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LOCOMORPH

Robust Robotic Locomotion and Movements Through Morphology and Morphosis

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1 (Coordinator)	Universitaet Zurich	UZH
~~2~~	~~Friedrich-Schiller-Universitaet Jena~~	~~UJEN~~
3	Ecole Polytechnique Federale de Lausanne	EPFL
4	Syddansk Universitet	USD
5	Universiteit Antwerpen	UANT
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Abstract

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Locomorph: another concept towards legged robotic locomotion

Authors: members of the EU-FP7-ICT-Locomorph consortium

In alphabetic order

Peter Aerts (UANT), Lijin Aryananda (UZH), Kristiaan D'Août (UANT), Sten Grimmer (TUD), Martin Groß (TUD), Helmut Hauser (UZH), Auke Ijspeert (EPFL), Rico Möckel (EPFL), Jørgen Larsen (USD), Rolf Pfeifer (UZH), Soha Pouya (EPFL), Andre Seyfarth (TUD), James Smith (RYE), Kasper Støy (USD), Frank Peuker (TUD)

Abstract

A classical approach in bio-inspired robotics is to impose prescribed behaviour to a hardware design that is copied as closely as possible from an animal model. This typically results in monolithic robots limited in behavioural versatility. The present paper describes an alternative approach for the development of versatile legged robots. Based on the general appearance of the Spring Loaded Inverted Pendulum (SLIP)-behaviour in natural terrestrial legged locomotion, the abstract SLIP model was selected a priori to serve as the central theoretical concept (the template model) on which the basic physical limb module of the robot is inspired. The complexity of this model is stepwise increased (e.g. adding limb masses, increasing limb number, increasing the degrees of freedom...) and for each step, forward simulations are used to predict morphological and control parameters essential for stable locomotion. The latter information is fed into a simulation model to develop the control, and is used to guide the design if the hardware. This 'step by step' and 'hand in hand' progression of the template model, the simulation model and the hardware guarantees exploitation of the intrinsic mechanics and dynamics of the robot's morphology by the controller (morphological control), leading to efficient, 'natural' robotic behaviour. Starting from a general principle (SLIP) borrowed from nature, the final design is thus inherently modular, versatile and generic. This is illustrated by the gradual development of a 3D-modular SLIP-based quadruped able to morph from an upright-sagittal to a sprawling posture.

Introduction

To date, moving across a variable, complex and unpredictable terrain in an energy efficient and adequate way remains a challenge for terrestrial robots. Consequently, the seemingly effortless and graceful manner by which animals perform in their natural environment is often perceived as a nearly boundless source of inspiration for engineers aiming to develop of similarly versatile and efficient robots. However, when borrowing from nature, it should be kept in mind that also nature's solutions to real world problems are just optimisations to often highly specific niches, impeding animals to perform efficiently and adequately outside of the niche's boundaries. Moreover, the process of adaptation by natural selection is constrained by its own history, by physical and chemical limitations, by the existence of functional trade-offs, etc. (for more information see, for instance, Aerts et al., 2000), resulting in suboptimal or compromise 'morphologies'. As such, firmly adhering to specific animal models to develop new robots may definitely optimize concrete performance targets, but will almost inevitably compromise the versatility of the design.

An alternative approach in 'borrowing from nature', may be the comparative analysis of the diversity of animal morphology and (loco)motor behaviour in relation to the animal's ecology. Effective links between form and function can inductively be evidenced and the challenge for robotic implementation now becomes the integration of bio-inspiration extracted from multiple models. The general principles behind nature's solutions to fulfil an ecological function or role (e.g. terrestrial locomotion), rather than one specific bauplan, becomes the source of inspiration. For cyclic legged terrestrial locomotion, the spring-loaded-inverted-pendulum or SLIP is a paradigmatic example of such a general principle. Irrespective the number of limbs (bipeds to decapods) or the gait-type used (walk, trot, gallop…), gravitational and cyclic inertial loading obviously constrain limb morphologies to this SLIP template (Full & Koditschek, 1998; Dickinson et al., 2000, Full & Farley 2000). When moving over a horizontal surface, the SLIP behaviour typically determines the body dynamics in the vertical plane (Fig.1). Moreover, the same morphologies are argued to function as inertially loaded springs in the horizontal plane as well (the lateral-loaded-springs or LLS; Full & Koditschek, 1999, Chen et al., 2006) when limbs are sprawled (Fig.1). The ability to sprawl undoubtedly increases the versatility of the locomotor behaviour: stability can be increased on rough terrain (due to the lowered body centre and the increased base of support at slow gaits), steep inclines can be tackled (due to the lowered body centre of mass) and low passages can be crossed (see for instance: Zaaf et al., 1999, 2001a,b; Zaaf & Van Damme, 2001).

