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STARLETH: A COMPLIANT QUADRUPEDAL ROBOT FOR FAST, EFFICIENT, AND VERSATILE LOCOMOTION*

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This paper introduces Starl*ETH*, a compliant quadrupedal robot that is designed to study fast, efficient, and versatile locomotion. The platform is fully actuated with high compliant series elastic actuation, making the system torque controllable and at the same time well suited for highly dynamic maneuvers. We additionally emphasize key elements of a powerful real time control and simulation environment. The work is concluded with a number of experiments that demonstrate the performance of the presented hardware and controllers.

Keywords: compliant quadruped, legged locomotion, torque control, SEA

1. Introduction

Inspired by locomotion in nature, research in legged robotics is currently undergoing substantial changes. In contrast to the early walking machines [1] which were built stiff and controlled kinematically, more and more compliant systems are nowadays finding their way into robotics; thereby offering an entirely new field of research. Due to their mechanical softness in terms of back-drivability and low system inertia, these systems are perfectly suited to continuously interact with their environment. They can cope with (unexpected) ground contact collisions and are at the same time inherently save for hand-in-hand collaboration with human operators. Similar to nature, where compliant elements in muscles and tendons largely contribute to the energetic efficiency [2,3], springs can be exploited in robotics to support non-linear oscillations.

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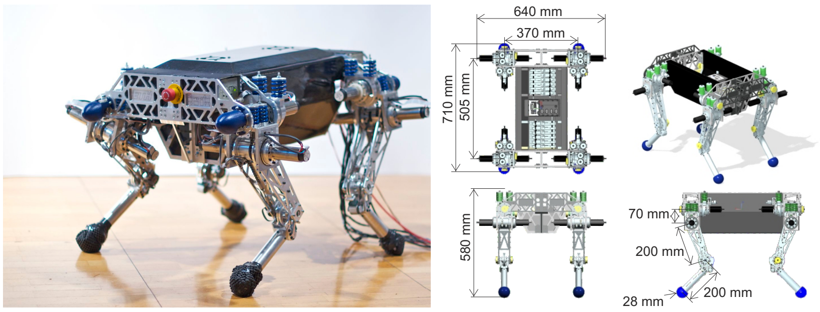


Fig. 1. Starl*ETH*, a compliant quadruped developed at the Autonomous Systems Lab to combine *efficient* and *versatile* locomotion. (Foto: François Pomerleau)

The transition from classic industrial robots to such novel platforms is accompanied by a paradigm shift from position control to torque control strategies. To give an example, research done within the DARPA learning locomotion challenge [4] has impressively shown, how far position control strategies can be pushed through precise kinematic trajectory planning and execution. However, at the same time this challenge clearly demonstrated the limitations of stiff position control, since detailed knowledge, not only about the internal states of the robot, but also about the environment was required. As a solution to cope with these limitations, new torque control approaches (e.g. whole body control [5] or inverse dynamics [6]) allow to modulate the system's behavior in a sophisticated and adaptive manner.

To combine the advantages of *efficiency* and *versatility* in a single device, we developed Starl*ETH* (Springy Tetrapod with Articulated Robotic Legs) that pushes the state of the art in the field of compliant quadrupeds. This paper introduces the hardware prototype and reports on tests in several static and dynamic experiments. We address the setup of a simulation and control environment in detail and show how a proper integration of soft- and hardware can lead to an extremely powerful tool for development. While we will briefly outline possible control approaches and give precise references to existing literature in the corresponding fields, a full description of the employed controllers is not within the scope of this article.

2. Hardware Description

Starl*ETH* is based on four identical legs that are arranged in an X configuration. With linear dimensions of about 0.6 m and a total weight of 23 kg, it has the size of a medium-sized dog. Every leg has a total of 3 degrees of

Table 1. Key data of Starl*ETH*

total leg length	488.5	mm	max./min. hip AA[1]	-30/30	°
leg segment length	200	mm	max./min. hip FE[2]	-40/80	°
total mass	23	kg	max./min. knee FE	-145/0	°
payload	25	kg	max. hip AA,FE speed	600	°/s
max. hip AA,FE torque	24	Nm	max. knee FE speed	350	°/s
max. knee torque	40	Nm	motor power	200	W

