D5.2 Legged Robot ANYmal

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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 heavy and 0.5 m tall robotic dog is precisely 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. It is demonstrated in a series of experiments that ANYmal can execute walking gaits, can 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.

1 Introduction

For a long time researches have been attracted by legged robotics due to the potential advantages in terms of mobility and versatility 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.

Despite all these advanced, the performance of the human-like robots in particular with respect to locomotion 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.

Significantly better locomotion performance 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. Almost similar locomotion performance as 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 impressively demonstrated dynamic running on different grounds or to dynamically overcome obstacles - however, none of these machines was ever used in a real world application.

This paper presents ANYmal , a highly mobile and rugged quadrupedal platform developed for autonomous operation in challenging environment. ANYmal was designed to combine outstanding mobility with high-dynamic motion capability that enables it to climb large obstacles as well as to dynamically run. This completely autonomous machine paths the road for first real world applications. It is in use for the NCCR Search and Rescue grand challenge as well as in the ARGOS oil and gas site inspection challenge - both scenarios with very harsh and demanding environments. In the following, we present the underlying mechanics and actuation concept, we illustrate the electronics and software setup, sketch

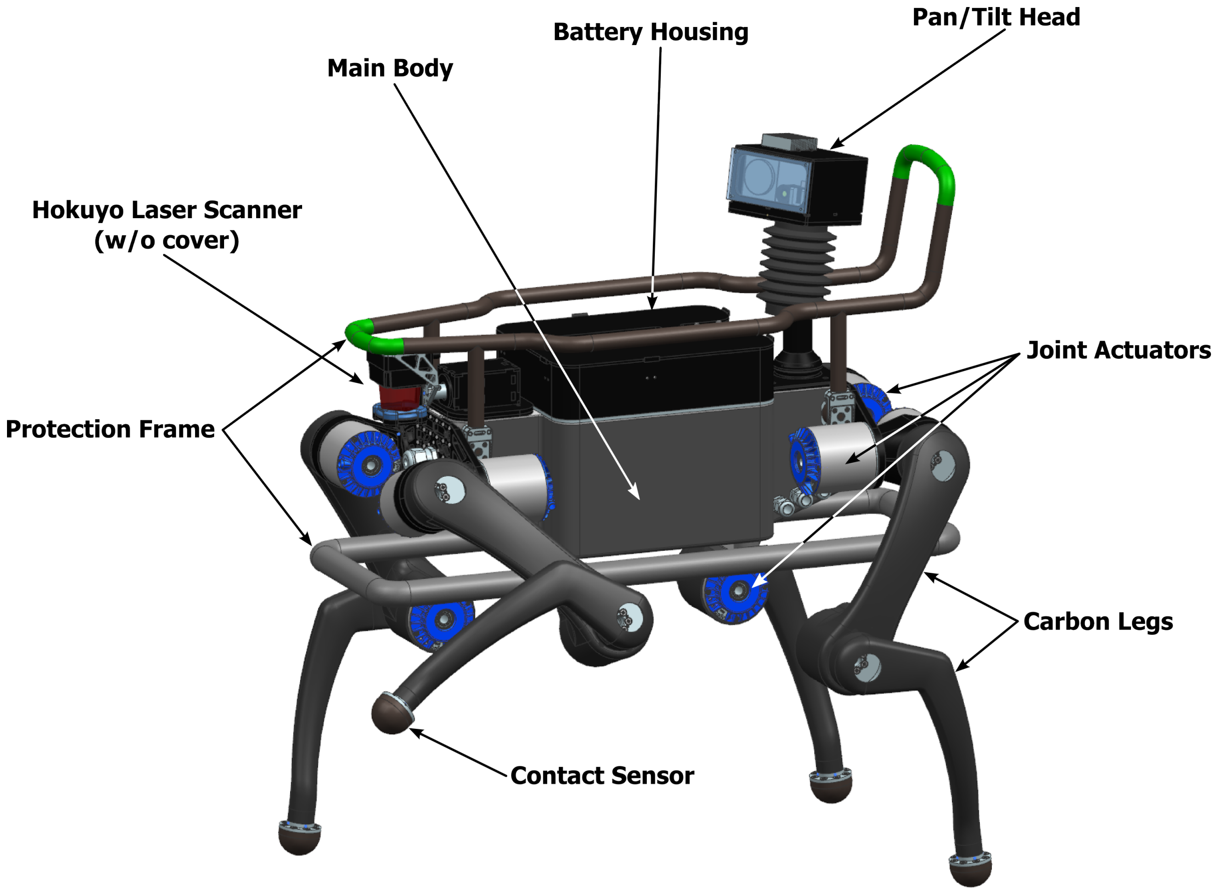


Figure 1: Main components of ANYmal

out the applied locomotion control algorithms with appropriate references to their implementation, and finally summarize the paper with a series of experiments highlighting the overall system performance. For illustration, a summary movie with all experiments is available at https://youtu.be/ZdeRi_5xK5U.

