

Humanoids that Crawl: Comparing Gait Performance of iCub and NAO Using a CPG Architecture

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Abstract—in this article, a generic CPG architecture is used to model infant crawling gaits and is implemented on the NAO robot platform. The CPG architecture is chosen via a systematic approach to designing CPG networks on the basis of group theory and dynamic systems theory. The NAO robot performance is compared to the iCub robot which has a different anatomical structure. Finally, the comparison of performance and NAO whole-body stability are assessed to show the adaptive property of the CPG architecture and the extent of its ability to transfer to different robot morphologies.

Keywords: CPG; Crawling; Infant development; NAO; iCub

I. INTRODUCTION

A central pattern generator (CPG) is a neural network or neural circuit which can produce coordinated rhythmic movement patterns without any rhythmic inputs from sensory feedback or high-level control centres [1]. Experimental research has proved the neurobiological function of CPGs such as in fictive motion in some primitive animals including both lamprey and salamander [2]–[4] and in treadmill running decerebrated cats [5]. Also, CPGs have been verified to be located in the human spinal cord permitting primitive locomotion capabilities for coordinating human movement [6].

As a biologically motivated methodological tool, CPGs in robotics research are used in modelling primitive locomotion. For example, anguilliform swimming of lamprey/eel robots [7]–[9], quadruped walking robots [10], [11], CPG-controlled biped locomotion models [12] and crawling infant robots [13]. Ordinarily, networks are composed of coupled oscillators which provide particular properties: 1. Symmetric stability, 2. Gait transitioning, 3. Ability to adapt to the changes in internal (mechanical) and contextual states using sensory feedback and limit-cycle stability. Furthermore, it appears that in order for CPGs that mediate basic locomotion to function stably top-down regulation from higher cognitive centres (e.g. as modelled by neurodynamic architectures, numerical simulation) is necessary (cf. [6]).

CPGs appear to provide an interface between brain centres focused on basic locomotion control and those focused on high-level cognition: Firstly, CPGs significantly reduce the necessary bandwidth between the higher-level brain centres and the spinal cord in which case time delay in the motor control loop and dimensionality of control signals can also be reduced [14], see also [6]. Secondly, CPGs link the low-level

to the high-level Mesencephalic Locomotor Region (MLR) in the brain which governs gait transition [14]. Furthermore, since the development of higher cognitive competences may depend on the crawling-walking transition in infants [15] the above two points suggest CPGs offer roboticists a neural basis for modelling the development of *infant* cognitive behaviour. CPGs are also practical from an engineering perspective. As a form of adaptive control they are more energy efficient than classical control theoretic approaches as they exploit limit-cycle dynamics [13].

In this article, a generic CPG network based on Righetti’s model [16] is used on the NAO robot platform to generate crawling gaits. The work presented in this paper provides the following insights: Firstly, we demonstrate the extent of the Righetti model to generalize across humanoid robot morphologies which thus serves as an index of its strength. Secondly, the investigation constitutes a unique application for the NAO robot which has previously only been demonstrated to exploit walking and not crawling gaits. Furthermore, in terms of developmental infant behavior, this work hints at candidate CPG tuning parameters for interfacing with high-level cognitive capabilities.

The paper breakdown as follows. A general design approach is proposed in section 2. Some details of implementation are given in section 3 and an analysis of the whole-body stability of crawling is provided in section 4. Finally, in section 5, we provide a brief conclusion regarding possible future work.

II. APPROACH TO DESIGNING CPG NETWORKS

A general approach to designing minimalist CPG networks for forms of locomotion has been an ongoing quest in the scope of CPG research. At the present time, there is still not a well-established set of design principles. However, researchers in robotics and artificial intelligence mostly apply different ‘explore-and-exploit’ approaches to build their own CPG models, including hand-coding, a dynamic systems approach and learning/optimization algorithms [14]. There are still a lot of open research problems on the neurobiology of CPGs such as the underlying mechanisms for how CPGs construct and develop themselves and how diverse locomotion gaits have emerged evolutionarily. Therefore, a principled approach to designing a CPG network is an important study (cf. [13]).

