Trot Gait Locomotion of a Cat Sized Quadruped Robot

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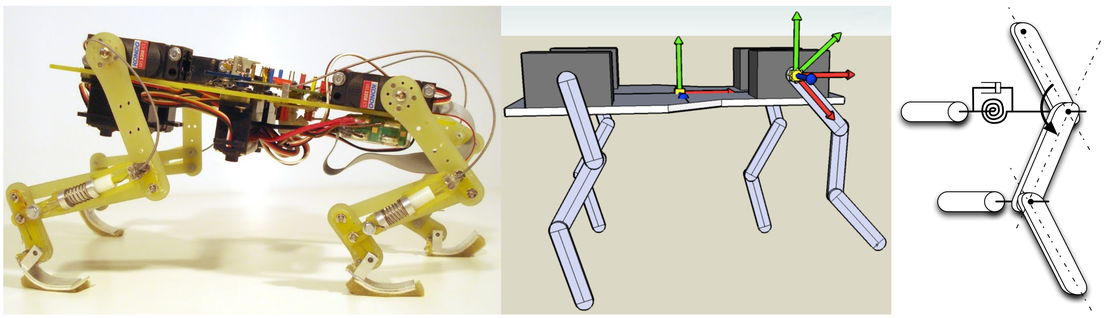
Motivation

We are proposing and testing two model-free approaches for locomotion control of a light-weight, compliant, quadruped robot: open loop central pattern generators (CPG) [1], and open and closed-loop dynamical movement primitives (DMP) [2]. We are presenting two different knee joint controllers, based on the hypothesis that the passive-compliant leg design might require less control effort for the knee joint control.

Robot Design

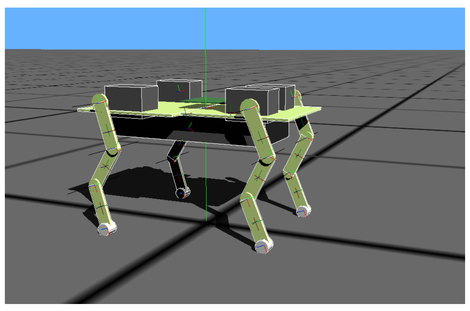


Left: Our previous quadruped robot "Cheetah"—basis for the robot used in the experiments applying DMP and CPG. The robot's leg design is three-segmented, pantographic, featuring a passive, gravity loaded spring mechanism spanning over two mid-leg joints. All actuators are placed proximally, the mid-leg joints are actuated through a cable mechanism. *Middle and right:* The robot used for this paper. Simulation environment is Webots. The three segmentation of the Model robot is kept, the panthographic behavior is hard-coded by a dedicated joint controller. This keeps proximal and distal leg segment parallel at all times. Compliance is introduced by serial elasticity in the proximal knee joint.

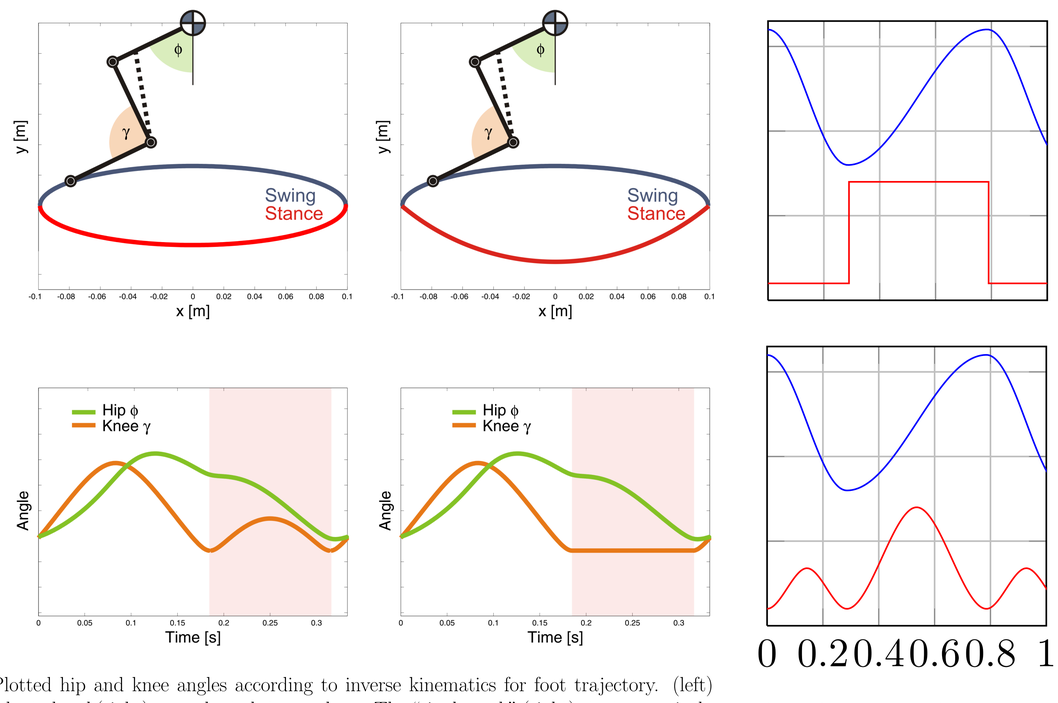
Both the physics-based simulated version and the in-construction version of our robot are based on a mammalian animal, of approximate size and weight of a house cat. Improvements in the new model (hardware):

