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Author(s)	Ashtiani, Shafiee Milad; Sarvestani, Aghamaleki Alborz; Badri-Spröwitz, Alexander
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Tackling sensorimotor delays and low control update frequencies during drop impacts with hybrid parallel leg compliance

Milad Shafiee Ashtiani[a,*], Alborz Aghamaleki Sarvestani[b,*], Alexander Badri-Spröwitz[c]
Dynamic Locomotion Group, Max Planck Institute for Intelligent System, Stuttgart, Germany
[a]*shafiee@is.mpg.de*, [b]*sarvestani@is.mpg.de*, [c]*sprowitz@is.mpg.de*, [*]*equal contribution*

1 Introduction

Animals' central nervous system exhibits large sensorimotor delays, i.e., the period between sensory input and the corresponding muscle excitation triggered by a spinal cord reflex. More and Donelan report that the sensorimotor delay scales with the animal's mass M as $t_{delay} = 0.031M^{0.21}$ [1, Figure 3]. Hence, a cat-sized animal of 4 kg would manifest a total delay of 41 ms. Cats run up to 5 Hz locomotion frequency, with a stance phase duration of less than 0.1 s [2]. In this example, the animal would be touch sensor-blind almost half its stance phase. Swing-to-stance transitions are notoriously demanding, and leg forces ramp from zero to body weight within half a stance phase. Passive elastic joint structures can produce the required forces in time. They act physically, hence independently from sensorimotor delays. Purely passive-elastic structures are also harder to control; either the elasticity adds an uncontrolled degree of freedom (series elastic), or an actuator works against the partially charged compliant structure (parallel elastic). Both in-series and parallel elastic structures are known in animals. And animals run robustly and agile, adapt rapidly, and react fast [3]. Do animals use complex elastic structures to avoid the detrimental consequences of sensorimotor delays, and how?

Legged robots have become agile and fast [4, 5]. Fully active-actuator systems are controlled with high control frequencies, above $f = 500\,\text{Hz}$, to set actuator torque, speed, and read out sensors. Electronic data signals travel in the range of speed of light. Therefore, intra-robot delays are practically independent of wire length and robot size and weight. Instead, communication delays in the range of a few milliseconds are caused by analog to digital signal conversion and software and firmware execution time [4].

Robot sensors measure joint position, force, or motor current, which makes them indispensable for control. Locomotion impacts induce force peaks, material stresses, and parasitic oscillations in force sensors. It is necessary to distinguish the signal from sensor noise reliably, but filtering will add delay [6, 7]. Communication delays can destabilize controllers in high-distance applications like teleoperating legged robots. The complexity of high-level planners can take significant time to compute, in the range of 10 ms and more [8]. Physical elasticity-based robot legs run without system-state feedback, but with limited versatility [9, 10]. Like animals, legged robots should benefit from intrinsic robustness against sensorimotor delays. Else, delays will potentially destabilize robot control.

Our inspiration is the animal leg joint morphology with multiple, parallel insertions of muscle tendons and passive and active compliant leg actuation [3, 11]. In the following, we demonstrate a leg system with robustness against delays and low control frequencies at leg impacts. We test a hybrid parallel leg with varying passive and active joint compliance ratios, controlled by a virtual leg spring controller.

2 Materials and Methods

We tested a parallel passive and active elastic leg by exposing its controller to large sensorimotor delays and low control update frequencies. We ran computer simulations in PyBullet, the leg is an instance of the Solo robot leg [12, 4], which we augmented with an in-parallel mounted knee spring of varying passive stiffness. The leg is two-segmented with a mass of 0.6 kg and a length of 0.34 m. The knee joint torque is the sum of the actuator torque and the torque produced by the in-parallel mounted knee spring inserting into a knee cam. The passive compliance ratio $\lambda_{passive}$ is the ratio of the passive knee stiffness $K_{passive}$ and total knee joint stiffness $K_{active} + K_{passive}$:

$$\lambda_{passive} = K_{passive}/(K_{active} + K_{passive}) \tag{1}$$

The spring-based knee torque is:

$$\tau_{spr} = K_{total}(\lambda_{passive})(\theta_{sl} - \theta) \tag{2}$$

The angle $\theta_{sl} = 170°$ is the knee angle with its spring slacked (sl). θ is the instantaneous knee angle, all rotational stiffness values K are in [Nm/rad]. The simulated motor torque is calculated as:

$$\tau_{mot} = K_{total}(1 - \lambda_{passive})(\theta_{sl} - \theta_{fb}) \tag{3}$$

We chose a total leg stiffness of $K_{total} = 1.7\,\text{Nm/rad}$. The angle θ_{fb} is the measured knee angle fed back (fb) to the controller, augmented with an artificial time delay. We limited the hip movement to vertical motions, i.e., we dropped the robot leg from 1.3 leg length vertically. We systematically varied $\lambda_{passive}$ from 0.0 to 1.0 in steps of 0.05, the sensorimotor delay from 0 ms to 60 ms in steps of 5 ms, and the control update frequency between 20, 50, 100, 250, and 1000 Hz. We defined unsuccessful landings if the robot's hip joint position did settle only after a 0.7 s settling time, or below a settling height of 0.3 m.