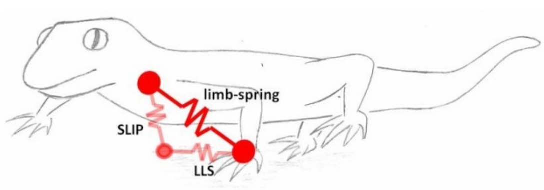

Figure 1 : SLIP & LLS template in a hypothetical lizard-like animal; in a vertical plane, the limb spring represents the SLIP, in the horizontal plane, the same spring represents the LLS

As such, the diversity of cyclic legged locomotion observed in nature can be represented by one design-template. This does not necessarily mean that all components of the locomotor behaviour are always optimised simultaneously by natural selection: cursorial mammals, for instance, optimised the SLIP-function for highly efficient and fast endurance locomotion, but lack, due to constructional constraints, the ability to sprawl. For locomotor generalists, on the other hand, the 'jacks of all trades are masters of none'-principle usually holds (i.e. they do not excel in any of the components; cf. Bauwens et al., 1995). However, the insight of a single template as gained from the comparative biological approach can be inspirational for a new design concept of versatile robots.

The concept

A classical view on a bio-inspired development of a robot, based on a specific animal model, is represented in figure 2A. Morphological data and information on kinematics (e.g. step-time-variables, gaits…) are transferred from the biologists to the engineers developing a monolithic robot. Via simulations, mimicking the robot construction, several iterations can be run to optimize control and hardware until the premised performance target is reached.

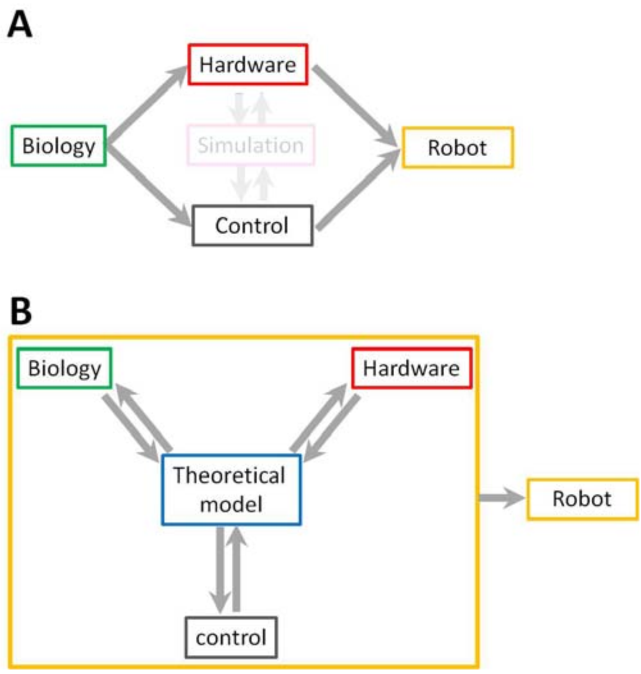

Figure 2: Approaches for robot design; A) classical approach, B) 'Locomorph' approach.

According to the alternative concept (Fig. 2B), the template-model (based on the comparative biological analysis) takes a central position at the start. Based on the continuous feedback from control and hardware simulations (later implementations), the central theoretical model evolves gradually towards a more and more elaborate '*in silico*' representation of what must become the template-unit of a modular robot. Results of simulations of new interim stages of the theoretical model are fed progressively into the control and hardware implementation and *vice versa*. The performance of the gradually developing model can be checked against the present biological database or new biological experiments can be set up to test the relevance of, or to amend, new model-improvements. These stepwise reciprocal interactions finally lead to the physical modular template-unit. The same procedure repeats to combine modules in a versatile robot.

Implementation of the approach in Locomorph project

The goal of the Locomorph-project (EU-FP7-ICT-2007-3; collaborative project) was, amongst others, the development of a modular robot by the implementation of the above mentioned concept. The robot should be versatile in that it can change interactively its morphology (i.e. locomotion-morphing) from sagittal to sprawling limb postures, thus enabling performance on a diversity of terrains (rough, inclines, low passages…).

Based on the general appearance of the SLIP-behaviour in natural terrestrial locomotion (cf. above), it was purposely and a priori decided to use the SLIP-LLS template as the initial central 'Theoretical Model'. In concept, before any hardware or control issues were taken into account, it was determined that the robot should be composed of SLIP-based 'limb-units', two of which should be combined in a fundamental 'Bipedal Unit', the BU. The robot could then be composed of several of these BU-modules to obtain quadrupeds, hexapods, octopods etc. Starting from this entirely conceptual framework, modules are developed according the approach presented in figure 2B. This implied, starting from the abstract SLIP, the synthesis of physically more representative and complex SLIP-models; development of control strategies for these models and the implementation of both in the final hardware.