A summary of the design approach in our investigation is addressed in this section based on a generic CPG model [17] of infant behaviour combined with an extension of the model applicable to the NAO robot platform.

We make four main design decisions: 1. Selection of oscillators, 2. Core CPG architecture, 3. Sensory feedback, 4. Extended (NAO-specific) CPG architecture.

A. Selection of Oscillators

Definition 1: An oscillator is an autonomous dynamical system, i.e. a system of differential equations with at least one limit cycle attractor. In other words, the solution of the system (after a transient time) is a closed cycle, which is asymptotically stable, i.e. if the system gets perturbed out of the limit cycle it returns to it [18].

In order to design a suitable CPG, we should have a good understanding of the properties of behaviors we need to model. An oscillator can be designed on the basis of inspiration taken from physical artefacts like a spring [16] or selected from pools of generic oscillator groups like the Matsuoka oscillator and the Van Del Pol oscillator [19], [20]. For our bio-inspired design, two-dimensional oscillators are used as CPGs. In many implementations of locomotion such oscillators implicitly represent the activities of extensor and flexor muscles [21]. On the grounds of general design, the oscillator should meet several requirements:

1) *Dimensionality of the oscillator:* The selected oscillator should be as simple as possible in order to offer more scope to exploit sensory feedback and also behavioural change following modifications of the ODEs which can increase the adaptivity of the CPG to both contextual and bodily change. However, the first order oscillator, the simplest oscillator the output of which cannot change with the input (other than through direct functional coupling), is not able to mimic the complex nonlinear rhythmic movement of multi-pedal locomotion. Hence, mostly, we use at least the second order oscillator.

2) *Stability (limit-cycle attractor):* The oscillator must be stable so that the limit-cycle system has the ability to receive sensory feedback. In our work, we choose a simple modified Hopf oscillator (1)(2)(3) [22], to constitute the CPG — a single control neuron.

$$\dot{x} = a(u - r^2)x - wy \quad (1)$$

$$\dot{y} = b(u - r^2)y - wx \quad (2)$$

$$w = \frac{w_{stance}}{1 + e^{-fy}} + \frac{w_{swing}}{1 + e^{fy}} \quad (3)$$

where $r = \sqrt{x^2 + y^2}$; x, y = periodic signals of amplitude \sqrt{u} and frequency w ; a, b and f are scaling constants.

The duration of crawling includes a stance phase and a swing phase. The swing phase is shorter than the stance phase. In Figure 1, the phase synchronization of contralateral limbs and (approximately half period) out of phase relation

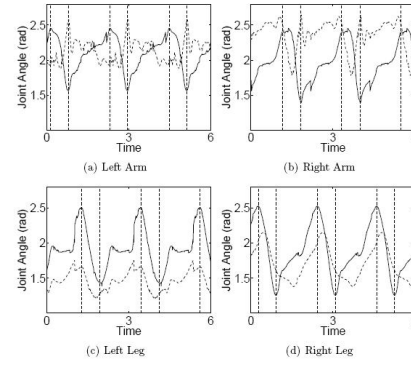


Fig. 1. Time evolution of the joint angles of an infant during crawling. This is a reconstruction of a crawling sequence from the recordings (averaged performance) of 6-12 month old infants. The four joints shown here correspond to left shoulder, right shoulder, left hip, right hip, respectively. Hip (c, d) and shoulder (a, b) joints are plotted in plain line; knee (c, d) and elbow (a, b) joints are in dashed line. The vertical lines delimit the swing and stance phases; the swing phase is the shortest one [16].

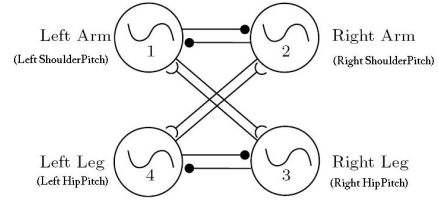


Fig. 2. The architecture of the CPG network and its corresponding relation to each main joint. Inhibitory coupling between opposite limbs (standard subtractive coupling) is adopted to enforce the half a period phase shift; additive coupling between contralateral limbs guarantees their in-phase relation.

of ipsilateral limbs are the main two traits of an infant crawling gait. Since the swing phase is short the stance phase largely determines the speed of crawling. We thus need an oscillator with which we can specify the durations of the swing and stance phases. The modified Hopf oscillator with phase-dependent frequency would be a good choice fitting with this key point [16].

