Towards Hybrid Active and Passive Compliant Mechanisms in Legged Robots

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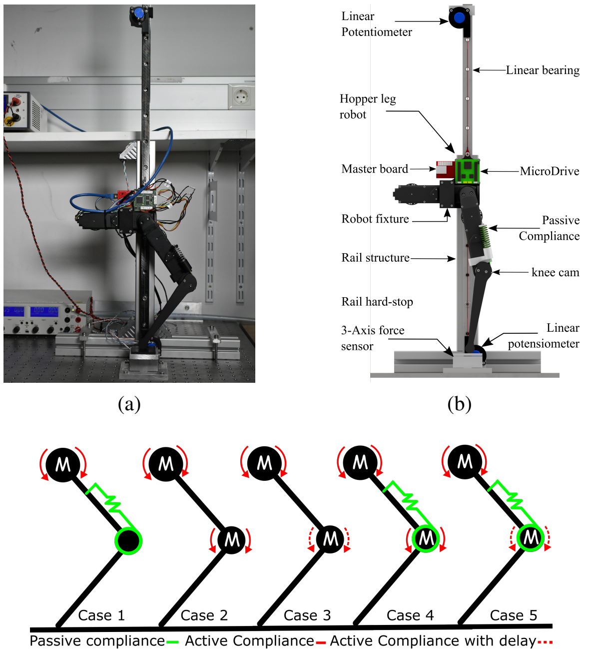
I. INTRODUCTION

The newest generation of legged robots is showing good dynamic behaviors and parkour-like maneuvers [1, 2]. Legged robots with active impedance or virtual spring leg control use quasi-direct actuation, with full control authority on all actuators. These robots also rely on high-frequency control loops with communication/control delays of a few milliseconds and less [3]. The actuation principle's choice comes at a second cost: the robot consumes energy for simple tasks such as standing. Observing what kind of dynamics legged animals are capable of, it is somewhat surprising that their neuro-muscular control shows comparatively large sensorimotor delays [4]. Animals differ in multiple, significant aspects; compared to their robotic counterparts, they benefit from passive and active compliant elements in their leg actuation mechanism [5]. We believe that compliant structures might allow animals to save energy during locomotion and provide robust behavior in the presence of neuro-communication delay. Bio-inspired robots equipped with passive, compliant parts similar to animals can drastically reduce control effort and increase robustness against external disturbances. Legged robots with in-series and parallel joint elasticity can locomote purely driven by feed-forward control, and no feedback information from touch-down, leg angle, or joint loading [6, 7]. However, robots with pronounced compliant leg mechanics often suffer from lower controllability because mounted springs lead to under-actuation. Adding actuators in parallel to springs leads to antagonistic actuation, which can also be limiting the accuracy and maneuverability of the robot.

In teleoperated systems, time-delay can occur due to the communication distance [8]. Force feedback works well in minimal-delay systems, but large feedback delays will eventually cause control instabilities. Thus, the communication delay is a significant challenge for legged robots and teleoperation scenarios. In legged robots, communication delays are effectively all occurrences where feedback is transmitted well beyond the expected time-frame, which also happens during step-down or push-like perturbations.

In this research, we start with the knowledge that fully passively, spring-loaded legged robots work well with open-loop control, i.e., without any control feedback. On the other end of the design spectrum are high-bandwidth, fully actuated legged robots with quasi-direct driven motors.



(a) (b)

(c)

Fig. 1. (a) Experimental setup: A 2-DoF leg with one-directional spring extending the knee joint. The spring is replaced or removed during experiments. A rail guides the robot's fall, a potentiometer measures its height. (b) Component details. (c) Experimental scenarios for combinations of active/passive compliance.

This research shows how robots with a hybrid passive and active approach to joint stiffness might successfully overcome significant communication delays of sensor information. We show that by selecting a certain ratio of active to passive stiffness, we can tackle up to 37 ms time delay during drop-landing tasks. In comparison, state-of-the-art quasi-direct driven legged robots implement delays below 1 ms to 2 ms [1]. Our legged robot runs on comparatively low actuator power, resulting from the partial contribution of passive elasticities. However, its in-parallel active joint compliance leads to a sufficient joint control level, much better than robots with passively compliant leg designs.

