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ANYmal - A Highly Mobile and Dynamic Quadrupedal Robot*

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***Abstract*— This paper introduces ANYmal, a quadrupedal robot that features outstanding mobility and dynamic motion capability. Thanks to novel, compliant joint modules with integrated electronics, the 30 kg, 0.5 m tall robotic dog is torque controllable and very robust against impulsive loads during running or jumping. The presented machine was designed with a focus on outdoor suitability, simple maintenance, and user-friendly handling to enable future operation in real world scenarios. Performance tests with the joint actuators indicated a torque control bandwidth of more than 70 Hz, high disturbance rejection capability, as well as impact robustness when moving with maximal velocity. It is demonstrated in a series of experiments that ANYmal can execute walking gaits, dynamically trot at moderate speed, and is able to perform special maneuvers to stand up or crawl very steep stairs. Detailed measurements unveil that even full-speed running requires less than 280 W, resulting in an autonomy of more than 2 h.**

I. INTRODUCTION

Legged robotics has potential advantages in terms of mobility and versatility as compared to tracked or wheeled vehicles. So far, the technological complexity to build and control such vehicles has prevented these systems from being applied in real world scenarios and only few teams managed to develop machines that work beyond laboratory test-bench settings. With major advances over the recent years, pushed by various large scale research programs or investment from industry, our community is about to overcome the last technical hurdles and make legged robots available for real world applications. Most prominently, the DARPA Robotics Challenge (DRC) brought together some of the best research groups in the field of humanoid robots to successfully use such machines in a disaster mitigation scenario [1]. Since the scenario is very close to reality, all teams were forced to massively invest in hardware development to improve not only versatility but also reliability and ruggedness of the robots. These developments resulted in many high-performance machines like ATLAS[2], Valkyrie [3], DRC Hubo [4], HRP2+ [5], Walkman and others, most of them based on earlier robot versions. This new generation of humanoid robots commonly feature some sort of force or torque control - either by integrated load cells in the joints or at the end-effector, or by a series elasticity in every actuator. This allows them to properly control interaction forces with the environment and hence to balance the system or manipulate the environment.

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Fig. 1. ANYmal, an autonomous quadrupedal robot for rough terrain operation

Despite all these advances, the locomotory performance of the human-like robots is still far behind the natural counterparts. All these robots are relatively slow, require a lot of power, and can only negotiate small terrain obstacles.

Better locomotion performance in terms of speed, energetic efficiency, and obstacle negotiation skills, is achieved with multi-legged systems. Paramount example is Boston Dynamics' Spot robot, a direct successor of Big Dog [6], of which unfortunately no scientific publications are available. Similar locomotion performance, demonstrated in various highly dynamic gaits and maneuvers, was also achieved by research groups around IIT's hydraulic HyQ [7] and its follower HyQ2max [8], MIT's directly electrically actuated cheetah [9], or ETH's serial elastic robot StarlETH [10]. All these robots have demonstrated dynamic running on different grounds or to dynamically overcome obstacles - however, none of these machines has been used in a real world application.