Note: [1] abduction/adduction, [2] flexion/extension

freedom, one each for hip abduction/adduction, hip flexion/extension, as well as knee flexion/extension. The robot's design is based on earlier studies that we conducted to optimize a planar running leg [7,8]. This leg was extended with an abduction degree of freedom. The key data of the mechanics as well as the actuation are summarized in Table 1. We put emphasis on keeping the inertia of the moving segments minimal by concentrating all actuators at the main body through the use of chain and cable pulley systems. This is beneficial to ensure fast swing leg motion and to reduce impact losses at the intermittent ground contact. The lightweight main body is fabricated as a carbon fiber sandwich monocoque with aluminum front- and back connectors. It contains well protected all electronic parts that are cooled through active air circulation. The key elements of Starl*ETH* are the high compliant series elastic actuators that are implemented in all joints using linear compression springs in a pre-compressed setup (antagonistically at the hip joints). Springs decouple the motor (*Maxon EC-4pole* 200 W) and gearbox (*Harmonic Drive CSG-14*, 1:100 reduction) from the joint. This setup ensures robustness against impacts, allows for energy storage to improve the efficiency [7], and provides full torque controllability. All joint angles, motor angles, and spring deflections are precisely measured in every joint [8]. The lightweight ball feet (70 g, Figure 3(b)) are based on air filled racquet balls that provide amble cushioning with minimal weight while having a high contact friction coefficient. To detect changes in the contact force, we tightly integrated force sensing resistors (FSR). The proprioceptive sensor equipment is completed with a *X-sense MTi IMU* that includes an accelerometer and gyroscopes.

3. Simulation and Control Framework

Controlling highly complex and inherently unstable systems like Starl*ETH* with 12 actuated joints and 6 unactuated (floating base) degrees of freedom in an often unknown environment requires a very powerful and reliable

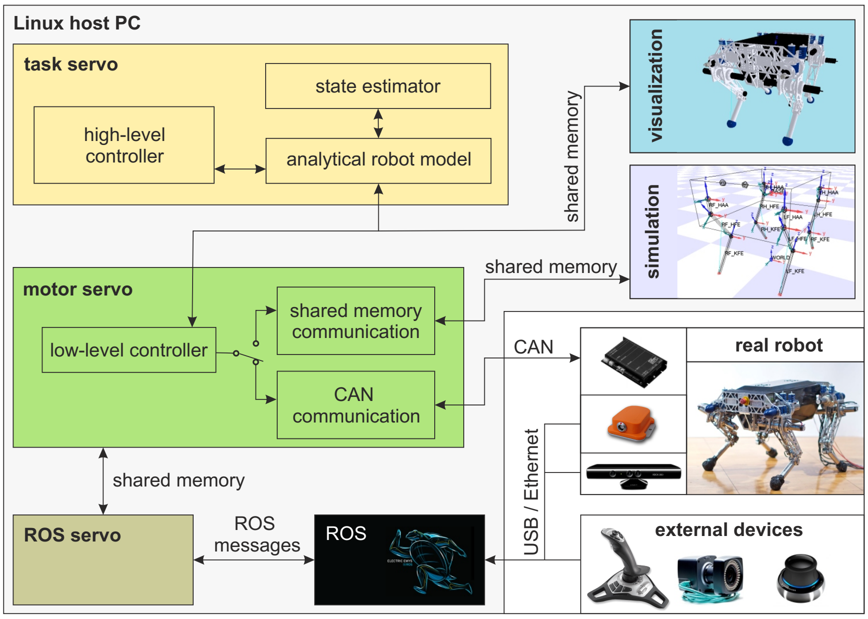


Fig. 2. The real-time simulation and control environment is based on SL [9] and analytical global kinematics and dynamics. The framework allows an immediate exchange of simulation and actual robot, as well as a direct integration into ROS.

control setup. After several iterations through different configurations, we realized a framework as depicted in Figure 2. The setup is based on a single centralized host-PC that is responsible for the entire high-level control part. The software contains the real-time simulation and control environment SL [9], which is used as a multi-body dynamics engine, for visualization of the robot and its environment, as well as for handling the internal messaging between the different servos through shared memory. It additionally provides tools for data logging and post-processing.

As a core element, the *motor servo* is responsible for timing and coordination of the individual actuators. It contains all low level regulators (position, velocity, torque, ...) and signal filters. Using either shared memory to access the simulation, or a CAN gateway to communicate with the actual robot, the user has the possibility to run simulations and experiments (even in parallel) with exactly the same controller implementation. This is highly advantageous for controller development, since it avoids code reimplementation, simplifies debugging and testing, and ensures certain safety if the controllers show good robustness in the simulation.