Theoretical models

In its simplest form, the SLIP-model consists of a point mass (Fig. 3), representing the body centre of mass, connected to a massless spring that mimics limb behaviour. The model performs in one (sagittal) plane (i.e. 2D simulations). Despites this simplicity, the SLIP model can predict ground reaction force patterns from animals and humans in a forward simulation (Full & Koditschek, 1999, Geyer et al., 2006). That is, given initial conditions at a certain time, the model is able to describe the corresponding development of the ground reaction force in the future. Small deviations in the shape of the force patterns between model and experiment may occur e.g. due to impact forces at touchdown when the leg is contacting the ground. The spring-mass model's key control parameter is the premised "angle of attack" which prescribes the initial leg orientation with respect to ground at each new contact. Additionally, the leg spring must be specified to describe the force response of the leg during leg compression in stance phase. Also leg spring parameters (leg stiffness, rest length) can be used for locomotion control, e.g. for running over uneven ground (Müller and Blickhan, 2010, Blum et al. 2010).

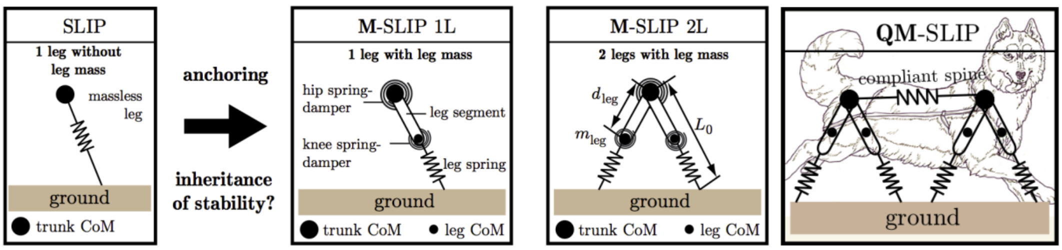

Figure 3: Based on the SLIP template (left), theoretical models with an increasing level of complexity were derived. In the M-SLIP models (right three panels), leg properties were represented in more detail (leg masses, viscoelastic hip and knee properties). M-SLIP models with two legs (2L) are used to represent a bipedal unit (BU) with 2 legs. Attached to a rigid or compliant trunk (right panel), multiple BU's can be combined, e.g. to assemble a quadrupedal system (QM-SLIP). Adapted from Peuker et al., 2012b.

To advance beyond the limitation of a prescribed landing angle and to account for the impact of leg masses, a mass is attributed to each of the two springy limbs in addition to the initial SLIP mass that loads the springs (Fig. 3). This M(leg **m**ass)-SLIP model of a BU enables to calculate the leg orientation in a forward simulation (Peuker et al., 2012a). Control schemes that initiate forward swing of the leg and that prepare the ground contact of the leg can be identified. Both are crucial for legged robots: after ground contact, these schemes have to deal with the problem of propelling the leg forward and to form cyclic movements. With the bipedal M-SLIP (2L) representing a BU (Fig. 3), cyclic bipedal gait patterns for walking and running could be simulated. Geometry and mass distribution are defined according to the morphometrics of a biological model; for instance the hind limbs of dogs as used in the present biological analyses (the anatomical hip joint is most representative for the fixed rotation centre of the M-SLIP in the body frame of reference; forelimbs of mammals are suspended at the level of the shoulder girdle by a muscular sling resulting in a more complex trajectory more challenging for simulation and further implementation in the development of a robot).

Insights for hardware design/control: Based on the bipedal M-SLIP model, hardware specifications of a BU regarding mass distribution between leg and trunk could be provided.

Another additional element in the ontogeny of M-SLIP towards the physical BU-design is the introduction of a massless rotational spring-damper at the level of the hip joints to control and drive forward and backward swinging of the limbs (Fig. 3). Offset leg orientation is defined by adjusting the rest angle of the hip spring, e.g. for positioning the leg for landing or to actively retract the leg (energy supply) during stance phase. This is required to compensate energy losses (e.g. due to impact forces and joint damping, e.g. in the knee joint).

To simulate walking and running, it was sufficient to apply two alternating hip spring rest angles in the M-SLIP model: in the swing phase, the hip spring rest angle moves the leg to a forward position and thus prepares ground contact; in the stance phase, hip spring rest angle is switched to a backward nominal position to inject energy. This corresponds to the observation that locomotion in quadrupeds is mainly powered by the hip joint (in contrast to humans)

Combining two bipedal M-SLIP systems with a horizontal trunk leads to a quadrupedal M-SLIP model (QM-SLIP, Fig. 3). This extension allows simulations of quadrupedal gaits like walk or trot. Based on the dog-morphometrics (cf. above) trotting at different speeds (running gait) could successfully be reproduced. Starting from a quadrupedal trotting gait, the QM-SLIP model also produced stable tripedal gaits when one hind limb was lifted during locomotion. Interestingly the predicted footfall pattern was similar to those observed in two hind-limb amputated dogs.