This paper presents ANYmal (Fig. 1), a highly mobile

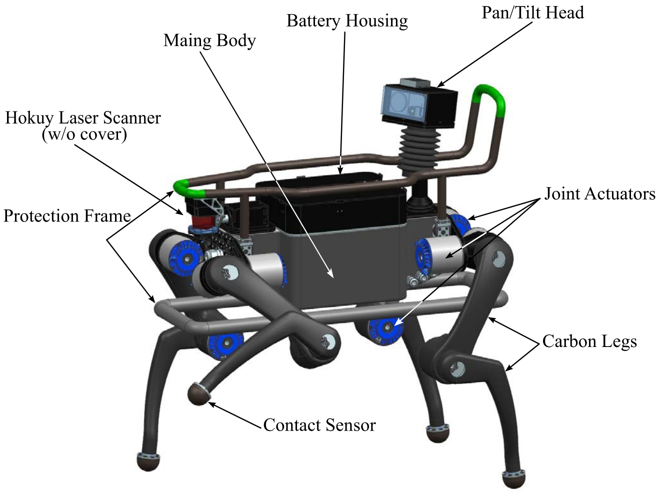


Fig. 2. Main components of ANYmal

and rugged quadrupedal platform developed for autonomous operation in challenging environments. ANYmal was designed to combine outstanding mobility with dynamic motion capability that enables it to climb large obstacles as well as to dynamically run. This completely autonomous machine paves the road for real world applications. It is in use for the NCCR Search and Rescue grand challenge[1] as well as in the ARGOS oil and gas site inspection challenge[2] - both scenarios with very harsh and demanding environments. In the following, we present the underlying mechanics and actuation concept, illustrate the electronics and software setup, sketch out the applied locomotion control algorithms with appropriate references to their implementation, and finally summarize the paper with a series of experiments[3] highlighting the overall system performance.

II. System description

ANYmal was specifically built for long endurance autonomous operation in harsh environments. Focus was put on *large mobility*, *fast and dynamic locomotion skills*, *high robustness*, *simple maintenance*, and *safe handling by a single operator*.

A. Overview

The presented quadrupedal robot, with the main components depicted in Fig. 2, features three actuated joints per leg with point feet. With an approximate link length of 250 mm for thigh and shank, and a total weight of slightly less than 30 kg, it resembles a medium-sized dog. To achieve this lightweight design, the main body and the leg segments are built from aluminum and carbon fiber. Onboard batteries of about 650 Wh energy and 3 kg weight provide power for more than 2 h autonomous operation. A protection frame and pads at the legs prevent the system from damage when falling and allows for handy transportation and deployment.

[1] http://www.argos-challenge.com
[2] http://www.nccr-robotics.ch/RescueRobots
[3] for illustration, see http://www.rsl.ethz.ch/robots-media/anymal

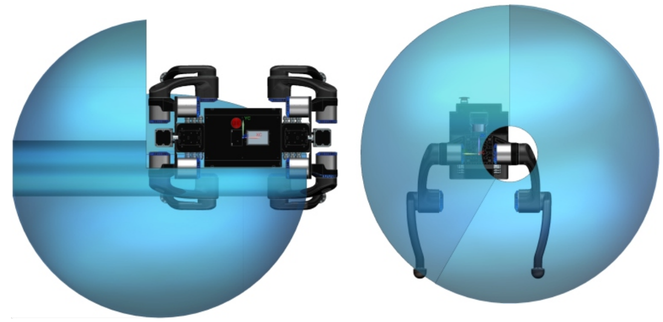


Fig. 3. Range of motion of a single leg of ANYmal

Optofoce sensors are used as tactile feet and rotating Hokuyo UTM-30LX sensors provide 3D perception of the environment. To make ANYmal applicable for different scenarios, a modular pan-tilt head with variable sensory payload can be mounted. For example, in the setup for the ARGOS challenge, the sensory head includes an optical zoom and thermal camera for visual inspection, a gas detection sensor, microphones for sound identification, as well as artificial lighting.

B. Modular joint setup

Key to simultaneously achieving the design goals are the robotic joint units described in Sec. III. This enabled the creation of a very simple mechanical topology with three equal joint units per leg that are linked by rigid mechanical segments and interconnected with a power and communication bus. Since the encapsulated and sealed joint units integrate drive electronics and sensing, as well as the joint axle bearing, the robot does not require any additional bearings, transmission, proprioceptive sensors, or electronics in its legs. Such a setup combines several advantages: Given the drive units, the robot is simple to manufacture, assemble, and maintain. In case of failure, a complete joint can be quickly exchanged. Furthermore, design variations to build different robots requires only to change the mechanical links.