B. Core CPG Architecture

CPGs are connected to form a network which can generate the desired gaits (i.e. phase differences between the CPGs). The goal in this section is to identify the simplest structurally stable network that reproduces quantitatively the different infant gaits. Thanks to Golubitsky and his colleagues work on group theory, a temporal-spatial symmetric model with 8 cells which can generate all the motor gaits of quadruped animals, such as walk, trot, gallop, bound, has been proposed according to a dynamic systems theory extension [23]. Inspired by their work, a 4-cell simplified network (Figure 2) was proposed by Righetti to produce a subset of the gaits produced by the Golubitsky model including crawling — a trot-like gait. In our work, the Righetti network constitutes our core architecture which is implemented on the NAO robot.

According to H/K theorem:

“Let Δ be the symmetry group of a coupled cell network in which all cells are coupled and the internal dynamics of each cell is at least two-dimensional. Let $K \subset H \subset \Delta$ be a pair of subgroups. Then there exist periodic solutions to some coupled cell systems with spatio-temporal symmetries H and spatial symmetries K if and only if H/K is cyclic and K is an isotropy subgroup. Moreover, the system can be chosen so that the periodic solution is asymptotically stable” [23].

The structural stability of Righetti’s network can be easily guaranteed on the grounds of the H/K theorem. In this 4-cell network: $H = I, ((13)(24), 0), ((12)(34), \frac{1}{2}), ((14)(23), \frac{1}{2}), K = ((13)(24), 0)$, so H/K is cyclic. Therefore, the periodic solution is stable which means this network can generate stable trot-like gaits including crawling under perturbations. Other than trot gaits, the 4-cell network can still ground a lot of other gaits, like walk, bound, pace and gallop with different symmetric permutations, which elucidates the generality of this CPG network. With H/K theorem, we can always seek out the stable gaits. The theoretical proof is not given in this article. The reader interested in this can refer to the group theory literature [23]. Within this network, the ordinary differential equations (1)(2)(3) can be rewritten as (4)(5)(6):

$$\dot{x}_i = a(u_i - r_i^2)x_i - w_i y_i + f_1 \quad (4)$$

$$\dot{y}_i = b(u_i - r_i^2)y_i + w_i x_i + \sum_j k_{ij} y_j + f_2 \quad (5)$$

$$w = \frac{w_{stance}}{1 + e^{-f y_i}} + \frac{w_{swing}}{1 + e^{f y_i}} \quad (6)$$

where $r_i = \sqrt{x_i^2 + y_i^2}$, x_i and y_i provide periodic signals of amplitude $\sqrt{u_i}$ and frequency w ; the term $\sum_j k_{ij} y_j$ controls the couplings with other CPGs and k_{ij} is the weight; $f_{1,2}$ is the sensory feedback. Note, our model described above is an adaptation of the Righetti [16] model according to the inclusion of an extra sensory feedback term used in equation (4) (see next section for details).

A generic CPG network must fulfill the following:

1) *The network must be structurally stable:* H/K theorem also provides a warranty that this network is structurally stable. But we can explain the structural stability in a general way: For a symmetric coupled cell system composed of cells the internal dynamics of which is at least two dimensional, if the network is strongly connected (i.e. all cells influence each other, or there is a cell or a strongly connected group of cells that drives all the other cells), then such solutions can be structurally and dynamically stable. Otherwise, the network cannot be stable unless there exists one cell that stops oscillating [24].

2) *The network must have a generic structure that allows generation of different gaits:* Using the Righetti 4-cell structure, through the permutations of the symmetries in the network, we can find out the potential gaits it can produce and whether they are stable.