II. EXPERIMENTS, PRELIMINARY RESULTS

To investigate the effect of hybrid passive and active joint stiffness in the presence of communication delay we designed five experiments for a vertically dropped 2-DoF robot leg. It is released from a fixed height onto solid ground,

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AAS is supported by the International Max Planck Research School for Intelligent Systems (IMPRS-IS). We thank Jad Saud and Felix Grimminger for the support developing the robotic leg. Authors are with the Dynamic Locomotion Group, Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany {shafiee}{sarvestani}{sprowitz}@is.mpg.de

and should rapidly converge to its standing height. The experimental parameter combinations are shown in Section II.

	Total (sum) Compliance [N/m]	Active Compliance [N/m]	Passive compliance [N/m]	Control Frequency [Hz]	Delay [ms]
Case 1	3120	0	3120	1000	0
Case 2	3120	3120	0	1000	0
Case 3	3120	3120	0	1000	37
Case 4	3120	1610	1510	1000	0
Case 5	3120	1610	1510	1000	37

TABLE I

Parameters of the experimental case study.

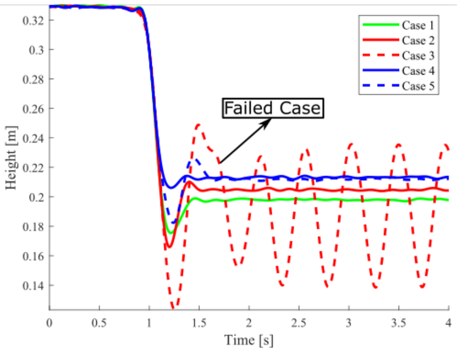

Fig. 2. Experimental result of five cases. **Case 1 (green):** Passive knee compliance, **Case 2 (red solid):** Active one-directional knee compliance with zero communication delay. **Case 3 (red dashed):** Active one-directional knee compliance with delay. **Case 4 (blue solid):** Combination of passive and active knee compliance without delay. **Case 5 (blue dashed):** Combination of passive and active knee compliance with delay.

We are using a single leg taken from the open-source robot 'Solo' [1], with small modifications. The leg is equipped with two active degrees of freedom (hip and knee). A small, powerful brushless motor is mounted to a 9:1 belt transmission gear ratio. Joint encoders measure each motor's rotor position. We added a knee spring in parallel, producing passive knee torque via a cable inserting into a fixed-radius cam (18.5 mm radius). The spring can rapidly be replaced by a softer/harder one, between experiments. For simplification, the robot legs drop while guided on a rail (Figure 1b). We monitor the robot's vertical position, and quantify its landing and subsequent standing behavior to evaluate the effectiveness of our hybrid active/passive joint stiffness framework. Two experimental parameters are altered: **a)** The robot's knee joint is equipped with a parallel-mounted spring acting on a cam, via a cable. The resulting passive joint elasticity captures between 50 % to 100 % of the robot's weight. The parallel spring is also removed to show results with a fully actuated, robot leg (0 % parallel joint stiffness). In all cases, the leg's joint controller monitors the knee joint angle and adds an active torque, so the sum of passive and active torque leads to an overall nominal joint torque carrying the robot's weight. In sum, three joint stiffness settings are tested. **b)** We implemented a communication delay of 37 ms delay for sending actuator commands in reference to the measured joint angle. In total two communication delays are tested: 0 ms and 37 ms. For an experiment to run successfully, the robot leg drops and lands, and rapidly converges to a standing posture with few overshoots in height. Failed experiments show, for example, continuous oscillations for more than 5 cycles (Figure 3).

Fig. 3. Spring loaded knee joint with a bidirectional actuator, quadrupedal platform, robot modified from the Open Dynamic Robot Initiative [1].

Our first results (Figure 3) show ho **case 5** has a robust behavior at 37 ms delay. **Case 3** is unstable in the presence of a 37 ms delay and requires much higher joint power, compared to **case 5**. Both **case 1 and 3** have similar body trajectories, with a small difference in steady-state height caused by friction of moving elastic elements in **case 1**. In **case 1**, the robot's knee joint consumes no electrical power, but we also lack the ability to control its joint for high-level tasks.

III. FUTURE DIRECTION

We plan to transfer our insights to a quadrupedal platform, to implement a hybrid landing and walking controller for a quadruped robot. We expect to observe a lower-power robot locomotion design, with the high fidelity of fully actuated robots.

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