The joint arrangement of ANYmal is chosen mammalian with successive hip abduction/adduction (HAA), hip flexion/extension (HFE), and knee flexion/extension (KFE). In contrast to its predecessor StarlETH [10], the MIT cheetah [9], IIT HyQ [7], Big Dog [6] or other legged systems, the leg links of ANYmal are built with an offset such that all joints can be fully rotated. So far, this was typically only done in walking machines like JPL's robosimian [11] that moves in a quasi static manner. As depicted in Fig. 3, the joint offset enables a huge range of motion which is key to high mobility. With this, ANYmal is able to use its feet high above ground for tasks like opening a door or surmounting large obstacles, it can be folded for transport or deployment, and can change its leg configuration (Fig. 4).

C. Main body package

Computers, batteries, network devices, the power management system, and basic navigation sensors are integrated in a single box-shaped and ingress protected main body. Three

Fig. 4. Full rotation in all joints of ANYmal allow for various configurations.

intel NUC PCs connected over an internal gigabit network form the removable brain of ANYmal that is accessible via WiFi link from any operator machine. To get proper heat dissipation from the sealed main body, all components are thermally coupled to the main body which is used as heat sink. The main body is controlled from a small touch screen on the back of the robot which allows to individually enable PCs and sensors. A rotating Hokuyo UTM-30lx laser sensor and an Xsens MTi-100 IMU are fixedly installed for localization, navigation, and environment mapping.

D. Software architecture

The three PCs share the work load of the locomotion, navigation and inspection tasks as illustrated in Fig. 5. The data is transferred over the network by the Robot Operating System (ROS) running on a low-latency patched Ubuntu 14.04. The ROS master, which manages the connections between the different processes, runs on the locomotion PC. The real-time critical whole-body controller and state estimator are timed by the CAN driver that communicates with the actuator units at 400 Hz. The readings and commands are exchanged through shared memory and published through ROS to less time-critical workers like the foothold planner. The localization and mapping tasks are outsourced to the navigation PC that is responsible for the laser-based localization and mapping of the environment. High-level navigation tasks are coordinated by a mission planner and executed by a path planner that sends velocity commands to the locomotion controller. Optionally, a third application specific PC can be activated to handle for example the computationally extensive video processing for inspection.

III. ANYDRIVE - MODULAR JOINT UNITS

Dynamic locomotion imposes very demanding requirements on the actuation system, namely:

- High impact robustness
- Fast motion tracking
- Low impedance force controllability

Furthermore, actuators must be lightweight and energetically as efficient as possible.

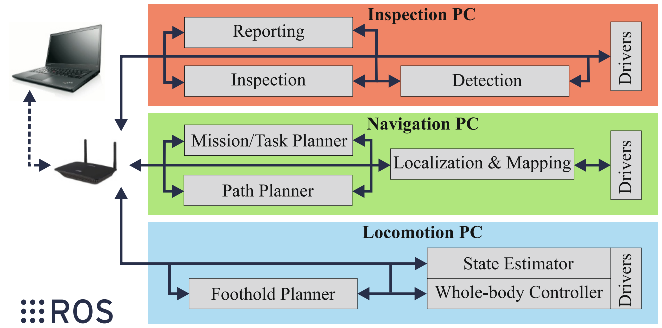


Fig. 5. The software architecture with clear real-time priority ranked separation on different PCs.

A. A brief review on existing actuation concepts

The classical approach of electric motors with high-reduction mechanical gears as employed in almost all industrial robot arms does not satisfy the first requirement. Legged robots using such actuation approach are limited to slow and static locomotion in order to prevent the actuators from impulsive forces. For dynamic locomotion, three major concepts have established as adequate actuation technology.

1) Hydraulic actuation: Hydraulic actuators as used in machines like HyQ [7], BigDog [6] or Atlas [2] are naturally robust against impulsive loads and provide extremely high power and force density. Thanks to very fast valve units in combination with load cells for force measurement or pressure based force estimation [12], hydraulic actuators provide also high performance torque control.

On the negative side, hydraulic systems tend to be energetically inefficient, in particular when operated with constant pressure. For this reason, many systems used in research still rely on off-board supply. At the cost of increased system complexity, this can be overcome to certain extent by sophisticated pumps and variable pressure levels. Another problem is scalability which makes hydraulic legged systems rather large and heavy.