2 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*.

2.1 Overview

The presented quadrupedal robot, with the main components depicted in fig. 1, features three actuated joints per leg in mammalian configuration 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 enclosed main body and the leg segments are built from carbon fiber while the joint units are made of high-tensile aluminum. 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. 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[1], 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.

[1] www.argos-challenge.com

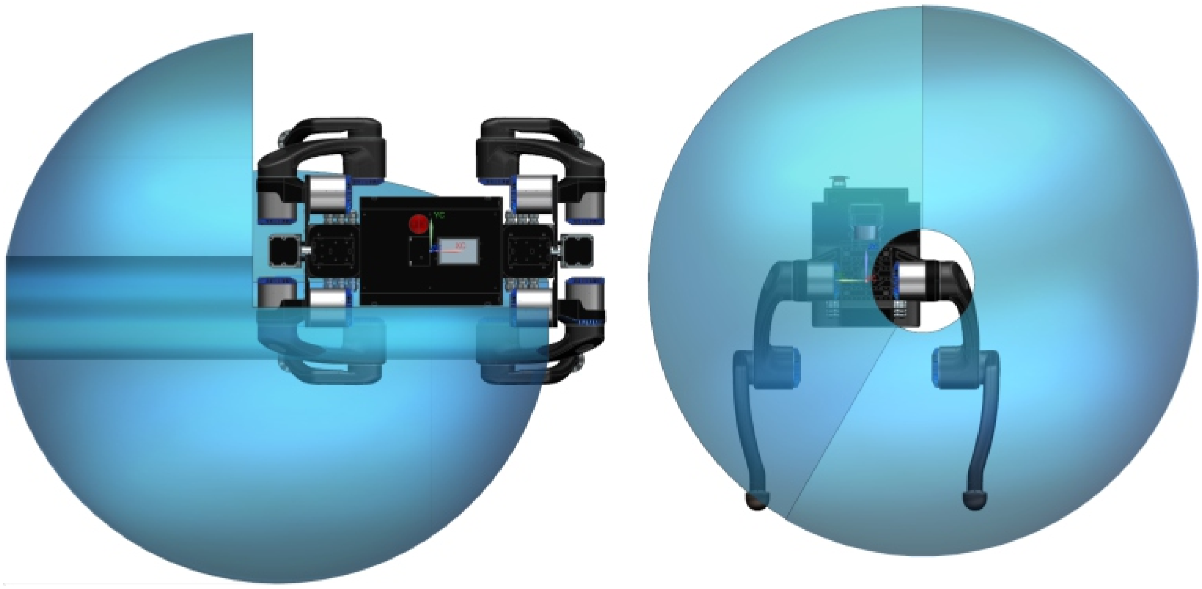


Figure 2: Range of motion of a single leg of ANYmal

2.2 Modular joint setup

Key element to simultaneously achieve the design goals are the robotic joint units described in detail in deliverable D3.2. 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 by a power and communication bus. Since the encapsulated and sealed joint units feature integrated electronics and sensing, as well as 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 [11], to the MIT cheetah [9], IIT HyQ [7], Big Dog [6] or other well known 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 [12] that moves in a rather static manner. As depicted in fig. 2, 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 to get onto large obstacles, it can be folded for transport or deployment, and can change its leg configuration (fig. 3).

2.3 Main body package

Computers, batteries, network devices, power management system, and basic navigation sensors are integrated in a single box-shaped and ingress protected main body. Three Zotac ZBOXNANO-ID69-PLUS mini-PCs with Intel Core i7 4500U (dual-core, 1.8 GHz) and 8 Gb DDR3 connected over an internal gigabit network build the removable brain of ANYmal that is accessible via WiFi link from any operator machine. To get proper heat dissipation from the sealed mainbody, heat pipes are installed from the CPUs and power management board to heat sinks on the outer surface of the robot. The mainbody 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.

2.4 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

Figure 3: Full rotation in all joints of ANYmal allow for various configurations.

