\ 0, & \text{otherwise} \end{cases} \quad (19)$$

Delaying mechanisms are enabled on the boundary region between two step phases (description b), d)), which defines $a_{i,\text{del}}$ from swing to stance and $b_{i,\text{del}}$ from stance to swing.

$$a_{i,\text{del}} = \begin{cases} 1, & \phi_i \approx \frac{\pi}{2} \\ 0, & \text{otherwise} \end{cases}, \quad b_{i,\text{del}} = \begin{cases} 1, & \phi_i \approx -\frac{\pi}{2} \\ 0, & \text{otherwise} \end{cases} \quad (20)$$

A phase transition mechanism is triggered if a determined loading or unloading condition is verified in the respective leg i. For mechanisms a) and b) we detect if foot force sensors are loaded beyond a threshold by the function $\delta_{i,\text{l}}$. Mechanisms c) and d) require the detection of unloading conditions under a threshold, returned by function $\delta_{i,\text{u}}$. These thresholds are determined according to experimentation.

We implement the described mechanisms by changing eq. (1) and eqs. (2) for all leg joints:

$$\dot{\phi}_i = \ldots \times \frac{\tau_{\text{adv}}\left(a_{i,\text{adv}}\delta_{i,\text{l}} + b_{i,\text{adv}}\delta_{i,\text{u}}\right)}{1 + \tau_{\text{del}}\left(a_{i,\text{del}}\delta_{i,\text{u}} + b_{i,\text{del}}\delta_{i,\text{l}}\right)}, \quad (21)$$

$$\dot{z}_{i,j} = \frac{\ldots}{1 + \tau_{\text{del}}\left(a_{i,\text{del}}\delta_{i,\text{u}} + b_{i,\text{del}}\delta_{i,\text{l}}\right) + \tau_{\text{adv}}\left(a_{i,\text{adv}}\delta_{i,\text{l}} + b_{i,\text{adv}}\delta_{i,\text{u}}\right)}, \quad (22)$$

where τ_{adv} and τ_{del} are positive constants that adjust the strength of delay and advance effects.

The objective of adding members in eq. (21,22) is to increase or decrease the rate of change of the CPG phase ϕ_i and stop joint motion $z_{i,j}$ during phase regulation. Making $\dot{\phi} \approx 0$ delays phase transition, while increasing $\dot{\phi}$ above the nominal frequency achieves an earlier transition. For stopping the joint motion, $\dot{z}$ is set to ≈ 0.

This interplay, between phasic dependent feedback and triggering conditions from physical exhibitions of the walking dynamics, adjusts the nominal walking trajectories.

V. SIMULATIONS AND EXPERIMENTS

In our simulations with Webots physics simulator we use the models of HOAP and DARwIn-OP, lightweight humanoid robots with 28 and 20 DOFs, respectively. For

TABLE I

PARAMETERS FOR STRAIGHT WALKING.

Amplitude	HOAP	DARwIn	Offset	HOAP	DARwIn
$A_{\text{balancing}}$	9	11	O_{hYaw}	0	0
A_{hip}	20	20	O_{hRoll}	-2	1
A_{knee}	40	50	O_{hPitch}	-19	-25
A_{yield}	2	2	O_{knee}	30	40
A_{rotation}	2	2	O_{aRoll}	2	-1
A_{compass}	$[1, 16]$	$[1, 12]$	O_{aPitch}	-15	22
$\omega(\text{rad.s}^{-1})$	4.18	5.24	k	7.5	7

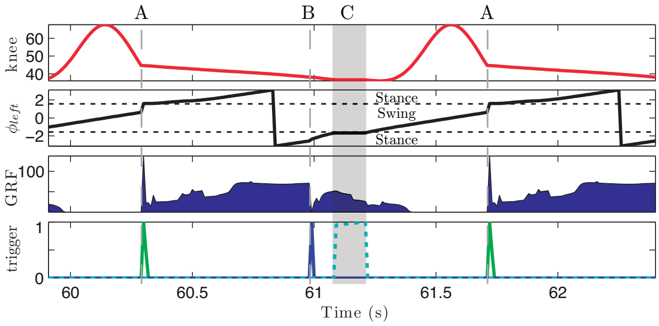


Fig. 3. Left knee trajectory and phase adjustments during one step cycle. A transition was elicited from swing to stance due to early foot touchdown (A). When the load decreased under the threshold a transition from stance to swing is elicited (B). However, the foot was not fully unloaded before entering the swing phase, so the oscillator was delayed to enter the swing phase (C).

our experiments we use a DARwIn-OP robot equipped with eight Force-Sensing Resistors on the soles of the feet.

In this section, we demonstrate the adequacy of the system to produce walking behaviors for different robots in simulation and the deployment to a real robot; and verify the adequacy of the proposed feedback mechanism to adjust the generated trajectories to the current environment, according to the sensorial context. Parameter values used in our simulations and experiments are presented in table I.

A. Simulations

In fig. 3 we describe how phase regulation is elicited and changes the nominal knee trajectory in a straight walk on flat terrain.