2) Pseudo-direct-drive systems: When using gearing systems of very low reduction and high efficiency, electric actuators can become very transparent and the reflected inertia of the actuation compared to the output becomes small. As a result, motor current control, which can be done at very high bandwidth, is equivalent to regulation of the output force [13]. These benefits have been exploited for many years in rehabilitation engineering and for haptic devices. Thanks to recent advances in actuator development, pseudo-direct-drive concepts find application in high-dynamic legged robots as in the example of MIT-cheetah [9], which is able to run and jump at high speeds.

Unfortunately, while electric motors have extremely high power, their torque is limited. Therefore, direct actuation without any gear is not possible with existing technology. Furthermore, motors of large diameter must be used to create high forces, which largely limits flexibility in system design.

3) Series elastic actuation: Inspired from biology and along the seminal work of Pratt [14], the third common actuation approach for legged robots are series elastic actuators.

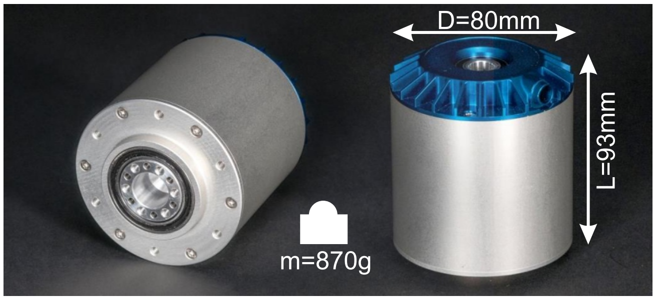


Fig. 6. ANYdrive: Compact, compliant joint units for advanced interaction

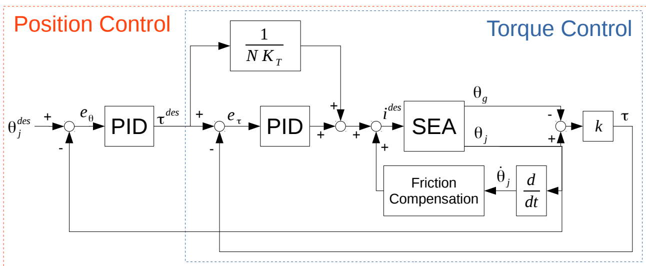


Fig. 7. Block diagram of the cascaded joint position and torque control loop. The SEA block represents the physical actuator unit including field oriented control (FOC) to apply the desired current i^{des}

By integrating a carefully selected mechanical compliance between the gearbox output and joint, classical geared motors can be adapted for applications with dynamic interactions. Several state of the art robots like the humanoid Valkyrie [15] or the quadruped StarlETH [10] showed how to use such actuators not only for precise output force regulation, but even to temporarily store energy during locomotion and hence to increase locomotion efficiency [16]. In order to simplify the use of such actuators, different groups target the development of modular units [17], [18].

The mechanical compliance in the system is not only a low pass filter (and hence protection) for the impact loads at the output, but additionally limits control bandwidth and requires careful design of the joint level control structure.

B. Overview

ANYdrive (Fig. 6), the joint units of ANYmal, is a highly integrated series elastic actuator. It is built upon high torque motors and harmonic drive gears in series with a rotational spring. Joint output position and spring deflection are measured using absolute position sensors providing a position accuracy of 0.025°and a torque resolution of 0.08 Nm. Thanks to integrated custom motor control electronics, the joint torque, position, and impedance can be directly regulated without any additional components. The corresponding command values are sent over CAN bus using CANopen standard. With a nominal voltage of 48 V, the joint reaches a speed of 12 rad/s and a maximal torque of 40 Nm.

C. Control structure

Joint torque, position and impedance control is realized as a cascaded structure that considers the motor as torque source (c.f. [19]) as illustrated in Fig. 7. Similar to the work by Paine [20], which is also the basis of the control of Valkyrie [15], we realized a simple PID torque feedback loop with feedback friction compensation. The position PID control builds upon the torque controller as an additional cascade.

