Humanoid Robot *LOLA* – Research Platform for High-Speed Walking

Sebastian Lohmeier, Thomas Buschmann, Heinz Ulbrich and Friedrich Pfeiffer

Abstract This paper describes the design concept of the performance enhanced humanoid robot *LOLA*. Our goal is to realize a fast, human-like walking motion. The robot has 22 degrees of freedom, including 7-DoF legs with actively driven toe joints. It is characterized by its lightweight construction, a modular, multi-sensory joint design with brushless motors and an electronics architecture using decentralized joint controllers. Special emphasis was paid on an improved mass distribution of the leg apparatus to achieve good dynamic performance. The sensor system comprises absolute angular sensors in all links, two custom-made force/torque sensors in the feet and a high-precision inertial sensor on the upper body. The trajectory generation and control system currently being developed aim at faster, more flexible, and more robust walking patterns.

1 Introduction

Recent developments in enabling technologies (biped walking control, mechatronics, computer technology) have lead to the design of sophisticated humanoid robots, like *ASIMO* [5], *HRP-2* [9] and *WABIAN-2* [15]. Even if all robots achieve reliable dynamic walking – compared with human beings – high walking speeds still remain challenging.

Obviously, the control problems inherent in fast walking are the most challenging field, since there are still many unsolved problems, e.g. fast walking and running [6, 8], sudden turning motions, walking on rough terrain and trajectory generation in complex environments. In our opinion, however, a careful design of the mechanical hardware and the sensor system is just as essential, and and cannot be separated from controller design. Rather, all components must be seen as tightly coupled parts of a highly integrated mechatronic system. For example, the structural

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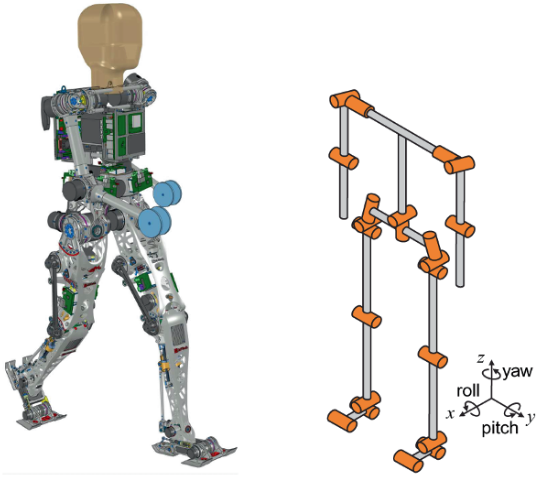


Joint	DoF
Head	2 (planned)
Shoulder	2
Elbow	1
Waist	2
Hip	3
Knee	1
Ankle	2
Toe	1
Total	**22+2**

Fig. 1 22-DoF humanoid robot *LOLA* (left) and kinematic configuration (right).

stiffness and mass distribution can positively influence the dynamics of the overall system. Moreover, the validity of model simplifications, e.g. the inverted pendulum model used in the stabilizing controller, can be aided if disturbances by the highly accelerated leg masses are minimized.

With the biped robot *JOHNNIE* which was developed at our institute from 1998 to 2003, a maximum walking speed of 2.4 km/h has been achieved [10]. Figure 1 (left) shows our new humanoid walking robot *LOLA*. The aim is to realize a fast, human-like walking motion, including a significant increase in walking speed (goal: 5 km/h) and more flexible gait patterns. Furthermore, we want to increase the robot's autonomous, vision-guided walking capabilities. *LOLA*'s physical dimensions are based on anthropometric data and correspond with a 180 cm tall adult. The weight of the robot is 55 kg without batteries.

LOLA's hardware approach tries to settle most of the technical problems discovered in experiments with *JOHNNIE* and a thorough hardware analysis. The distinguishing characteristics of *LOLA* are its redundant kinematic structure with 7-DoF legs, an extremely lightweight construction and a modular joint design using brushless motors. The sensor system was revised in order to improve signal quality and bandwidth. In our opinion, one of the keys to faster walking is greater robustness and stability. The new control architecture tries to achieve this by adding an on-line adaptation of gait parameters such as step length and width in real-time (cf. [1]).