3) *The network needs to have the ability to support gait transitions:* By changing the couplings or weights of the network connections, the gait the network produces can be

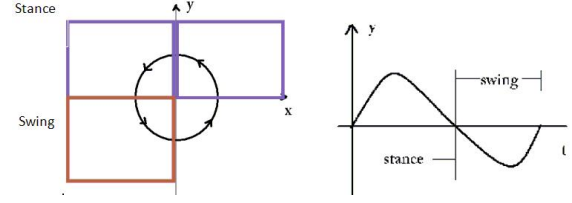


Fig. 3. Left: the limit-cycle of the CPG. The blue framed part is the area where the stop transition takes effect and the red framed area is where the fast transition takes effect. Right: the standard output y without sensory feedback.

transitioned into another gait. The 4-cell network we addressed above has this ability [16].

The above three points not only meet the demands for supporting the development of motor abilities (e.g. transitioning from crawling to walking) but also for supporting high-level cognitive abilities (e.g. decision-making).

C. Sensory Feedback

Sensory feedback can render CPGs more adaptive to unknown environments. It has been demonstrated that CPGs modulated by sensory feedback can lead to stable locomotion on complex and uneven terrain [10], [11]. The inclusion of sensory feedback can make CPGs inextricably coupled to the sensorimotor system for a given morphology. Transferring a general CPG model from an iCub to a NAO provides a good example. In the crawling NAO, we use a modified version of Righetti’s model to construct $f_{1,2}$ (7) in the differential equations (4)(5).

$$f_{1,2} = \begin{cases} f_1 = -\text{sign}(x_i)F & \text{fast transition} \\ f_2 = -\text{sign}_1(y_{opp})(-b(u_i - r_i^2)y_i - w_i x_i - \sum_j k_{ij} y_j) & \text{stop transition} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

x_i is the CPG value obtained each run via the angle sensor in the joints of the NAO robot. When $x_i > 0$, $\text{sign}(x_i) = 0$. The swing period starts when $x_i < 0$, $\text{sign}(x_i) = -1$. The value F is greater than other terms in order to accelerate the beginning of swing and make the speed of swing adjustable. This represents the *fast transition* from stance to swing (Figure 3). We choose $F = 50$ because of its superior performance. If F is too large, swing will be too fast and this can cause instability (hysteresis). y_{opp} is the CPG value of the contralateral limb, if $y_{opp} < 0$, $\text{sign}_1(y_{opp}) = -1$; otherwise, the $\text{sign}(y_{opp}) = 0$. When a given limb begins the swing phase, the contralateral limb should be static (i.e. in the stance phase) which represents the *stop transition*. Since the NAO robot (that has no articulated torso) cannot compensate for the lowering of the whole body during transition, during the stance period, the supporting limbs must stop moving in the pitch direction so that the movement of the roll direction can lift up the body leading to a fast swing in the contralateral limbs.

TABLE I
MECHANICAL CONFIGURATION OF ICUB AND NAO

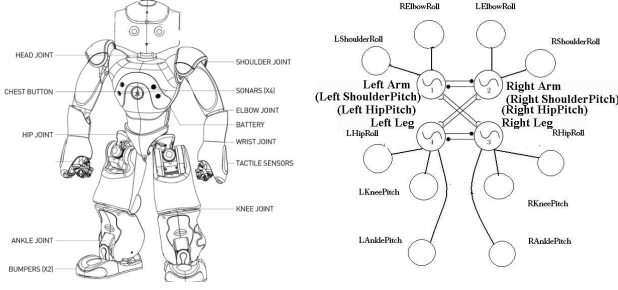


Fig. 4. Left: the parts of the NAO robot. Right: extended (NAO specific) CPG architecture.

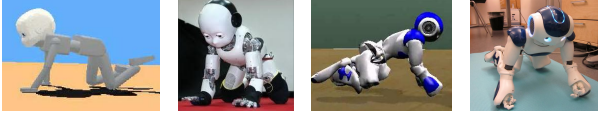


Fig. 5. Left (first two pictures): the crawling iCub (RobotCub project – <http://www.robotcub.org/>). Right (last two pictures): the crawling NAO. Pictures shown in Webots simulation and the actual robots.

D. Extended (NAO specific) CPG Architecture

So far we have described the control of the four main joints (4 nodes in the *Core CPG Architecture*) of the robot. Below is a description of the configuration of the other joints so that the whole body can move synchronously with the main network. Figure 4 (right) shows the *Extended CPG Architecture* accommodating the other joints in the NAO.