- Brushless, high power motor
- Rich sensor setup
- Optimized gearbox
- Battery supplied
- RT Linux on-board

Characteristic	Value
Leg length	165 mm
Leg segmentation	$\frac{1}{3}\frac{1}{3}\frac{1}{3}$
Total mass	2 kg
Body length	300 mm
Servomotors stall torque	3 Nm
Servomotors maximal speed	29.60 rad s^{-1}



Foot Locus Design



Plotted hip and knee angles according to inverse kinematics for foot trajectory. (left) adapted and (right) non-adapted stance phase. The "single peak" (right) strategy actively only flexes the leg during swing phase, the "double peak" (left) strategy flexes the knee also during stance phase.

Simplified prototype for "single peak" and "double peak" knee commands for one step cycle. Blue lines represent hip commands, red lines knee commands. control.

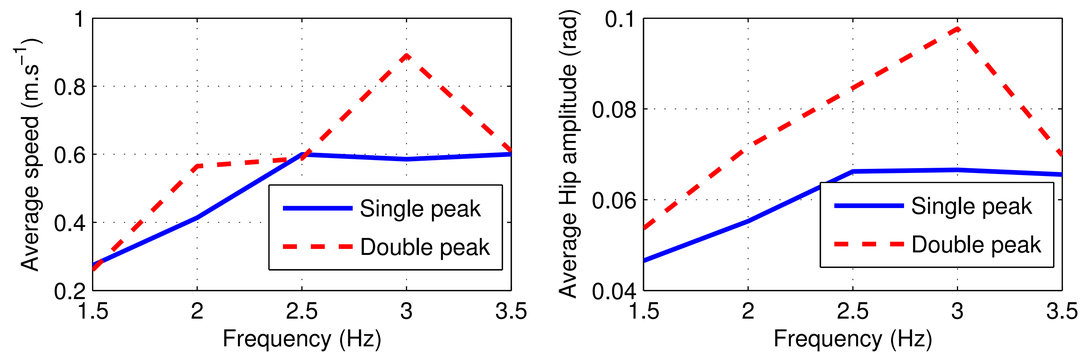
Acknowledgments

The research leading to these results has received funding from the European Communitys Seventh Framework Programme FP7/2007-2013-Challenge 2-Cognitive Systems, Interaction, Robotics-under grant agreement No. 248311 [AMARSi].

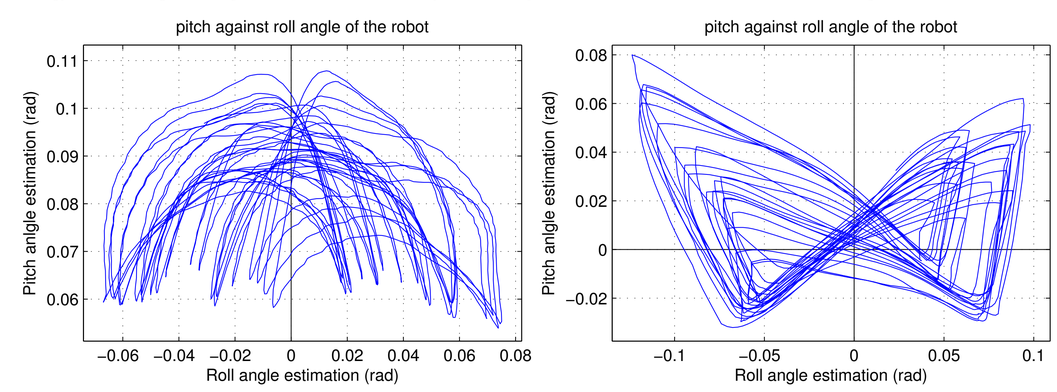
Open-loop CPG Optimization and Control

A fully-connected network of four amplitude-driven phase-coupled oscillators optimized with Particle Swarm Optimization (PSO) [3] to:

- Maximize the traveled distance in the front direction;
- Minimize the pitch and roll variations of the robot's trunk.