Insights for hardware design/control: Our results indicate that quadrupedal locomotion like trotting can be successfully described by the QM-SLIP system. This is reflected in the design of the Locomorph robot, which consists of a combination of two BU's connected by a trunk (connective unit, CU). With this design approach, there was no need to control the phase relation between fore- and hind limbs. This holds even for the dramatic case of hind limb loss. Here, it was sufficient to adjust the mechanical parameters of the remaining hind limb (e.g. higher leg stiffness or/and higher hip stiffness).

Additionally, design strategies for the combination of BU's with rigid or compliant connective units (CU's) could be derived.

In order to further bridge the gap between the theoretical models and real world systems (animals, humans and robots), the SLIP model is extended to represent 3D movements (Fig. 4). As such, a SLIP and LLS is combined in a limb-spring (cf. Fig. 1). Of particular interest is whether 3D locomotion based on spring-like leg function can equally result in self-stable running patterns as found for sagittal plane locomotion (Seyfarth et al., 2002). Self-stability means that the model predicts asymptotically stable running patterns even with fixed leg spring parameters (leg stiffness, rest length, angle of attack).

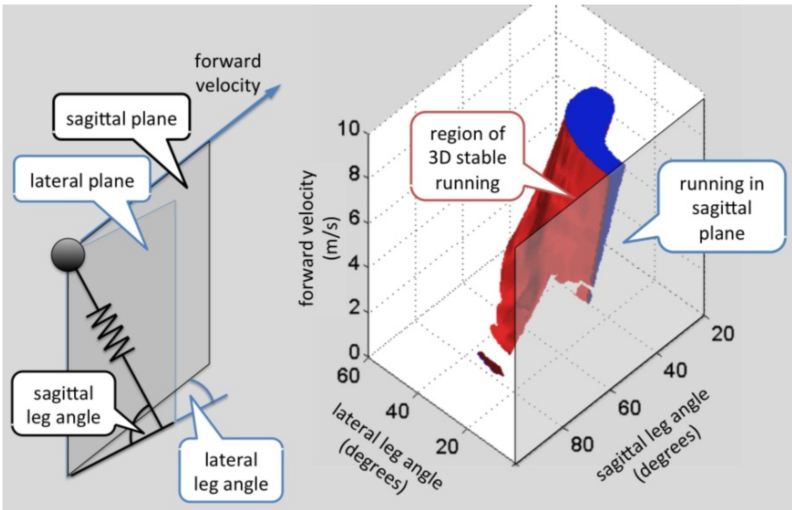

Figure 4: 3D-SLIP model. In order to achieve stable running patterns, a lateral leg angle as defined with respect to the plane spanned by the velocity vector (left). The region of 3D stable running is clearly enlarged of moderate lateral leg angles between 20 and 40 degrees (right).

This was investigated and already tested by Seipel and Holmes (2005). Surprisingly, they did not find self-stable patterns in 3D SLIP running. Therefore, the way in which the leg is positioned at touchdown, which is described by the sagittal and the lateral leg angle (Fig. 4, left), is slightly altered. In contrast to Seipel and Holmes (2005), the leg is positioned laterally, not with respect to a desired movement direction, but with respect to the current plane spanned by the velocity vector. With this assumption stable running solutions, which were neutrally stable in lateral direction, were obtained. Hence, the gait pattern was following a certain direction until a lateral perturbation (e.g. push, uneven ground, etc.) occurred. After the perturbation the movement would follow the new running direction until a new perturbation (or a turning manoeuvre) was introduced. Figure 5 shows the 3D-M-SLIP representation used in the optimization modelling for control development (see further).

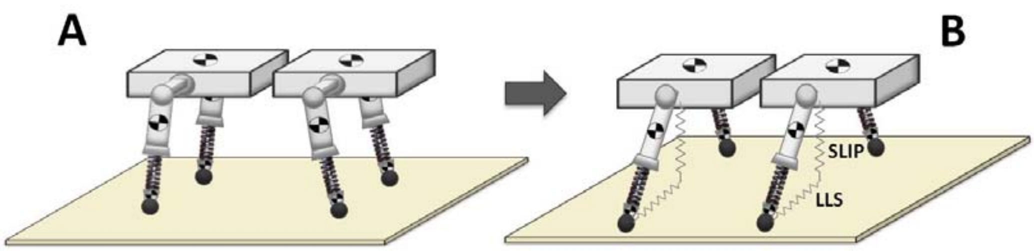

Figure 5: 3D-M-SLIP showing how abduction of the M-SLIP produces a sprawling posture

Insights for hardware/control: Our analysis showed that the concept of self-stable running with spring-like legs is not restricted to 2D sagittal plane but can seamlessly be extended to 3D locomotion (Fig. 4). The region for 3D stable running increases with larger lateral leg angles (20-40 degrees). It was important to align the leg laterally not with respect to a desired movement direction but with respect to the current velocity vector. Further advantages for 3D running are found when the sagittal leg angle is also placed in relation to the velocity vector (Peuker et al., 2012b).