3 Results

The results of a systematic search with 1365 computer-simulated drop-landings are shown in Figure 1, in the left panels. The measured settling time of successful drop-

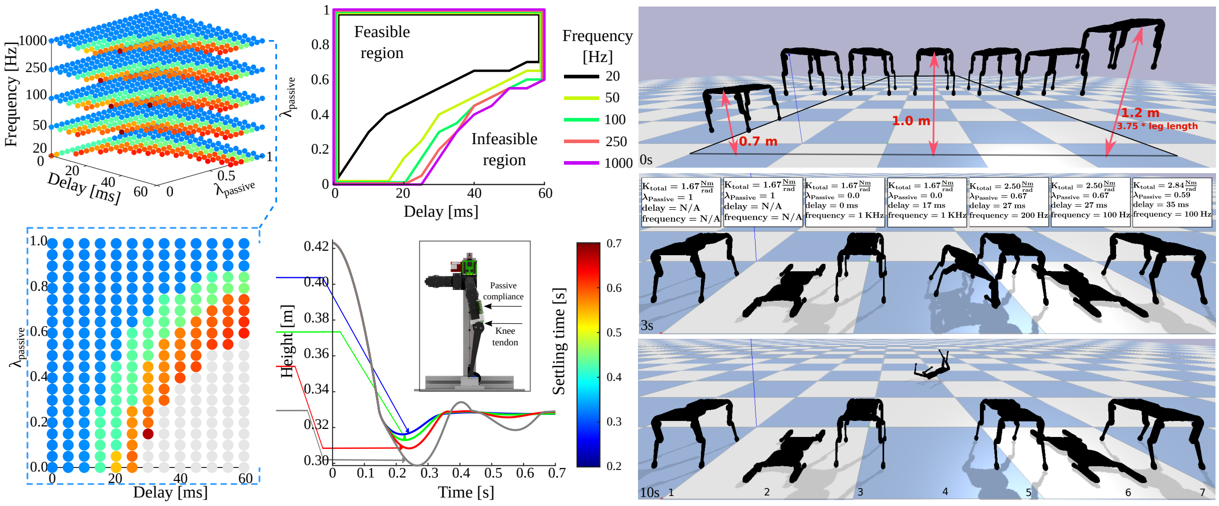

Figure 1: *Simulation results:* (left) Dropping the hybrid actuated robot leg from a height of 1.3 leg length. In this systematic test we varied control frequency, feedback delay, and passive compliance ratio $\lambda_{passive}$ of leg stiffness. (right) Computer simulated landings of quadruped robots in seven control and stiffness ratio configurations. Figures are modified from [13].

landings is color indicated, between blue (0.2 s) and red (0.7 s). Unsuccessful landings are shown in gray.

As a general tendency, we observe that large sensorimotor delays require large ratios of passive compliance. The control frequency can be decreased down to 20 Hz, but at the price of reduced feasible parameter space, compared to 1 kHz control frequency. Interestingly, the feasible space changes little between 50 and 1000 Hz but drops much when switching to 20 Hz. Control parameter combinations successfully rejecting large sensorimotor delays above 30 ms are found for passive compliance ratios above 0.5, and control frequencies above 50 Hz. In most $\lambda_{passive} > 0.6$ we observe successful landings, including critical combinations of 60 ms delay and 20 Hz update frequency.

To extended our tests to non-constraint experiments, we simulated drop-landings with a quadruped robot with hybrid actuated legs. Here we varied the robot's initial height. Snapshots of the quadruped robots before and after drop-landings are shown in Figure 1 (right). For example, the case 1 robot simulates a compliance ratio of 1.0, i.e., a fully passive elastic knee joint and a drop from 0.7 m height. The robot landed successfully. The case 7 robot features a large active motor contribution with a $\lambda_{passive} = 0.59$, and landed successfully from a height of 1.2 m and with a sensorimotor delay of 35 ms at a control frequency of 100 Hz.

We showed how a hybrid parallel system could be successfully controlled with low update frequencies and high feedback delays during impacts from drop-landings and compared these results to fully actuated and fully passive robot legs. The parallel, passive knee spring contributes to a lower actuator power consumption during standing and an immediate leg force response at impact [9]. The in-parallel mounted active motor provides control authority. We found that robot legs built with compliance ratios around 0.5 controlled by a virtual leg length controller show good intrinsic robustness and control authority during drop-landings.

4 Acknowledgments and References

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