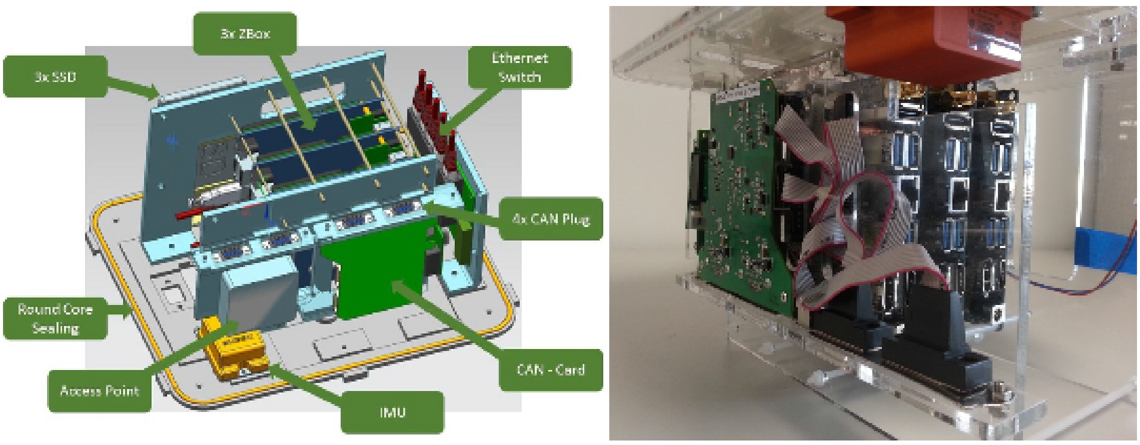


Fig XX: a) schematic picture (bottom view) and b) close up (top-front view) of the Brain-module

Figure 4: The brain of ANYmal consists of three mini-PCs

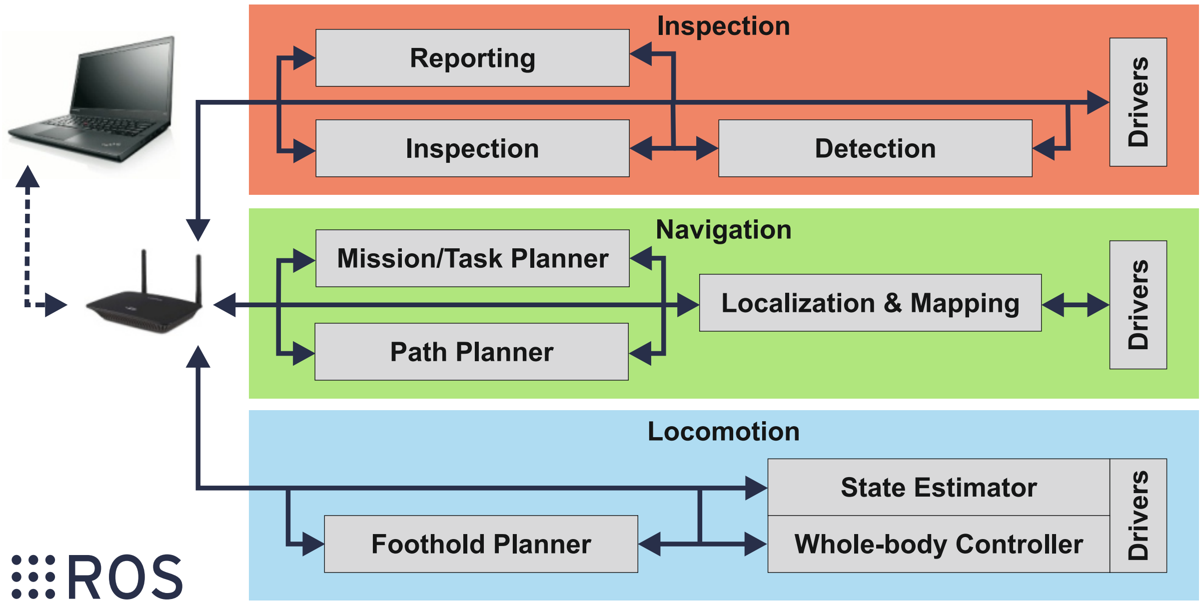
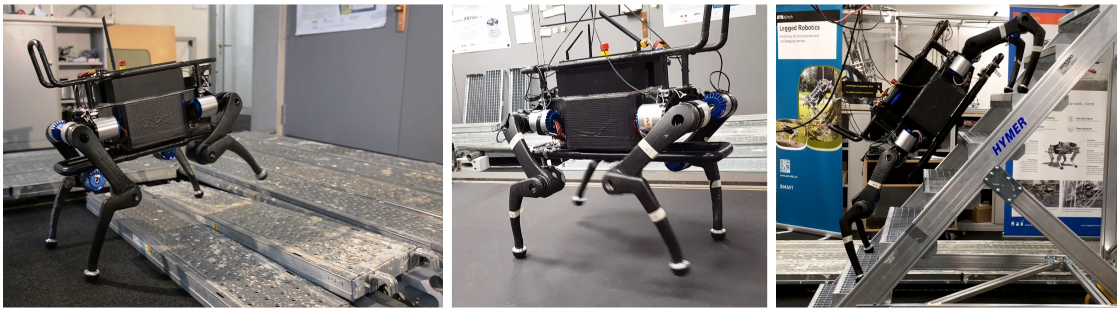