2 Design Concept

Fast locomotion still poses a significant challenge for humanoid robots and requires an accurate design of the overall mechatronic system. Especially the legs and feet require careful engineering in order to achieve a good dynamic behavior. Since the robot's mass and its distribution have a strong influence on global system dynamics, the lightweight construction is of great importance and must be balanced with the demand for high stiffness and powerful drives.

2.1 Kinematic Structure

One of the most important conceptual challenges is the definition of a kinematic structure, enabling a natural, stable and fast gait. From experiments and simulations we have seen that additional, redundant DoF can increase the robot's range of motion, flexibility and stability of gait patterns and walking speed. Considering results from biomechanical research on dynamics and kinematics of biped walking (e.g. [3, 14]) and experience with *JOHNNIE* [10] we chose a configuration with 22 actively driven DoF for *LOLA* (Figure 1 right): The legs have 7 DoF each, while the upper body has two and each arm has three DoF.

Nearly all humanoid robots are designed with 6-DoF legs – 3 DoF in the hip, one in the knee and two in the ankle. Each foot consists of one rigid body, therefore heel lift-off during terminal stance phase can hardly be realized. Even small disturbances lead to instabilities due to the line contact of the foot leading edge and the floor. In human walking heel lift-off in the stance leg occurs during terminal swing, i.e. shortly before the swing leg has floor contact [16]. Biped robots with one-piece foot segments, however, cannot perform forward roll across the forefoot. Especially for larger step lengths, this leads to an extended knee configuration at initial contact of the swing leg resulting in large joint accelerations.

Therefore an additional, actively driven link between forefoot and heel, equivalent to the human toes is proposed for *LOLA*. Heel lift-off in the stance leg allows the swing leg to be in a more extended configuration. Area contact of the toe segment stabilizes the robot and facilitates forward roll across the forefoot which is expected to reduce the joint loads in hip and knee compared to a 6-DoF leg configuration. There are only very few humanoid robots with actively driven toe joints, e.g. *H6* and *H7* [13]. Recently, Ogura et al. [15] presented the robot *WABIAN-2* walking with passive toe joints.

2.2 Further Requirements for High-Speed Walking

Besides a suitable kinematical structure, further design goals can be defined to improve the robot hardware for fast walking:

- Minimum overall mass,
- sufficient structural stiffness,
- high center of gravity,
- low moments of inertia of the leg links.

Obviously, the overall mass should be minimized, while a sufficient stiffness of the robot's structure must be maintained. This prerequisite is common to all mobile robots with high dynamic demands.

Unlike humans, the largest portion of a biped robot's weight resides in its legs, since motors and gears determine approximately a third of the overall weight. Therefore the center of gravity (CoG) height is lower than that of humans, i.e. typically at the height of the hip joint or even below. According to the *Linear Inverted Pendulum Model* (3D-LIPM) by Kajita et al. [7], the CoG trajectory of the robot is a piecewise hyperbolic curve, where the CoG lateral swing y_{CoG} increases with lower CoG positions:

$$y_{CoG} \sim \cosh\left(\sqrt{\frac{g}{z_{CoG}}}\, T_s\right)$$

The 3D-LIPM illustrates the influence of the CoG height z_{CoG} on the lateral swing of the upper body during walking: Especially at higher walking speeds, the stability of the robot increases when the lateral swing of the upper body is low. But mass distribution in the legs not only influences CoG height, but also the inertia of the leg segments. Therefore, during the final iteration of the mechanical hardware we chose three additional measures to further improve mass distribution: First, we designed the leg segments as investment cast parts using FE-based topology optimization methods to achieve high stiffness at a minimal weight (Section 3.4). Moreover, by choosing an appropriate kinematic actuation principle for the leg links, the mass distribution can strongly be influenced: For the knee joint, a roller screw-based linear actuator is used (Section 3.2). The ankle joint is actuated by a 2-DoF parallel mechanism with linear drives, where the motors are mounted on the thigh next to the hip joint (Section 3.3).

3 Mechanical Design

3.1 Modular Joint Concept

A detailed analysis by Gienger [4] has revealed that structural components make 43% of a humanoid robot's weight. With approximately 31% the drive chains make the second largest part, making the development of compact and lightweight joint units a crucial factor. From the manufacturing and maintenance point of view, a fully modular structure of the whole robot would be desirable, however, it collides with the demand for minimal weight. For *LOLA*, all joints have the identical structure with the sizes of gear and motor adapted to the requirements of each link. Many parts are standardized for all drives, but some housings are specialized because of weight and optimal load spread and distribution. This turned out to be the most reasonable way to realize the robot at minimal weight while taking into account ease of manufacturing [12].