The *ROS servo* provides an interface to the *robotic operation system* that can not meet the hard real-time constraints of SL itself. This connection opens the door to a huge set of existing interfaces to different sensors and existing software packages. In our current setup, this includes the IMU, the Microsoft Kinect sensor, as well as several external devices such as a 3D joystick for control or a vicon motion capture system to track the main body position/orientation.

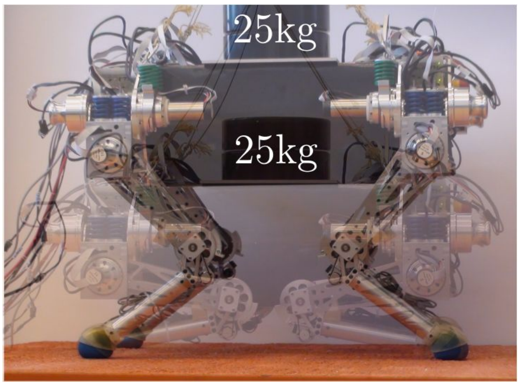
Finally, the *task servo* decouples the controller entirely from the multi-body simulation and provides the global kinematics and dynamics (robot model) of the system in analytical form. Therefore, we developed proNEu [10], a MATLAB framework that uses the Symbolic Math toolbox[a] to translate a relative kinematic tree into global kinematics using Euler rotations, and to derive the system dynamics using projected Newton-Euler equations. In addition to speed and simplicity of the implementation, this separation between the model used in the controller and the simulation has several benefits. First of all, the control engineer has user friendly access to any kind of updated kinematic or dynamic parameters. Second, sensor noise, imperfect state estimation, or (intentionally) introduced differences between simulation and controller allows to test the robustness of the controller against modeling errors and limits the problematic of instable plant inversion. The state estimator which is implemented on top of the robot model fuses kinematic information with the IMU sensor signals. It is based on an Extended Kalman filter [11] and estimates not only the base coordinates but is also able to generate a sparse ground elevation map using the contact feet.

In practice, the rate-limiting factor in our framework is the data connection of the CAN bus system between the host PC and the motor controllers. Although we managed to parallelize 4 channels (1 per leg), the bit rate of $1\,{}^{\mathrm{MBits}}\!/_{\mathrm{s}}$ limits the overall loop cycle time to about 400 Hz.

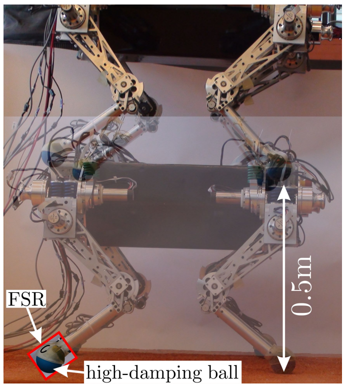
4. Experimental Results

In the first part of the experimental validation, we are focusing on hardware performance. First of all, walking and running machines need to provide sufficient torque that enables them to conduct various maneuvers. A representative scenario is standing up from a completely crouched position with maximal payload (Figure 3(a)). Due to the high power per weight ratio, we are able to stand up with a payload of 25 kg. This is more than the total weight of the actual robot and considerably better than for systems

[a]www.mathworks.com/products/symbolic



(a) standing up with 25kg payload



(b) falling down from 0.5m

Fig. 3. The torque capability (a) was experimentally validated with 25kg payload. Its passive compliance (b) protects the actuators from large peak forces at landing and allows for joint torque control.

such as Little Dog [12] or ALoF [13]. In theory, the peak torque at the knee of 40 Nm with a lever arm of 0.2 m results in a maximal total lift force of 800 N or a maximal stand-up payload of ≈50 kg. However, these peak loads should only occur in highly dynamic maneuvers and were hence not experimentally validated for safety reasons.

To be capable to perform dynamic maneuvers, it is crucial that the system can cope with impacts. In contrast to a stiff system (again c.f. Little Dog [12] or AloF [13]), pre-impact kinetic energy should not be entirely dissipated in an collision that harms the mechanical structure. Instead, the system is able to either damp out a certain amount of energy or to store it as potential energy in the actuator springs. To demonstrate both, we dropped Starl*ETH* from a height of ≈0.5 m. The passive mechanical compliance in the actuators, as well as the high damping feet elements protect the system from the impact at landing. This ensures that, even if all motors are blocked, none of the gearboxes gets damaged through high peak forces. The high compliant springs lead to large oscillations (red-dotted line in Figure 4) including a number of short rebounces (grey background) after landing. This can be avoided through active damping (black-solid line in Figure 4) using a virtual model controller that exerts the force $\mathbf{F}_{mb}$ and torque $\mathbf{M}_{mb}$ at the main body