The torque controller tracks a desired torque τ^{des} by measuring the actual output torque τ and setting the desired current i^{des} accordingly. The spring deflection is calculated from the difference in the joint position θ_j and the gear position θ_g. The output torque τ is then calculated using the spring constant k. The torque controller consists of three elements, i.e. a PID controller, a feed forward term and a feedback friction compensation. The feed forward term is determined from the inverse of the gear ratio N and the motor constant K_T, both typically provided in by data sheets. The friction compensation

$$i_{comp}(\dot{\theta}_j) = i_{ba} sSign(\dot{\theta}_j, \dot{\theta}_{band}) + \mu \dot{\theta}_j \tag{1}$$

takes two effects into account, namely stiction and viscous friction. Firstly the break-away current i_{ba} is modeled as Coulomb friction. To prevent undesired switching around the zero velocity point, it is implemented as simple smooth sign function

$$sSign(x, x_b) = \begin{cases} -1, & \text{if } x \ < x_b \\ 1, & \text{if } x \ > x_b \\ -1 + 2(\frac{x+x_b}{2x_b})^2(2 - \frac{x}{x_b}), & \text{otherwise} \end{cases} \tag{2}$$

Secondly, the joint velocity dependent viscous friction is linearly modeled with the friction coefficient μ. All these parameters can be experimentally identified from very few measurements.

The position controller is a PID controller that tracks a desired joint position θ_j^{des} by setting a desired torque τ^{des}. An important note is that the position gains are highly depending on the output load since there is no knowledge about the joint load in the control architecture.

D. Performance evaluation

The performance of ANYdrive with respect to torque and position reference tracking as well as impulsive disturbance rejection is evaluated on a single axis test bench. As illustrated in Fig. 8, the bandwidth for low amplitudes is as high as 70 Hz. Due to motor saturation effects, the bandwidth gradually decreases to 24 Hz for 10 Nm amplitude. These performance values are substantially higher than what was achieved with our previous system [21] and about the same as in Valkyrie [15]. Interestingly, this high performance was achievable without a disturbance observer as used in [22].

As illustrated in Fig. 9, the controller is very reactive showing a 90% settling time of 13 ms for a step of 10 Nm and 35 ms for a step of 40 Nm with only small overshoot.

Disturbance rejection to impulsive loads is evaluated in a collision test. To this end, a pendulum is mounted at the output and the actuator is requested to produce zero torque. The free swinging pendulum is crashed with high velocity into a hard wall and brought to instantaneous rest (ideal plastic collision with a restitution coefficient of zero). Despite

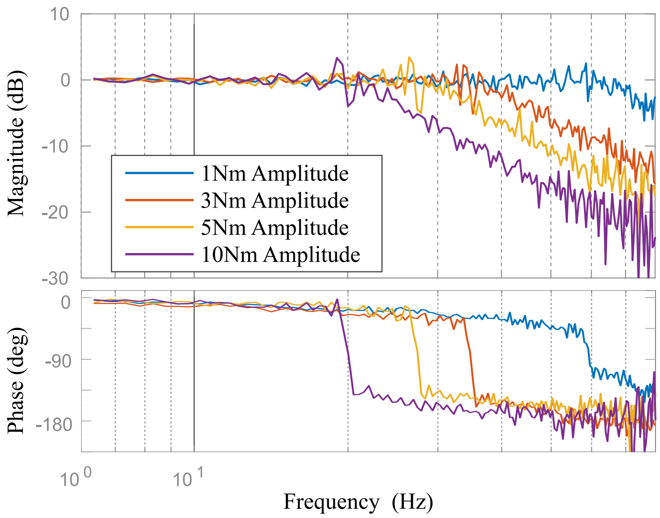


Fig. 8. Experimentally identified torque control transfer function indicating a bandwidth of 70 Hz.