Biology

As mentioned above, SLIP and LLS appears to be a nearly universal template for terrestrial locomotion in animals (Full & Koditschek, 1998; Dickinson et al., 2000, Full & Farley 2000, Alexander, 2003; Biewener, 2003; Chen et al., 2006). Assessing (variability of) SLIP/LLS characteristics of animal limbs during locomotion at different gaits (walking, running, trotting, galloping…), during different behaviours (steady state locomotion versus unsteady locomotion) and under variable environmental conditions (surface roughness, incline, habitat complexity…) provides an inspirational source on which the parametrical input of the theoretical SLIP/LLS models can be mapped. Moreover, information on the naturally applied spatio-temporal gait variables (step lengths, step frequencies, duty cycles) delimits the behavioural space of the SLIP/LLS models as exploited in nature. In this way, the SLIP/LLS-model- performance space can be explored inductively. On the other hand, the results of an inductive SLIP-modelling approach can be tested against selected animal-models (e.g. comparing stable gaits of 3-limbed SLIP-models with the natural gaits of fore or hind limb amputated dogs, an extreme example of morphing). Both ways of conceptual interaction (from 'biology' to 'theoretical model' and *vice versa*; see figure 2B) require the same kinds of functional morphological analyses.

A typical functional morphological gait analysis implies combined registration of 3D-segmental kinematics and (preferably single limb) 3D ground reaction forces. Multi-camera (high speed) video recordings of the moving animal allow to estimate 3D coordinates of anatomical markers (e.g. joint centres, segmental centres of mass,…) from the multiple 2D-views (DLT-routine). From the displacements of selected markers, limb length changes can be assessed and expressed against aligned single limb ground reaction forces. This relationship reveals the degree to which the limb behaves as a SLIP/LLS and yields an estimate for the limb-stiffness. From the 3D kinematics, spatio-temporal gait variables as well as limb sweep angles and end point trajectories of the limbs can be deduced. This kind of information can be fed into the theoretical template model to explore how stable and robust a far going abstractions of reality can perform.

Making the theoretical model more complex (e.g. adding limb masses, adding a trunk, applying hip actuation; cf. *Theoretical Model*) necessitates further data handling of the functional morphological data and biomechanical analysis to be able to understand the relationship between natural (animal) and theoretical model. Inverse dynamical analysis (combining ground reaction forces with segmental inertial properties and segmental linear and angular displacements, velocities and accelerations) enables to estimate joint torques (and stiffnesses) and joint power fluctuations. This kind of information transfers to the parameter settings and boundary conditions for the theoretical model and thus further to the implementation in hardware and control.

Insights for modelling/control/hardware design: Biological analyses specifically aims at the collection of data directly useful as input for the M-SLIP modelling (spatio-temporal gait characteristics, limb spring stiffness, linear dimensions, segmental mass distributions and inertia, joint torques...). Via the template model simulations, this information is transferred to the control and hardware design.

Control

The problem of motor control in robotics has largely been explored with classical engineering methods such as control theory and machine learning. On the other hand, several control approaches have been suggested which take inspiration from biological systems such as central pattern generators and sophisticated neuromuscular models. While classical engineering methods have the advantage that they are supported by well-developed methods and theorems, they can result in inefficient and unnatural behaviour especially if these methods are used to only 'brute-force' some pre-designed behaviours via robot control. Biologically-inspired control methods on the other hand, need well-defined methodologies that can capture the main involved principles and a way in which they can be applied to artificial living machines.

In contrast to classical engineering and biologically inspired methods, the present alternative 'Locomorph' approach mediates the control of robot locomotion through a hierarchical control framework exploiting template models based on the (M-)SLIP: i.e. the abstract representation of the general locomotion mechanisms (cf. above). As the complexity of the models increases (from SLIP to M-SLIP, QM-MSLIP and finally 3D-SLIP; see *'Theoretical Model'*), the process of 'control architecture design' includes similar step-wise progression. The control architecture is composed of different layers to resemble the widely accepted computational motor control hierarchy in neurobiology (Sabes, 2000; Schaal, 2005). In what follows, the different blocks of the framework are elaborated and their role in achieving the objectives (i.e. efficient and robust robotic locomotion with increased self-stabilization, energy efficiency, manoeuvrability, and adaptability to unknown environment) is discussed.