$$\mathbf{F}_{mb} = k_p\left(\mathbf{r}_{des} - \mathbf{r}_{act}\right) + k_d\left(\dot{\mathbf{r}}_{des} - \dot{\mathbf{r}}_{act}\right) \tag{1}$$

$$\mathbf{M}_{mb} = k_p\left(\boldsymbol{\varphi}_{des} - \boldsymbol{\varphi}_{act}\right) + k_d\left(\dot{\boldsymbol{\varphi}}_{des} - \dot{\boldsymbol{\varphi}}_{act}\right) \tag{2}$$

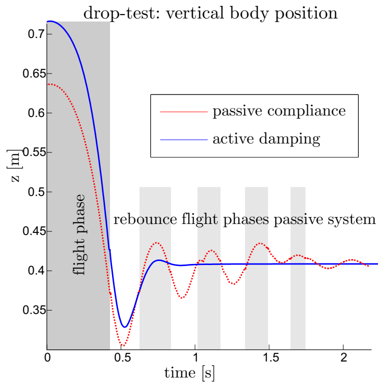


Fig. 4. The vertical main body position of the system dropped from $\approx 0.5m$ was estimated using IMU values during flight and kinematic information during contact phase: the red-dotted curve shows the high oscillations due to the passive compliance with intermittent flight phases (grey area), while active damping (blue-solid) using virtual model control ensures nearly critical damping of the system.

with $\mathbf{r}, \boldsymbol{\varphi}$ representing the main body position and orientation and the spring and damping constant k_p, k_d. In combination with additional gravity compensation $\mathbf{F}_j^g = -m_j \mathbf{g}$ for the $N_p = 4 \cdot 3 + 1$ bodies, the force is distributed onto the different contact forces $\mathbf{F}_i^c$ $(N \leq 4)$:

$$\begin{pmatrix} \mathbf{F}_1^c \\ \vdots \\ \mathbf{F}_N^c \end{pmatrix} = \begin{bmatrix} \mathbf{I} & \dots & \mathbf{I} \\ \tilde{\mathbf{r}}_1^c & \dots & \tilde{\mathbf{r}}_N^c \end{bmatrix}^+ \begin{pmatrix} \mathbf{F}_{mb} - \sum_{j=1}^{N_b} \mathbf{F}_j^g \\ \mathbf{M}_{mb} - \sum_{j=1}^{N_b} \mathbf{r}_j^g \times \mathbf{F}_j^g \end{pmatrix} \tag{3}$$

These contact forces are subsequently translated into joint torques $\boldsymbol{\tau}$ using Jacobian-transposed mapping with the relative Jacobians at contact points $\mathbf{J}_i = \frac{\partial \mathbf{r}_i^c}{\partial \mathbf{q}} = \frac{\partial \left(\mathbf{r}_i^{foot} - \mathbf{r}_i^{base} \right)}{\partial \mathbf{q}}$ and center of gravity $\mathbf{J}_j = \frac{\partial \mathbf{r}_j^g}{\partial \mathbf{q}} = \frac{\partial \left(\mathbf{r}_j^{CoG} - \mathbf{r}_i^{base} \right)}{\partial \mathbf{q}}$:

$$\boldsymbol{\tau} = \sum_{i=1}^{N} \mathbf{J}_i^T \mathbf{F}_i^c + \sum_{j=1}^{N_b} \mathbf{J}_j^T \mathbf{F}_j^g \tag{4}$$

5. Conclusion

The paper introduced Starl*ETH*, a compliant quadruped robot that was developed to study *fast*, *efficient*, and *versatile* locomotion. This lightweight system is driven by high compliant series elastic actuation that makes it fully torque controllable, robust against impacts, and hence perfectly suited for sophisticated dynamic maneuvers. A framework based on SL [9] in combination with an analytical global kinematics and dynamics implementation serves as a powerful real-time simulation and control environment. It gives the control engineer a compact and user friendly tool to develop and test control algorithms. Starl*ETH* was successfully tested in various experiments that demonstrated a high torque capability, its compliant protection against impact collisions, and full torque controllability. Hence, the presented platform in combination with the control and simulation environment is perfectly suited for dynamic maneuvers and sophisticated model based torque control strategies. As a first step, successful walking experiments were conducted using the presented virtual model controller (1)-(4) in combination with kinematic swing leg control [14]. This holds as a basis for future work towards more dynamic maneuvers.

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