All the joints with the exception of the elbow oscillate with reference to the oscillations of the corresponding main joints of the *Core CPG Architecture*. Thus, for example, (left/right) HipRoll, ShoulderRoll are coupled to the 4-node CPG network and are activated by their mechanically-articulated main joints, HipPitch and ShoulderPitch, respectively.

To make the elbow swing as quickly as possible in synchrony with the shoulder, we use an exponential function(8):

$$\dot{\theta} = \gamma e^{\frac{(y_i - \sqrt{w_{swing}})^2}{\tau}} \quad (8)$$

Where γ is the amplitude of the movement, τ is width of Gaussian, i corresponds to each main joint. The elbow joint swings as a consequence of a Gaussian movement.

III. IMPLEMENTATION OF THE CRAWLING NAO

The crawling gait has been implemented on the iCub robot based on the *Core CPG Architecture* successfully mimicking infant crawling [16]. Our work also manages to replicate crawling behavior but on the NAO robot.

A. Mechanics comparison between the iCub and the NAO.

As mentioned earlier, the crawling gait largely depends on arm, torso and leg parts. Table I illustrates the basic configurations of iCub and NAO from which we can intuitively sense the difference between them. It is obvious that the torso part plays a very important role in both infant and adult crawling in the sense of balance and stabilization of

Parts	iCub/Dof(Degree of freedom)	NAO/Dof(Degree of freedom)
Head	Neck_Pitch, Neck_Roll, Neck_Yaw/3	Head_Yaw, Head_Pitch /2
Arm	Shoulder_Pitch, Shoulder_Roll, Shoulder_Yaw, Elbow, Wrist_Propup, Wrist_Pitch, Wrist_Yaw/7	Shoulder_Pitch, Shoulder_Roll, Elbow_Yaw, Elbow_Roll, Wrist_Yaw/5
Torso	Torso_Yaw, Torso_Roll, Torso_Pitch/3	-/0
Leg	Hip_Pitch, Hip_Yaw, Hip_Roll, Knee_Pitch, Ankle_Pitch, Ankle_Roll/6	Hip_Pitch, Hip_Yaw, Hip_Roll, Knee_Pitch, Ankle_Pitch, Ankle_Roll/6

movement [25]. However, specifically for infants, the torso is strengthened and becomes more and more flexible during the early stage of development, i.e. around 3 to 12 months [26]. Hence, even in absence of direct experimental evidence, we may derive that the early-stage infants, especially the novice crawlers, use a crawling gait that involves minimal use of their relatively undeveloped and weak torsos. From this perspective, NAO crawling behaviour may be reflective of this early-stage crawling gait and provide insights into locomotion development therein.

In Table I, we can see some mechanical constraints of the NAO robot for the arm (the wrist part) and torso which reflects a different humanoid configuration where the *Core CPG Architecture* can be accommodated permitting similar crawling dynamics to the iCub robot. In Figure 5, a set of crawling snapshots show the similarities and differences of the crawling iCub and NAO. In order to reduce the influence of the torso part, for the crawling posture, more body weight must be placed onto the legs so that the arms can swing more easily. Unfortunately, the NAO’s large feet tend to touch the ground when crawling. For tackling this problem, we open both legs so that the feet do not prevent forward motion.

B. Implementation

Under the control of the *Extended CPG Architecture*, the NAO performs primitive crawling. In Figure 6, crawling motion is depicted in the Webots simulator [27]. This robot simulator not only simulates robot dynamics but also the physical properties of its chosen environment. In Figure 7, even though the robots’ crawling posture and mechanical structure are not the same, the stable trajectories of the four main CPGs of the *Core CPG Architecture* show similar dynamics for both NAO and iCub as found by Righetti. Hence, the generality of the 4-cell CPG network is conspicuously observed.