The control and learning framework is represented in figure 6. The whole framework is divided into two main processes; the higher level process of learning and lower-level process of executing the control loop. The latter is designed by taking the notion of an (M-)SLIP based 'internal model' into account: i.e. hypothetical computations in the 'brain' provide feed-forward predictions for the premised motions (Sabes, 2000). As for the template (M-)SLIP model itself, these predictions are only idealized abstractions of reality. Therefore, the simple feed-forward 'internal model' must be combined with feedback controllers to compensate for possible errors and external perturbations.

By taking into account internal models prescribing the behaviour of the robot and exploiting the robot's dynamics, energy-efficient and self-stabilizing behaviour can be achieved. With the '(M-)SLIP based internal model' and taking the intrinsic dynamics of the robot into account, the control required to obtain the desired behaviour is developed. As a result the robot's natural dynamics are not overwritten by the control but instead the control is actively taking advantage of the dynamics of the robot (i.e. for energy storage and self-stabilization).

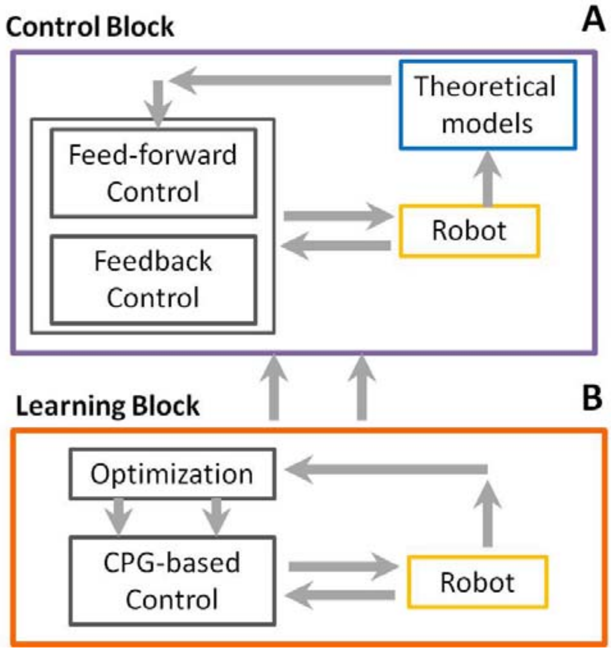

Figure 6: The proposed control-learning architecture composed of A) the learning process to find an optimal gait for the given robot dynamics, B) the control loop to reproduce the optimal gait composed of a feed-forward model (based on the theoretical models) and a feedback controller (decentralized PD controller)

In order to obtain task specific (e.g. fastest speed, following a given trajectory) optimised performance (minimised costs), the robot's controller goes through a learning process. Therefore, the dynamics of the embedded (Q)M-SLIP models are taken into account (mass distribution, inertia, stiffnesses,...), while local optimal solutions according to the optimisation criterion (e.g. speed) are extracted from the behaviour and fed back to the controller. This extraction results from optimisation process applied at the robot's 'joint position open-loop' profiles. These open-loop profiles are analogous to the rhythmic movement patterns generated in the spinal cord of animals (CPGs; Ijspeert, 2008); neural circuits capable of producing coordinated patterns of high-dimensional rhythmic output signals with simple low-dimensional input signals. CPG formulation facilitates the generation of different gait types through the coupling terms between different degrees of freedom. The CPG-based controller is well-suited for the optimisation process as it encodes the control profile with only a few tuning parameters.

This approach, elaborating on the (M-)SLIP model (Remy, 2011; Pouya et. al., 2012) , is used to analyse 3D quadrupedal locomotion in simulation and hardware. In this way, questions on optimal robot morphologies (dimensions, mass distribution, role of spine actuation …) could be addressed. Due to the similar model-inspired robot design, gained insights can easily be transferred to the robotic hardware as well.

Insights for hardware/theoretical model: Both Locomorph hardware and controller design are based on the (M-)SLIP models, taking the hierarchy of their complexity into account. This enables harmonious progressive development of theoretical model, controller and hardware. As a result, controllers and robot behaviour can be well evaluated by simulation models. Furthermore, the control learned in an optimisation process exploits the robot's natural dynamics rather than trying to overwrite it. After simulation, both learning and control methods can be transferred onto the hardware.

Hardware

One of the main challenges in using robots for fundamental research is the complexity of the hardware design, implying high costs and long development times. This typically limits hardware based research to larger projects and, even then, most often only one (in the best case a few) robot(s) can be realised to a level useful for research towards the end of the project. A more fundamental problem, however, is that because of its particular morphology (geometry, actuator strengths, gearing, materials, sensors, ...), a monolithic robot implementation is limited in the number of 'morphology'-related questions that it can address. Remark, however, that for control research, such a monolithic platform definitely keeps its relevance.

Generally, monolithic robots are designed either according to standard engineering principles or by mimicking the morphology of a particular animal model as closely as possible. The present 'Locomorph' approach is different in that (M-)SLIP model-based hardware modules are developed (see Fig. 7, top row) which enables to build robots with a variety of morphologies, capable of morphosis (i.e. active change of morphology). Moreover, because of the (M-)SLIP inspiration, general principles of limbed terrestrial locomotion can be studied with the Locomorph hardware.