Figure 5: The software architecture with clear real-time priority ranked separation on different PCs.



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

Figure 6: ANYmal was tested in different gaits like walking, trotting, or stair climbing

different processes, is running on the locomotion machine. 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.

3 Locomotion Control

Since ANYmal is fully torque controllable and of similar geometry as its predecessor StarlETH [10], locomotion control could be transferred relatively straight forward. Since a detailed description would go beyond the scope of this paper, we 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 [22, 23]. For static walking gaits, a ZMP planner [24] is implemented to plan a smooth main body trajectory while applying a standard crawling gait [25]. Foothold placement during dynamic gaits is based on simplified inverted pendulum models [26]. To balance the system, we build upon whole body control techniques that accounts for the complete system kinematics and dynamics [27, 28]. The optimal actuator commands are found at every time step by solving a constrained

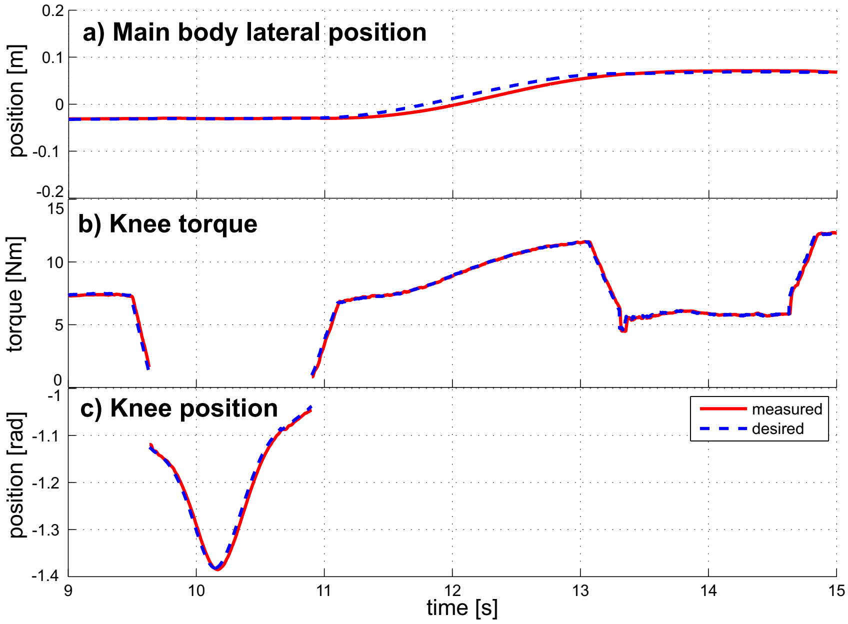


Figure 7: Torque and position tracking while walking.

optimization problem of prioritized tasks and constraints on joint torques, contact forces, and body motion.

4 Experiments

The performance of ANYmal was tested in different maneuvers and locomotion experiments illustrated in fig. 6 and in the attached video [2]. 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.

4.1 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. 7, 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 and without any joint position or impedance regulation. By applying a classical ZMP planner [24], 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. Having no constraints additionally implies that ANYmal can take fairly big steps.

4.2 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. In first experiments using a 50% duty cycle gait, the machine achieved a speed of about 0.8 m/s. Key element for robust trotting is fast and accurate position tracking. For a typical joint motion of a fast gait (fig. 8), joint positions and velocities are followed quite 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. 9, ANYmal requires in average