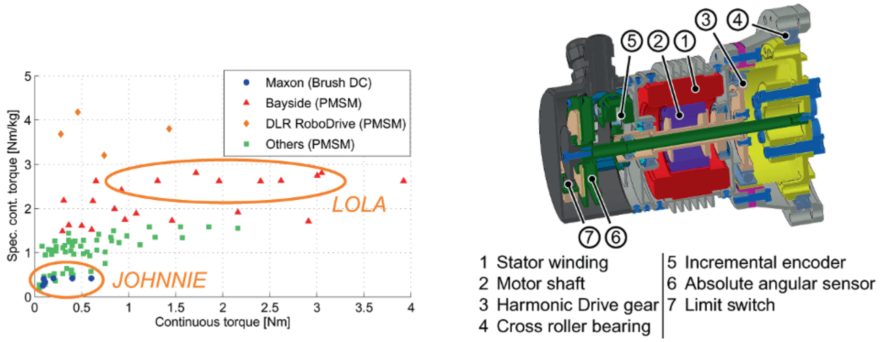


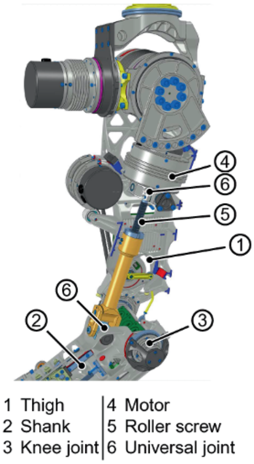
Fig. 2 Left: Comparison of the power density of commercially available DC motors and PMSM. Right: Mechanical design of Harmonic Drive based joints (e.g. hip joint yaw axis).

To realize highly integrated joint units with maximum power density it is necessary to use the latest technologies in the field of electrical drives, gears and sensors. We are using high performance permanent magnet synchronous motors (PMSM) from Parker Bayside because of their superior torque and speed capabilities (Figure 2 left). The motors come as kit motors, which facilitates a space- and weight-saving integration into the joint.

Except for the knee and ankle, all joints employ Harmonic Drive gears as speed reducers, which are the de-facto standard for humanoid robots. Their advantages are well known and include no-backlash and high reduction ratios at a low weight. The compact design of Harmonic Drive component sets allows a space-saving integration directly into the joint units. All gears are custom lightweight versions with a T-shaped Circular Spline which is, in our experience, the best tradeoff between weight and loading capacity. The Wave Generators, modified for low weight and inertia, are made from aluminum or steel. As an example, Figure 2 (right) shows the hip joint yaw axis.

3.2 Knee Joint

Even though the torques and velocities are comparable, using the hip joint pitch drive in the knee is problematic because its mass would unacceptably increase the thigh moment of inertia. In turn a large part of the enhanced hip joint output would be spent on accelerating a heavier thigh. By employing a roller screw-based linear drive (Figure 3 left), a better mass distribution in the hip-thigh area is achieved compared to a Harmonic Drive based solution with identical performance: The thigh inertia could be reduced by 65%, and the drive mass was reduced by more than 10%. Thus, the driving power of the knee could be enhanced without decreasing the hip joint's performance. The mechanism is nonlinear and the torque-speed characteristic corresponds to the human knee (Figure 3 right): The torque depends on the link



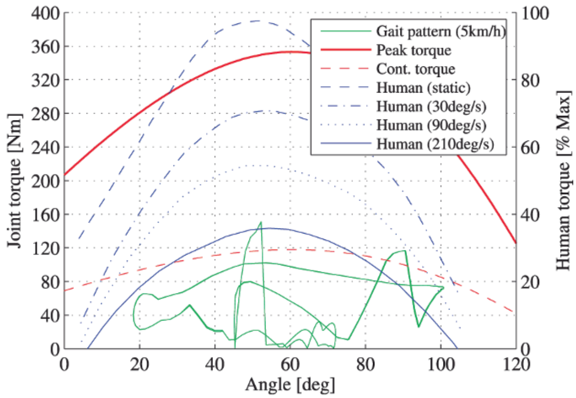


Fig. 3 Left: Knee joint with roller screw-based actuator. Right: Torque and speed requirements of knee joint (human torque capacity taken from [16]).

position and has its maximum at around 55°, which is advantageous for typical gait patterns of the robot. Conversely, maximum speeds increase at a stretched leg configuration, where they are needed.