Comparison between "single peak" knee command control (left) and "double peak" knee command control (right) for one step cycle. Blue lines represent hip commands, red lines knee commands. The "single peak" strategy actively only flexes the leg during swing phase, the "double peak" strategy also during stance phase. To more efficiently follow trajectories we smoothened out the "double peak" control.



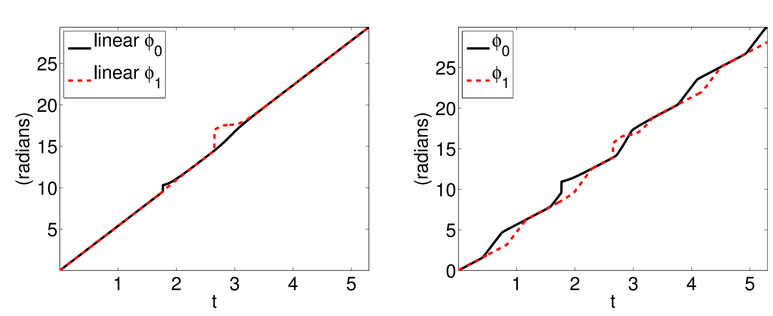
Roll angle versus pitch angle for two gaits generated by the two knee command methods. More limit cycle behavior is obtained with the "double-peak" knee command. This shows more robustness.

The "single peak" strategy exploits the natural compliance of the knee joint, and subsequently we could find a number of fast gaits for it. All of them are using a relatively low hip amplitude, and produce gait patterns with large and unstable pitch and roll motions. The "double peak" strategy actively reduces those pitch and roll motions by flexing the leg during stance phase. Through this gaits with higher amplitudes and velocities can be found by the optimization.

Closed-loop Dynamical Movement Primitives

DMP are capable of encoding any arbitrary signal, and accept sensory feedback in different forms. We enriched DMP with the capability to modulate the durations of swing and stance phases independently (as suggested by [4]) and introduced a mechanism to couple such controllers. We also exploited two sensory feedback strategies:

- Feedback from contact sensors for phase resetting (similar to [5]);
- Feedback from gyroscope to correct the direction of the robot.



Two coupled DMP with nonlinear phases. Each DMP has a nonlinearly changing τ, so their phase evolution ($\tau\phi = 2\pi$) is not linear. However these phases are not directly coupled. Instead, two correspondent linear phases are coupled (*left*), and the nonlinear phases (*right*), that are in result coupled, are calculated. So, $\phi = f(\phi_{linear})$. As it can be seen, disturbances are applied on the linear phases (around time: 2 sec and 3 sec), but both linear and nonlinear phases are able to reject the disturbances and remain synchronized.

Model	Front Slopes			Side Slopes			Step Down			Sagittal Perturbations			Arbitrary Perturbations		
	Success%	Avg. Spd.	Std.	Success%	Avg. Spd.	Std.	Success%	Avg. Spd.	Std.	Success%	Avg. Spd.	Std.	Success%	Avg. Spd.	Std.
OL	90	0.11	0.19	86	0.12	0.10	87	0.10	0.04	83	0.23	0.04	78	0.22	0.04
CL+TS	76	0.11	0.10	67	0.07	0.09	85	0.15	0.05	76	0.21	0.04	72	0.21	0.04
CL+TS+GY	76	0.13	0.09	67	0.13	0.05	64	0.12	0.03	75	0.20	0.07	70	0.20	0.05
CL+TS+GY+SW	90	0.16	0.09	90	0.13	0.07	76	0.16	0.03	82	0.23	0.06	77	0.23	0.05
CL+GY+SW	100	0.17	0.11	100	0.18	0.06	69	0.09	0.05	86	0.24	0.06	78	0.22	0.05
OL+SW	100	0.10	0.17	100	0.10	0.09	76	0.09	0.05	84	0.23	0.04	76	0.22	0.04

Benchmark results for six different DMP setups all identically trained with a 1.5Hz low COM gait. OL: open-loop, CL: closed-loop, TS: sensory feedback from contact sensor, GY: sensory feedback from gyroscope, SW: swing duration modulated to 2Hz

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