Consistent with Pfeifer and Bongard [28], i.e. that robot morphology affects locomotion patterns, we nevertheless observe differential *stop transition* performance. Concerning the NAO robot, its legs have a smoother transition trajectory since the tuck-in movement of the support contralateral limbs lifts up the whole body ensuring that the swing of the legs is free from obstruction. We might hypothesize that a subset of novice infant crawlers (below 6 months of age) use similar, relatively inefficient, gaits during an exploratory crawling developmental stage. Empirical data on very early stage crawling performance is, however, lacking at this time.

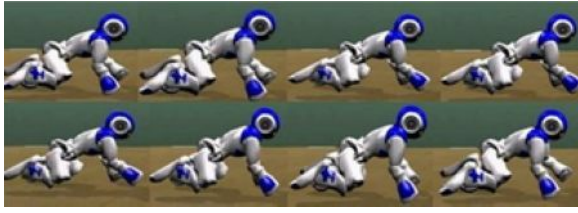


Fig. 6. The crawling NAO robot in Webots simulator. In this implementation, the fixed parameters in all above equations are as follows: $a = 2$, $b = 5$, $c = 100$, $\gamma = 0.1$, $r = 2.0$, $\tau = 2.0$.

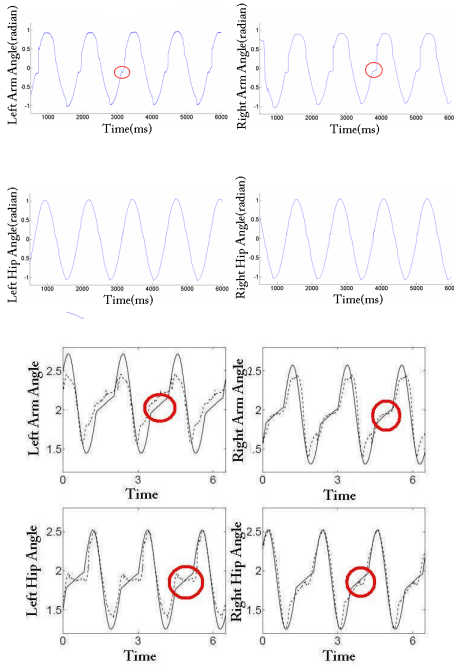


Fig. 7. The dynamics of *Core CPG Architecture*. Top half: Physical NAO robot. Bottom half: Physical iCub robot [16]. NAO robot oscillatory dynamics are qualitatively similar to iCub dynamics. The red circles highlight the qualitatively similar crawling momentum technique of the two robots. The NAO motion is smoother as when the (left) arm is in stance phase (at *stop transition* – see section II-C) the ‘tuck-in’ whole body movement allows the (left) leg to move more freely than in the iCub robot.

C. Tuning of the extended CPG architecture

The advantage of using a CPG model in robotics is not only that it is a bio-inspired adaptive controller but also it can offer much potential for parametric tuning as carried out by high-level mechanisms (e.g. neurodynamic models, cf. [29]). In this section, we demonstrate how to change the speed of crawling and direction by changing a subset of the *Core CPG Architecture* (4-cell network) parameters.

1) *Speed tuning*: The speed of crawling can be changed by modifying the frequency of the Hopf oscillator, i.e. via altering both w_{stance} and w_{swing} together (note, a change to only one of these parameters cannot lead to faster or slower crawling – see [16]). It is interesting that when we change both w_{stance} and w_{swing} to very large values, i.e. above 24π , the NAO robot no longer crawls. The movement of the body becomes very unstable, quite close to horse cantering or



Fig. 8. NAO crawling and turning behaviours. The left three graphs show crawling left with $Al = 0.15$, $Ar = 0.25$, $|Al - Ar| = 0.1$. The right three graphs show crawling right with $Al = 0.25$, $Ar = 0.18$, $|Al - Ar| = 0.07$. The degree of turning left is greater than turning right.

troting. Righetti mentions this finding on the iCub platform with the explanation that the crawling gait is not stable at high speeds and a new gait emerges from this instability [16]. If w_{stance} and w_{swing} are both equal to a very small value, e.g. 1, the NAO arm cannot swing any more which is the same for the crawling iCub. Therefore, the stable crawling gait parameter value range for $\frac{w_{stance}}{2\pi}$ and $\frac{w_{swing}}{2\pi}$ is in $[2, 10]$.