Compared to ballscrews that were used in our first designs [11], roller screws have a significantly higher load rating which allowed us to further reduce the drive's weight. Moreover, due to their multi-point contact design, roller screws have the ability to survive shock loads which makes them particularly suitable for the robot's legs.

3.3 Ankle Joint

As shown in [11], both axes of the ankle joint show clearly different torque-speed characteristics. By employing parallel drives, the required peak motor torque can be reduced by approx. 35%. Different from our previous designs, where the drives acted as length variable steering rods, the ankle joint drives were modified in the final design which is shown in Figure 4: The ankle joint (3) is actuated by two linear drives (7) with the motors (4) mounted on the thigh (1) as close as possible to the hip joint. Each linear drive (7) is connected to the motor (4) via a timing belt (5) and a bevel gear (6) in the knee joint axis which is then connected to the roller screw (8). Each linear drive consists of a roller screw (8) which is fixed to the shank, and a linear bearing (9) which keeps the roller screw free from radial loads. A steering rod (10) connects the roller screw nut and the foot segment. The incremental encoders for motor control are mounted on the motor shaft, but the absolute angular sensors (11) are mounted on the joint axes.

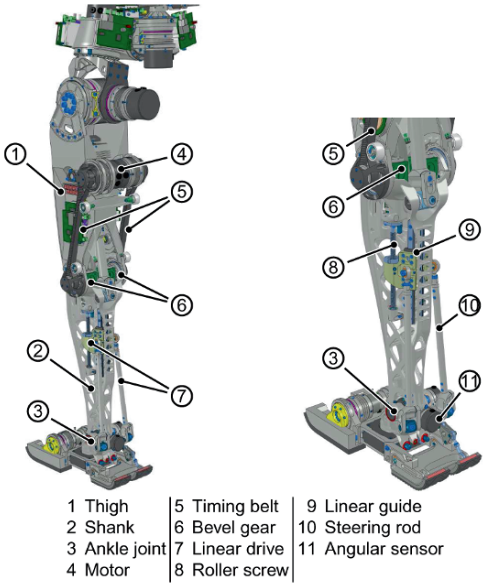


Fig. 4 2-DoF parallel mechanism in the ankle joint of *LOLA*.

3.4 Design of Structural Components

Both thigh and shank were designed as investment cast parts. By using Rapid Prototyping-based manufacturing, there are almost no limitations of a component's shape and it is possible to realize complex, thin-walled components. As an example, the design process of the shank is shown in Figure 5. It connects the 1-DoF knee joint and the 2-DoF ankle joint that are both actuated by roller screw drives. Therefore, loads are transmitted not only at the joint flanges, but also at the hinging points of the linear drives. Due to numerous points of force transmission of the linear drives, thigh and shank show quite complex multi-axial stress conditions and strict geometric constraints. Therefore we used the FEM-based topology optimization tool *OptiStruct* to find an optimal design proposal which meets weight and/or stiffness targets and other constraint criteria. Based on a mockup resembling the maximum allowable designed space, an optimization model is built. Realistic results can only be achieved if the force transmission by the roller screw drives is considered. Therefore the thigh and the linear drives of knee and ankle are modeled as elastic bending beams. The optimization result is the basis for the actual part design. After several iterations of structural analysis and design refinement, the final geometry of the component is developed. By using the original CAD data, the master pattern is made by laser-sintering of plastic, which is then cast from aluminum.

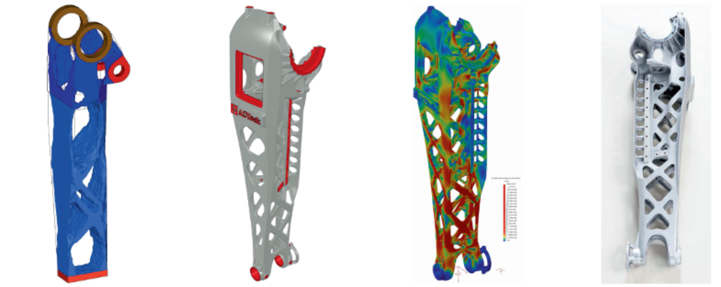


Fig. 5 Development process of structural components based on topology optimization, for example the shank.