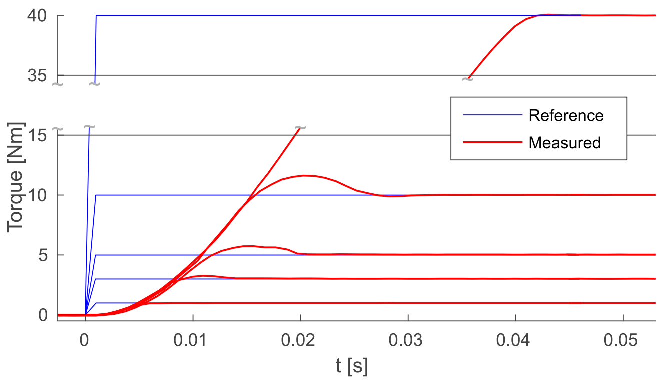


Fig. 9. Torque step responses show a quick response time and low overshoot.

high motor speed before the collision, the motor produces only little torque during the impact (Fig. 10). In fact, already 2 ms after the collision, the motor maximally decelerates to keep the torque in the spring as small as possible. Due to the motor and gearbox inertia, it takes about 10 ms to bring the motor to a complete rest. If the pendulum collides with the maximal motor velocity, the peak force is smaller than 7 Nm. This implies that, whatever collision a system that is built from these joint units experiences, forces occurring at the gear never exceed the peak loads it is rated for. In other words, the drive is "perfectly robust" against self inflicted collisions.

As final performance evaluation experiment, the actuator was again commanded to produce zero torque while the output is randomly moved by hand (Fig. 11). Despite very large disturbances (2 rad amplitude and about 4 Hz motion), the output torque can be kept at less than 0.2 Nm. A qualitative comparison to Valkyrie [3] indicates a significantly better disturbance rejection performance.

IV. Locomotion Control

Since ANYmal is fully torque controllable and of similar geometry as its predecessor StarlETH [10], locomotion control could be transferred relatively directly. A detailed description would go beyond the scope of this paper, we

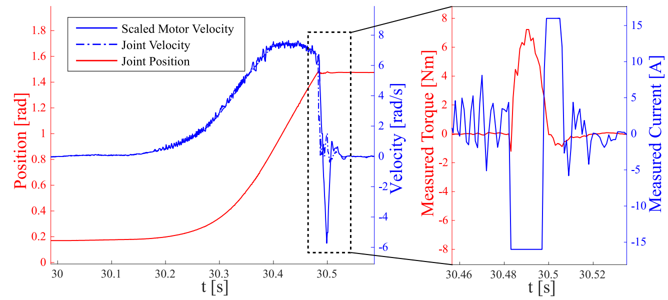


Fig. 10. Joint torque during impulsive collision. The motor velocity is scaled with the gear ratio for plotting purposes.

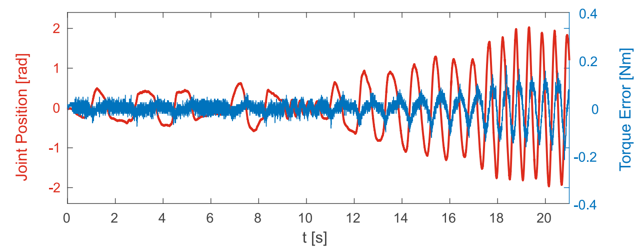


Fig. 11. Zero torque tracking error (blue) when the output joint is randomly moved by hand (red).

refer the interested reader to the related work introduced in the following.

ANYmal features a purely proprioceptive state estimation based on fusion of IMU, leg kinematics, and ground contact measurements [23], [24]. For static walking gaits, a ZMP planner [25] is implemented to plan a smooth main body trajectory while applying a standard crawling gait [26]. Foothold placement during dynamic gaits is based on simplified inverted pendulum models [27]. To balance the system, we build upon whole body control techniques that accounts for the complete system kinematics and dynamics [28], [29]. The optimal actuator commands are found at every time step by solving a constrained optimization problem of prioritized tasks and constraints on joint torques, contact forces, and body motion.