We observe an early transition from swing to stance at A (green, fourth panel), when the foot touches the ground (GRF, third panel) before the CPG reach stance phase (second panel). At A, phase is advanced from swing to stance, immediately adjusting the knee trajectory (top panel) to an adequate motion to perform the early stance phase.

At B the value of GRF decreases below the threshold defining lose of support, eliciting an advance in phase from stance to swing. However this lose of support is instantaneous and not sustained, which is shortly followed by an increase in GRF which delays the transition from stance to swing until the foot is sufficiently unloaded (C).

We performed several simulations with HOAP to compare the effects of phase regulation in the walk. We also systematically verify the locomotion for several values of A_{compass}, from $1°$ to $16°$, changing the nominal step length.

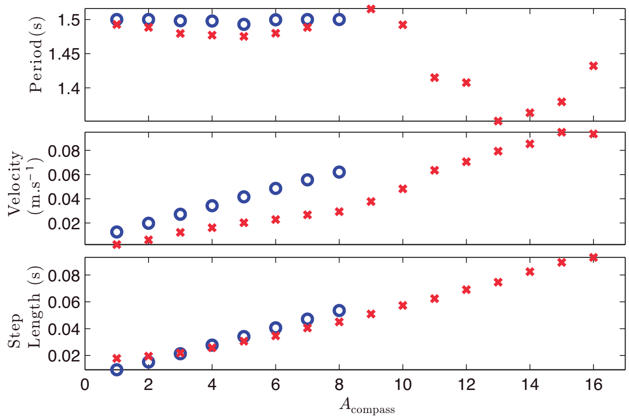


Fig. 4. The inclusion of phase regulation feedback allows for greater A_{compass} values (cross), compared to when the feedback is not used (circle). The range of useable values increased 100% for a successful walk with phase regulation.

In fig. 4 we see the achieved step period, velocity and step length with and without the feedback The inclusion of phase regulation allowed us to increase A_{compass} further than $8°$ without the robot falling. Globally, the achieved velocity was lower at the same amplitudes when the feedback was active (cross). This is due to effect of the delay of transition from stance to swing. The step period is similar in both situations, but for $A_{\text{compass}} > 9°$ the period is reduced due to the effect of elicited early transitions between swing and stance (cross). When phase regulation is active, the achieved step length os slightly smaller that when its disabled, mostly due to early advance of transitions.

We also have performed simulations with HOAP where the robot tackles up/down-slopes of $4°$. With the inclusion of phase regulation, nominal motions are adjusted and the robot is able to cope with non-flat terrains, walking up and down slopes without falling. It shows that the feedback was also able to adapt the phase timing according to the terrain resulting in a stabilization of the robot.

B. DARwIn-OP experiments

As in simulations, the robot walks successfully in flat terrain after a short parametrization of motions, and when phase regulation is active it adjust slightly the nominal gait. Walking slight sloped terrains (up: $\approx\ 4°$, down: $\approx\ 2.5°$) is not possible without the activation of phase regulation, reinforcing the obtained results from simulations.

The robot walks an up-slope of $\approx 2.5°$ with the phase regulation activated until 36.8 s in the experiment. Just about when the next step takes place, the robot loses balance and falls (fig. 5). In fig. 6 is depicted the joint trajectories for the right leg, ground reaction forces (GRF) from the right foot, right phase and triggered phase regulations. Clearly visible is the difference between the nominal joint trajectories when phase regulation is not employed ($t > 36.8$ s) and the adjusted trajectories when phase regulation is employed

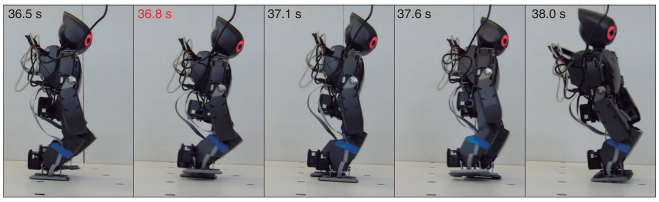


Fig. 5. DARwIn-OP walking down a slope up until phase regulation is deactivated at $t = 36.8$ s. Without phase regulation the robot loses balance and falls.

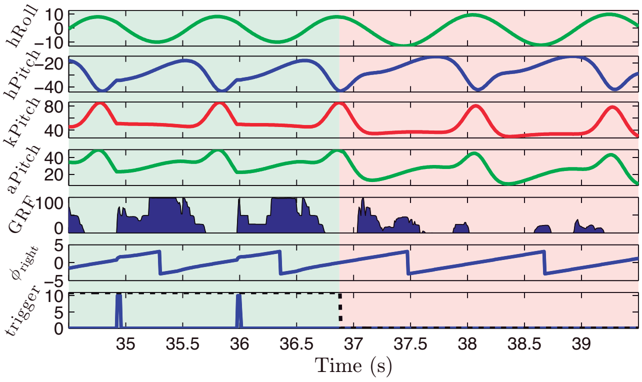


Fig. 6. After deactivating phase regulation ($t > 36.8$) nominal trajectories are no long adjusted according the sensed ground reaction forces (GRF). Just about the next step ($t = 37$ s) no phase advance is elicited due to an early touchdown, making the robot lose balance and fall.