4 Sensor System

4.1 Joint Sensors

Each joint contains an incremental rotary encoder, an absolute angular encoder used as link position sensor and a limit switch (cf. Figure 2 right). The incremental rotary encoder mounted on the motor shaft is mainly used for motor control. The absolute angular encoder (resolution 17 bit, accuracy 0.1°) compensates elasticities and non-linearities in the drive chain and eliminates the need for a homing routine, making startup faster and easier. To improve operational security and to prevent the robot from self-destruction each joint incorporates a limit switch in the form of a light barrier.

4.2 Force/Torque Sensors

LOLA is equipped with two six-axes force/torque sensors that are tightly integrated into the foot structure. The required measurement range was determined using our detailed multibody simulation model [2] for a walking speed of 5 km/h. Based on these data and multiple iterations of FEM-analyses, an optimal design of the sensor body was developed (Figure 6). The sensor consists of a single aluminum part with four deformation beams in a classic “Maltese-cross” arrangement. Each beam holds two pairs of strain gauges that operate in a half bridge configuration in order to compensate for temperature dependency. Thin membranes mechanically decouple the individual beam deflections to a far extent and reduce cross talk. In order to protect the sensor from damage during experiments, we have integrated an overload protection. Mechanical end-stops engage into the flux of force at a vertical load corresponding three times the weight of the robot and thus unload the sensitive measurement beams. Special emphasis has been devoted to the strain gauge application.

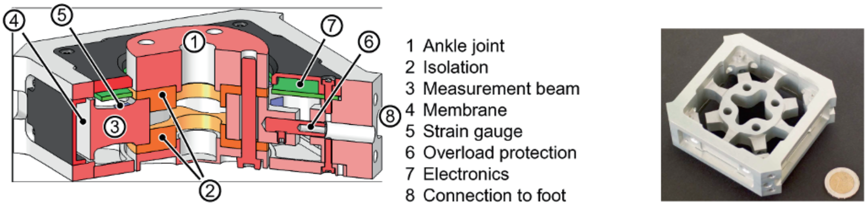


Fig. 6 Schematic display of the 6-axis force/torque sensor (left) and the monolithic sensor body before assembly (right).

The strain gauges are selected to match the elastic properties of the sensor material. An exact application in combination with an appropriate temperature treatment finally lead to a high zero point stability of the signal. The calibration was done using the least squares method. By applying more than 450 different load cases, a calibration error less than 0.5% could be achieved. At a total weight of 395 g the sensor includes all necessary electronics and a digital interface.

4.3 Inertial Measurement Unit

The inertial measurement unit (IMU) estimates the orientation and velocities of the upper body. Simulations and experimental results with the robot *JOHNNIE* have shown that the precision of this sensor significantly determines the performance of the stabilizing controller. Therefore, the IMU must show high accuracy and a high signal quality (i.e. low noise). Moreover, a low sensor bias results in a low long time drift and a reliable calibration. We are using the inertial measurement unit *iVRU-FC-C167* (from iMAR Navigation) in a custom made lightweight version. The sensor consists of three open-loop fiber-optic gyroscopes and three MEMS accelerometers. The sensor fusion comprises internal error models and is integrated into the sensor, which has a CAN interface.

5 Conclusions/Future Work

Despite recent advances, biped walking robots are still slow compared to humans and have limited autonomy. The intention of the research presented here is to diminish this gap. This paper focused on the design concept of our new, 22-DoF humanoid robot *LOLA* (180 cm, 55 kg). *LOLA*'s distinctive features are an extremely lightweight construction and a redundant kinematic configuration, which allows for more flexible and natural motions. All joints are equipped with absolute angular sensors and are driven by AC brushless motors through Harmonic Drive gears or linear mechanisms with roller screws. The electronics architecture is designed as an “intelligent sensor-actuator network” with a central controller. The new decentral components increase the system’s performance from a technological point of view. The trajectory generation and control system currently being developed aim at faster, more flexible, and more robust walking patterns. In the near future, we will integrate a camera head to enable autonomous locomotion. *LOLA* will serve as a research platform for fast walking and visual-guided, autonomous walking.

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