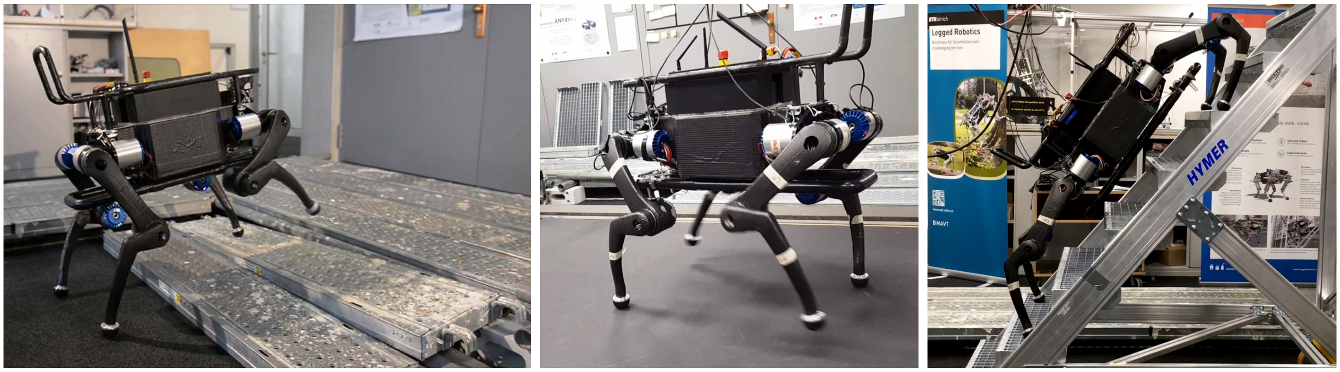
V. Experiments

The performance of ANYmal was tested in different maneuvers and locomotion experiments illustrated in Fig. 12[4]. In order to ensure fast and stable locomotion, particular attention was paid to accurate swing leg position and stance leg force tracking, as well as good following behavior of the target base motion.

A. Walking

ANYmal is able to perform a very smooth walking gait, whereby a single leg is moved at the time and the base is shifted in order to maintain balance. As illustrated in Fig. 13, joint torques and positions are followed very accurately during the entire gait cycle and hence also the base position can be accurately moved according to the preplanned trajectory. It is important to know that the latter follows only from virtual model control (task space control) at the base

[4]For videos, see http://www.rsl.ethz.ch/robots-media/anymal



(a) Walking (b) Trotting (c) Stair Climbing

Fig. 12. ANYmal was tested in different gaits like walking, trotting, or stair climbing

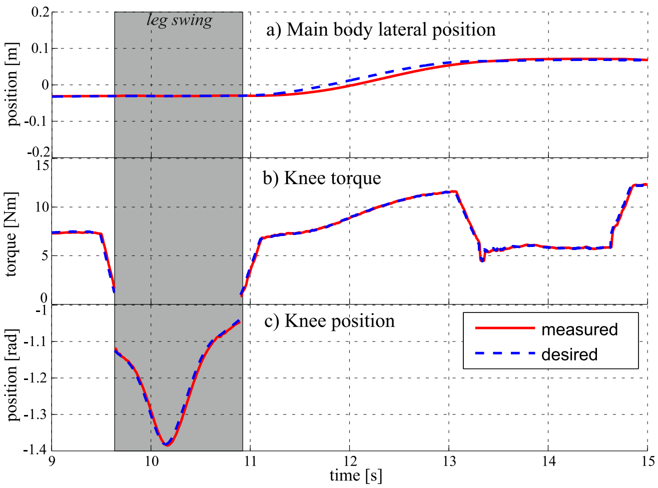


Fig. 13. Torque and position tracking while walking.

and without any joint position or impedance regulation. By applying a classical ZMP planner [25], forward locomotion results in a very smooth and almost straight line of the base as illustrated in the movie. In such gait, the robot moves with approximately 0.3 m/s. Thanks to the full rotation capability, the motion planner does not have to account for complex geometric collision constraints but only for limited abduction freedom due to the main body. Furthermore, ANYmal can take fairly big steps.