($t < 36.8$ s). We observe only advance transition from swing to stance is triggered at 35 s and 36 s, when the foot touches early the ground because of the inclination. These achieved adjustments changed the overall step period in up-slope walk from 1.20 s to 1.04 s and also reduced the performed step length from the nominal 0.0505 m to 0.0424 m. In the accompanying video we show this experiment and the robot walking a slope of $\approx\ 4°$.

Results from simulations and experiments suggest that with phase regulation the designer has more room in parameterizing the walking motions. It is not necessary to find the perfect parameters for slight variations in environment and is possible to use a greater range of values. We also verify an adaptation to slight environment changes, e.g. allowing the robot to walk in slight sloped terrains.

C. *OTHER LOCOMOTOR BEHAVIORS*

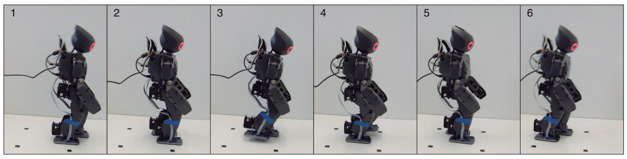
The proposed system was designed to be possible to achieve other locomotor behaviors in a simple scalable manner. The most straightforward method for addressing this gait modulation in the proposed framework is to: 1) perform parameter modulation of already defined motion primitives; 2) toggling between primitives or defining new ones to fulfill the required locomotor ability.

1) Parameter modulation: With parameter modulation we impose quantitative changes in the already established motions, which is quite useful for achieving a smooth continuous locomotor diversity. For instance, we can achieve smooth variation of forward velocity by adjusting the amplitude of the compass motion. This modulation also applies if we set negative values for the amplitude of the compass motion, resulting in the correspondent backwards walking (fig. 7(a)).

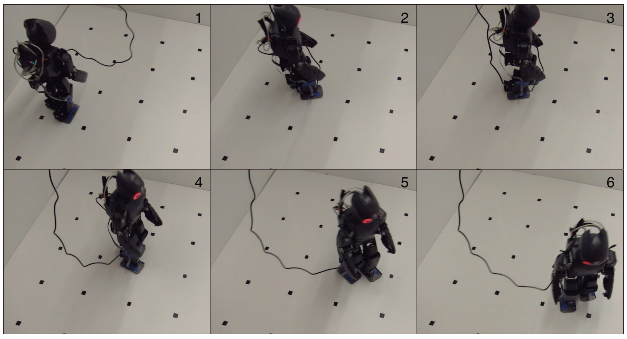
2) Primitive selection: Adding new, and selecting between the appropriate motion primitives may provide a whole new set of locomotor abilities for the robot. Just as achieving goal directed walking is a matter of selecting the correct primitives. A single sinusoidal motion primitive, just like the presented compass motion, acting on the robot's yaw joints can rotate the body by its vertical axis, proportionally to the modulated amplitude (fig. 7(b)).

All these different locomotor behaviors can be observed in the accompanying video.

In order to achieve other more complex behaviors, one could resort to mechanisms of developmental robotics. We are currently developing work with evolutionary approaches for improving locomotor performance or reach different locomotor behaviors.



(a) Backward walking achieved by modulation of compass motion amplitude.



(b) Turning behavior by the inclusion of a new motion primitive and turning amplitude modulation.

Fig. 7. Different bipedal behaviors can be achieved through changes in parameters and selection of motion primitives.

VI. CONCLUSIONS

In this work we presented a CPG approach able to generate bipedal walking. Using this approach we design, parameterize, generate and adapt the trajectories employed for walking. By incrementally adding basic motion primitives it is possible to easily reach a basic motor repertoire for bipedal walking, such as straight walking, turning, sideways walking.

The CPG here introduced includes phase regulation feedback that controls the transition between step phases according to foot load sensory information, creating a low level feedback loop. Transitions are delayed or elicited according to the current step phase and load information, adapting the nominal motions of the CPG to current physical information, matching the generated trajectories with the dynamics of the robot.

Results from simulations using models of different robots have enabled to show the generality of the approach. We have also shown that the system can easily be deployed in a real robot. Results have also shown the feasibility of the proposed phase regulation feedback. Namely, the system was able to adapt the locomotion to the robot dynamics; to allow a greater range of parameter values to be used, and also enabled the robot to walk up and down slight slopes, adapting to the current environment.

Currently we are exploring other feedback mechanism to increase the locomotor abilities of the robot, e.g. balance control, stumbling reflex, push recovery. The presented approach would benefit by including methods of autonomous learning for adapting existent or adding new motion primitives in order to increase performance. It is also possible to employ a higher level mechanism able to select and activate different motion primitives according to the behavioral context of the robot.

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