Each 'Locomorph' limb can be used in a configuration with two degrees of freedom (2DOF; see Fig.7, left column) – one for leg expansion/contraction and one for leg retraction/protraction. A third DOF for leg abduction/adduction can be added, allowing sprawling of the limbs (morphosis; see Fig. 7, compare middle and right columns).

- The first DOF for limb lengthening and shortening was directly inspired by the (M-)SLIP model. A variable passive linear spring allows for periodic energy storage and release within a gait cycle. In addition to the (M-)SLIP, the Locomorph limb can be actively extended and shortened by an actuator that drives this first DOF through a crank-slider mechanism. This actuator can be used to compensate for energy losses that are not captured in the original SLIP model but can also be removed if the motor is not required. Spring characteristics as well as required motor performance where a priori set based on the output of the simulations with the template models. This first DOF also enables the limb to morph by changing its offset length.

- The second DOF accords to hip actuation. In the original SLIP model hip actuation is not described during the swing phase and the limb angle at touchdown acts as the only control parameter. Actual robotic hardware cannot set the angle of attack instantaneously and smooth trajectories for the hip actuation are preferred. This insight triggered the progression from SLIP to M-SLIP in the 'theoretical modelling' (i.e. accounting for actual leg masses and energy losses in the hip actuation) and necessitated to include hip torques in the simulation analyses for control and learning.

- With the third DOF, limbs can actively adjust ab- and adduction, thus enabling to morph from an upright to a sprawling gait. When sprawling, hip retraction remains the major source for propulsion, but this gait requires adjustment of the slider crank geometry to optimize the end point trajectory, as well as tuned activation of the 3rd DOF actuators to complete the gait cycles (i.e. limbs must be abducted during swing and adducted during stance phases; cf. sprawled locomotion in animals).

As for the theoretical model, also the development of the robot is characterized by a series of ontogenetic steps. First, a single limb module based on the M-SLIP was developed and tested (Fig. 7, top row). Attaching two of such modules together results in the basic Biped Unit or BU (Fig. 7, middle row). More complex robot designs can be achieved by connecting BUs through stiff, passive compliant or actuated Connecting Units (CUs) to form quadrupeds (BUcuBU; Fig. 7, bottom row), hexapods (BUcuBUcuBU) etc. Freezing the actuation of one of the limbs of a quadruped during the swing phase results in a tripod gait provided that the 3th DOF of the contralateral limb is adjusted. Further variation in morphology can be obtained by using elements of different lengths to connect limbs within one BU or by changing the dimensions and mass distributions of the CUs between the BUs.