2) *Changing direction*: By changing the amplitude of the oscillators (Al , Ar) in both hip joints, the robot can turn right/left. We tested this in Webots (Fig. 8) and on the physical robot. Increasing the difference between the two amplitudes increases $Rol(9)$ – the degree of changing direction.

$$Rol \propto \frac{|Al - Ar|}{|Al + Ar|} \quad (9)$$

In our work, $|Al - Ar|$ is in $[0.02, 0.2]$, where $Al \in [0, 0.25]$, $Ar \in [0, 0.25]$.

D. Conclusion

The implementation of crawling on the NAO robot offers a new challenge for mimicking crawling behaviours in infants with an undeveloped torso. It is, to the authors’ knowledge, the first example of crawling behaviour demonstrated on the NAO robot platform. Our work also demonstrates the feasibility of utilizing the core (Righetti) CPG architecture in two humanoid robots with different morphologies. From the developmental robotics perspective, the model’s parametric tuning properties could in principle be modulated by a ‘high-level’ cognitive control centre, e.g. utilizing reinforcement learning techniques, which may allow for exploitation of CPG-induced emergence of the new gaits and directional control as described above.

IV. ANALYSIS OF WHOLE-BODY STABILITY

Crawling, as a highly-integrated form of locomotion, involves nearly all the joints of a humanoid robot. Hence, it is not easy to analyze the influence of each joint. The dynamics of the whole body of a crawling robot can be investigated for both pitch and roll angles. Intuitively, the limit-cycle behavior implies the stability of the whole body (Figure 9). Both simulation and physical robot implementation results illustrate that the dynamics are confined to a limit cycle. Even when falling out of the cycle, all the movements return to the whole-body attractor. The pitch dynamics explain the up-and-down motion in the pitch plane and the roll dynamics elucidate the

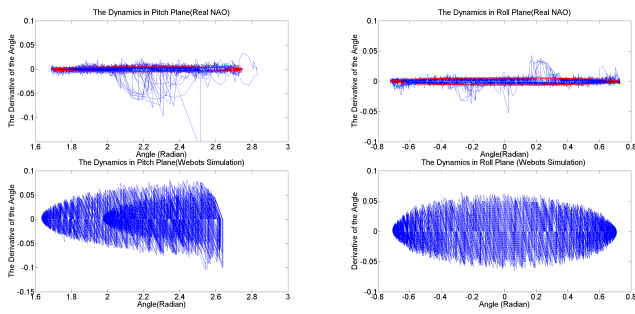


Fig. 9. Top: the dynamics of Pitch and Roll angle on the real NAO. Bottom: the dynamics of Pitch and Roll on simulation in Webots. All of the figures show the dynamics constrained by limit cycles. The red circle marks the limit cycles of the Pitch and Roll angle of the physical NAO robot. The Pitch angle includes the angles of shoulder, hip, knee, elbow and ankle; the Roll angle includes the angles of shoulder, hip and ankle.

sinusoid motion of the robot ‘spine’ consistent with work done on quadruped and invertebrate robots [16].

V. CONCLUSION

As a contribution to the RobotDOC project, the aim of our work is to further knowledge in developmental robotics and cognition. The work presented here represents the first stage of what is planned to be a longer term investigation into infant locomotion development concerning crawling to walking transitioning exploiting the capabilities of the NAO robot. CPG networks can not only proffer adaptive controllers for robots but also build a bridge between high-level control centres and basic sensorimotor capacities. More specifically, CPG networks can enable gait transitions which is a key function in a robot with developmental possibilities. The hypothesis in Dynamic Field Theory (DFT) is that new behaviours emerge from instabilities [30]. Therefore, interfacing CPG networks with DFT models offers future direction for investigating top-down control methods including gradual parametric modification that enables interactive modulation between cognitive and sensorimotor capacities, e.g. relevant to crawling to walking transitioning (cf. [15]).

ACKNOWLEDGMENT

This research has been supported by the EU project RobotDoc under G.A. 235065 from the 7th Framework Programme, Marie Curie Action ITN (<http://www.robotdoc.org>).

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