[2] https://youtu.be/jR066mQvclw

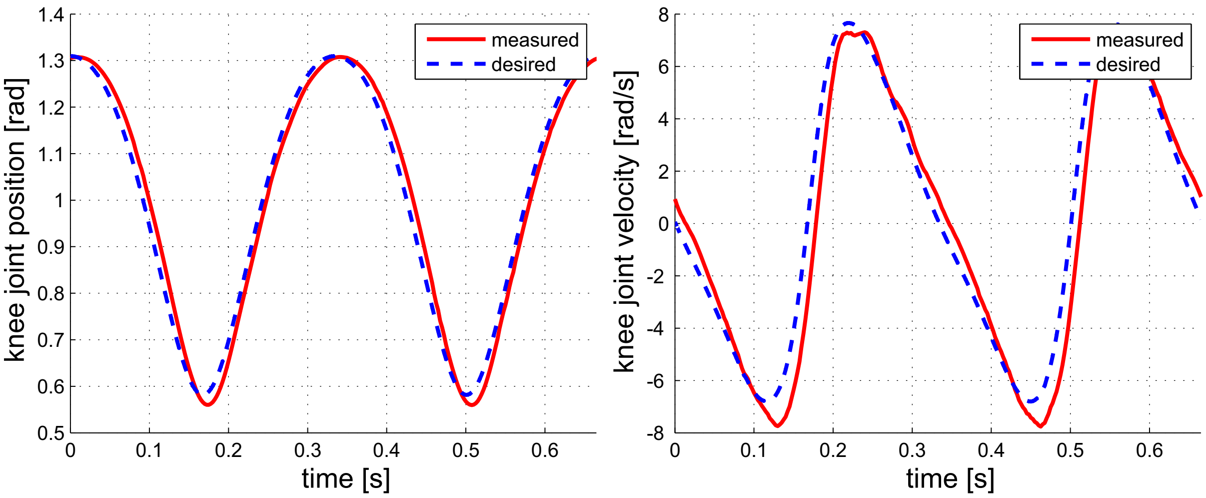


Figure 8: Tracking performance of the position and velocity of the knee joint.

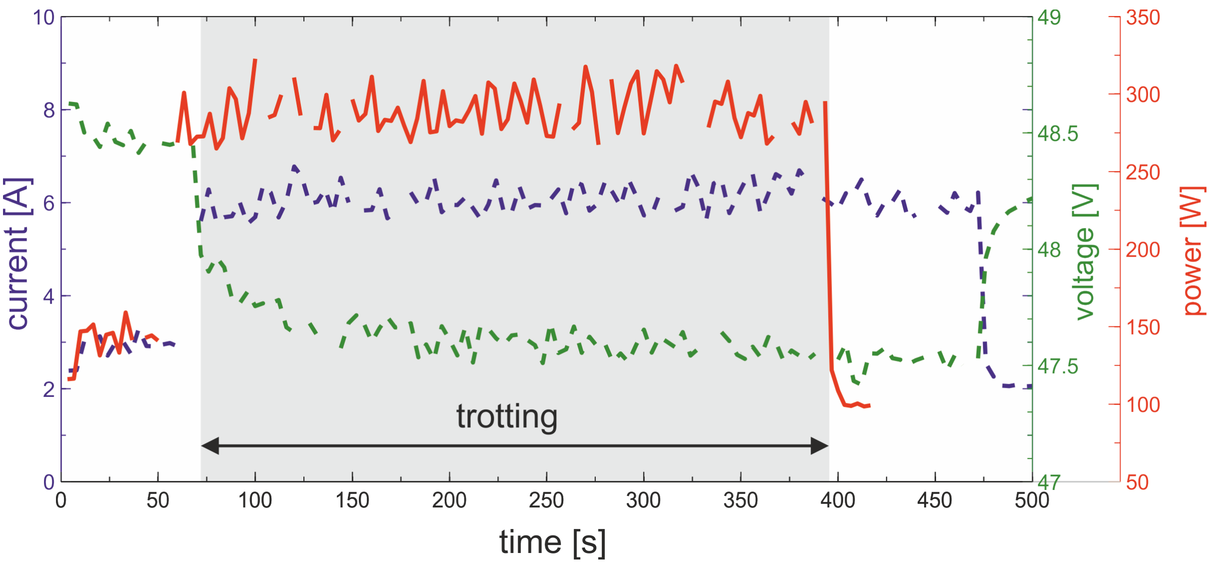


Figure 9: The power consumption during trotting.

about 290 W with about 5% fluctuation when trotting, about 100 W is consumed while idling in standing configuration. These measurements are comparable to our previous results with StarlETH [29] and enables the machine to autonomously run for more than 2 h with its current batteries.

4.3 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. Thereby, 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. 6(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 [30]. This machine successfully exhibited such gait to reliably overcome steep inclinations with loose sand during a moon testing scenario on a volcano.

5 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 autnomous walking machine could be confirmed in preliminary experiments ranging from careful stair climbing, over ZMP-based walking to 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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