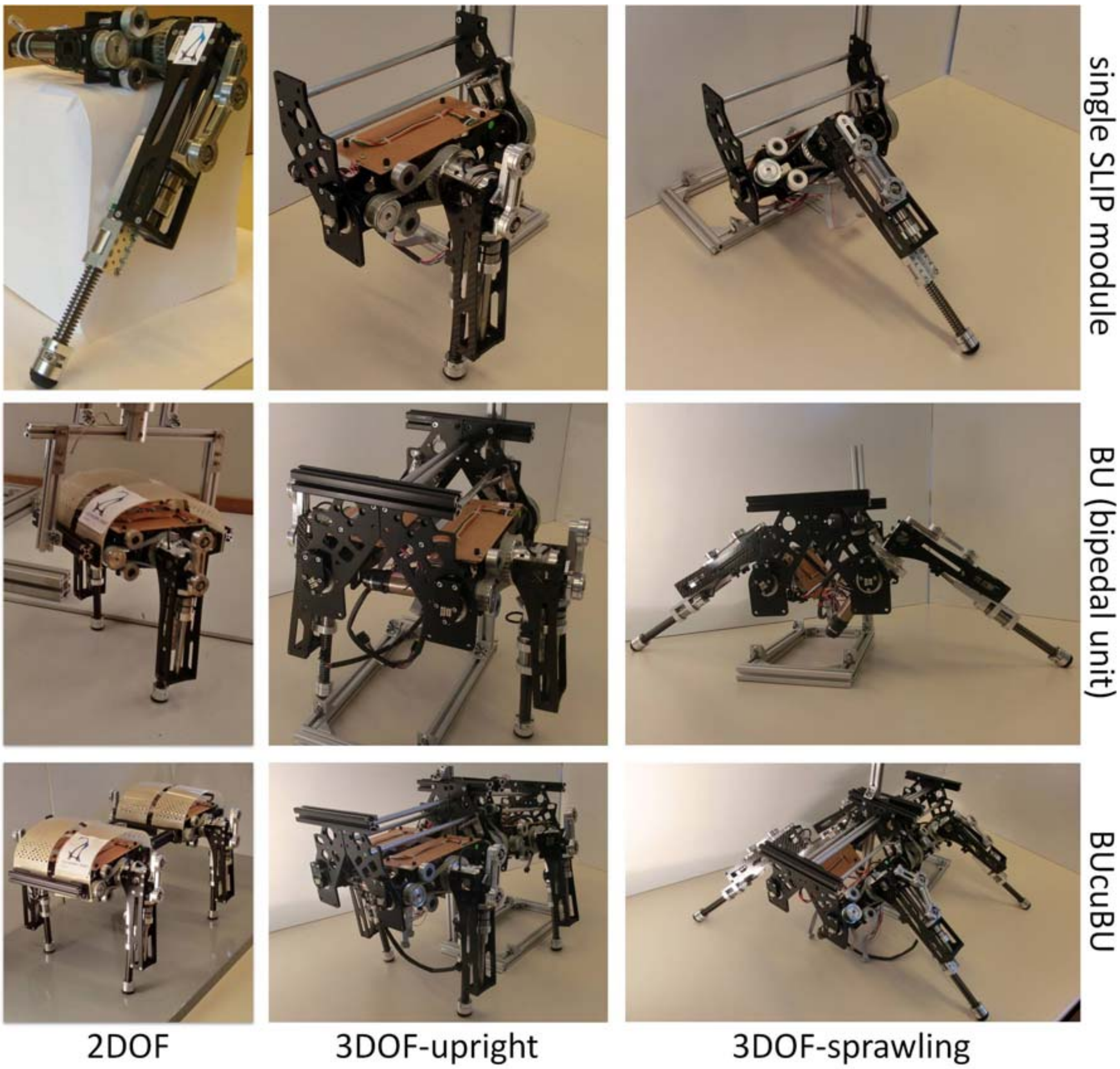

Figure 7: Step-wise development of Locomorph hardware; top row: single SLIP-module; middle row: BU (Bipedal Unit); bottom row: BUcuBU (quadruped built of 2 BU's connected with a Connective Unit); left column: 2DOF/limb-configurations; middle and right column: 3DOF/limb-configuration, resp. In upright and sprawling postures.

Insights for modelling/controller design: Robot performance provides the proof of concept. Evaluation of performance is carried out by means of the same methods and techniques as applied in the biological analyses. Similar data (spatio-temporal gait characteristics, ground reaction forces, limb stiffnesses) are extracted and fed back to the controller design.

General Conclusion

The ultimate goal of the conceptual approach presented in this paper is the construction of robots. In case of the Locomorph robot, the design should be useful for fundamental research of legged terrestrial locomotion, both for engineering applications (conceptual insights in control and hardware issues) and biology (fundamental insights in diversity of motor behaviour and ecology). For this purpose, Locomorph took a novel approach exploiting the advantages from both classical engineering and biologically inspired methods. However, there is neither opted for the one-to-one copy of a specific biological model, nor to confine the approach to 'brute-force' engineering. Instead, the general (M-)SLIP model of legged terrestrial locomotion is selected as the template for the basic module and is exploited for further elaboration and theoretical exploration in order to bridge the fundamental building blocks (biology, control and hardware) of the alternative bio-inspired robot design.

This approach is beneficial in several ways.

- Starting from a general principle (SLIP) borrowed from nature, the final design is inherently modular, versatile and generic (rather than over-specialized and monolithic).

- The stepwise, hand in hand progression of the complexity of the theoretical modelling (from SLIP to M-SLIP, QM-SLIP and 3D-QM-SLIP) and controller (learning by simulations, using the specific morphologies and the SLIP-'internal model') guarantees the exploitation of the intrinsic mechanical and dynamical features of the final construction (rather than forcing a premised behaviour to an abstract hardware design). As such, the robot behaviour becomes 'natural' because part of the control is embodied in the morphology (morphological computation and control). Benefits are efficiency (by guiding, instead of overruling the intrinsic dynamics of the system) and self-stabilisation (by using compliant properties and dynamics of the hardware instead of implementing additional actuation and sensory feedback).

- The strong, direct coupling between theoretical model and physical design (hardware modules, robot) allows the use of relatively simple and computationally inexpensive simulations models to study the robot's behaviour. The matching morphologies of model and robot become especially advantageous when control and morphological parameters must be tuned through optimisation techniques and when the models are used in closed-loop or feed-forwards model-based control.

Yet, it must be kept in mind that throughout the entire process careful analyses of the locomotion behaviour of robotic systems in comparison to biological observations and the predictions of conceptual models remains essential. In this way, weak links (e.g. required changes in the design and control of the robots, improvements of conceptual models, missing insights on biological systems) can be identified and feedback can be provided at any level of the scheme presented in figure 2B. This results in continuously updating of the design process.

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