B. Trotting

ANYmal is able to trot on different grounds and under large external disturbances. Similar to the walking gait, already the first experiments unveiled large advantages of the big range of motion as the legs can be moved relatively far in all directions. Using a 50% duty cycle gait, the machine achieves a speed of about 0.8 m/s. Key to robust trotting is fast and accurate position tracking. For a typical joint motion of a fast gait (Fig. 14), joint positions and velocities are followed accurately despite the joint compliance. A thorough evaluation of the overall energy consumption at the onboard battery indicated a relatively low consumption even during dynamic trotting gait. As depicted in Fig. 15, ANYmal requires in average about 290 W with about 5%

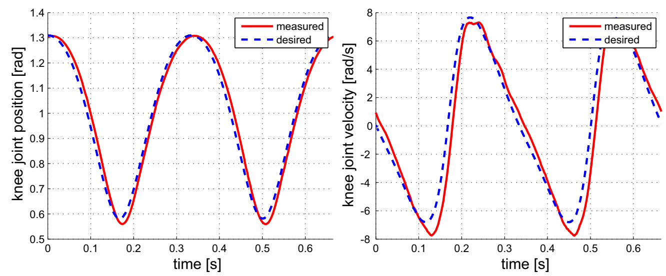


Fig. 14. Tracking performance of the position and velocity of the knee joint.

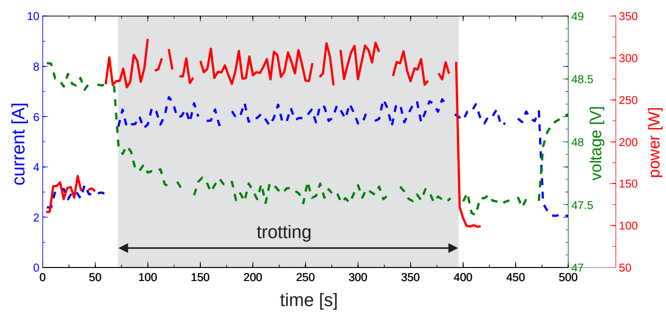


Fig. 15. Power consumption during trotting.

fluctuation when trotting, about 100 W is consumed while idling in standing configuration. The total power consumption corresponds to a cost of transport of about 1.2. These measurements are comparable to our previous results with StarlETH [30] and enables the machine to autonomously run for more than 2 h with its current batteries.

C. Stair Climbing

As a proof of high mobility, ANYmal was tested for the ability to get up an industrial ladder of about 50°. To do this in a save manner and to prevent falling by all possible means, a turtle like crawling gait was implemented. The main body lies on the ground, the legs are moved to find the next stable contact holds, and the machine is subsequently pulled upwards (see Fig. 12(c)). Due to ANYmal's large range of motion, the legs can be literally turned overhead to prevent collision with the ground or side rails. This maneuver was inspired by our work with ALoF, a kinematic quadrupedal robot that was developed for the ESA Lunar

Robotic Challenge [31]. This machine successfully exhibited such gait to reliably overcome steep inclinations with loose sand during a moon testing scenario on a volcano.

VI. Conclusion/Future work

ANYmal is considered a step towards unification of *high mobility* with *dynamic locomotion* capability.

From the beginning of the design phase, special attention was put on a rugged and simple to maintain system. This was achieved with the modular joint units ANYdrive that allow to very simply create robots of different kinematic structure. In case of failure, these modules can be easily and quickly exchanged without special knowledge. These actuators are based on a series elastic concept as already implemented on StarlETH, where we did not have a single gearbox failure in 4 years of almost daily operation with high-dynamic maneuvers. The presented experiments support the claim of robustness since even completely plastic and unexpected output collisions do not lead to higher gearbox loads than during nominal operation.

Beside the highly improved protection, the biggest advantage of ANYmal is clearly the outstanding range of motion in all joints. This enables a large variety of maneuvers to overcome obstacles or to get up after falling. Furthermore, it simplifies motion planning as there are less internal system constraints. The initial objectives of creating a dynamic and highly mobile autonomous walking machine could be confirmed in preliminary experiments including careful stair climbing, ZMP-based walking and dynamic trotting. The present development shall enable deployment of legged robots in real world scenarios such as for search and rescue or industrial inspection.

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