

The TUM Biped Johnnie and Lola

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2018

Preprint:

This is an accepted article published in Humanoid Robotics: a Reference (Book Chapter). The final authenticated version is available online at:

https://doi.org/10.1007/978-94-007-6046-2_13

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Abstract The robots *Johnnie* and *Lola* were developed at the Institute of Applied Mechanics at the Technische Universität München (TUM) to research hardware design, dynamics and control aspects of biped walking. Starting in 1998, biped walking research at the lab has been an active research area for almost 20 years. The development of both robots followed an iterative, model-driven approach and both robots heavily rely on model-based control methods, an approach that was combined with a strong emphasis on an experimental investigation of the walking systems. Both robots feature innovative hardware designs, novel control algorithms and were used to achieve advances both in dynamic walking control and autonomous locomotion among obstacles.

The Biped Johnnie

The biped walking robot *Johnnie* has been designed and built between 1998 and 2003. The project was funded as part of the German priority program *Autonomous Walking* of the Deutsche Forschungsgemeinschaft (DFG). While *Johnnie* was the first biped walking robot built at the TUM, significant experience in design and control of walking robots had been acquired before that with a six-legged walking robot, and an eight-legged pipe crawling robot [26,24].

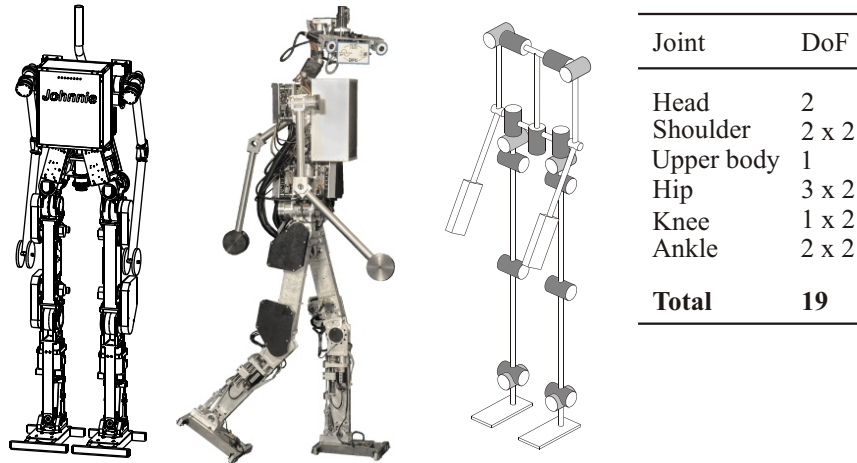


Fig. 1. Biped robot Johnnie. Left: CAD model. Middle: photograph with vision system from ([8]). Right: Joint structure.

The goal targetted with *Johnnie* was to realize a biped walking robot for locomotion at higher speeds. In the end, *Johnnie* was able to walk up to 2.4 km/h fast, which made him one of the fastest biped walking robots at that

time. The robot was a frequent guest on technology fairs, events and in TV documentaries. The development of *Johnnie* led to about 30 publications in international conferences, journals and books. It gave inspiration to the follow-up robot *Lola*, which will be introduced in the next section. This section will introduce the design concept behind *Johnnie*, explain the key elements of the mechatronic design, give an overview of the control architecture and close with the results that have been achieved with this remarkable robot.

0.1 Concept

Fig. 1 shows the kinematic structure of *Johnnie*. It has been selected to allow reproducing the major determinants of human gait from a biomechanical perspective. Each leg is equipped with six driven joints. The upper body is connected to the pelvis by a vertical joint. Its joint axis is aligned with the two hip yaw joints and allows for a pelvis rotation to increase the step length. Each shoulder is equipped with a pitch and roll joint. This allows to reduce the overall moment of momentum about the body vertical axis with the arm motion. The geometry of the robot is based on anthropometric data that corresponds to that of a man of a height of 1.80 m, the robot's weight is approx. 52 kg [12].

0.2 Mechanical Design

The design approach is based on an iterative process of simulation and construction. In the concept phase, a detailed multibody simulation program was developed. The simulation algorithm included effects such as the actuator's rotor dynamics, the nonlinear friction behavior of the gear components [27,15] and the contact situation between foot and ground. This allowed to implement control algorithms with an increasing grade of complexity, and to simulate detailed design specifications such as joint torques, joint angular velocities, work ranges and ground reaction forces. In parallel, the virtual mechanical design was performed employing a 3D-CAD system.

In order to achieve fast movements, the main mechatronic design objective was to realize a high power-to-weight ratio. The structural parts mainly consist of high strength aluminum, which has advantages in terms of strength and heat conduction. The geometry of the structural parts was developed with the help of a Finite Element structural optimization tool. The actuation of the joints was designed with core-less DC motors, Harmonic Drive gears and ball screw drives. These reducers are backlash-free, compact and have an extremely low weight.

Fig. 2 left shows the design of the hip joint. The arrangement of the joints was chosen to be yaw-roll-pitch. This is advantageous as the pitch motion is associated with the highest velocities and joint torque. The actuation for the yaw and roll axis are arranged coaxial with the joint axis and are integrated in the aluminum structure. The yaw joint is inclined with respect to the pelvis. This leads to a better power distribution among the hip motors. The pitch joint is actuated with two DC-motors via a timing belt, which turned out to be the solution with the highest power-to-weight ratio among the investigated actuation

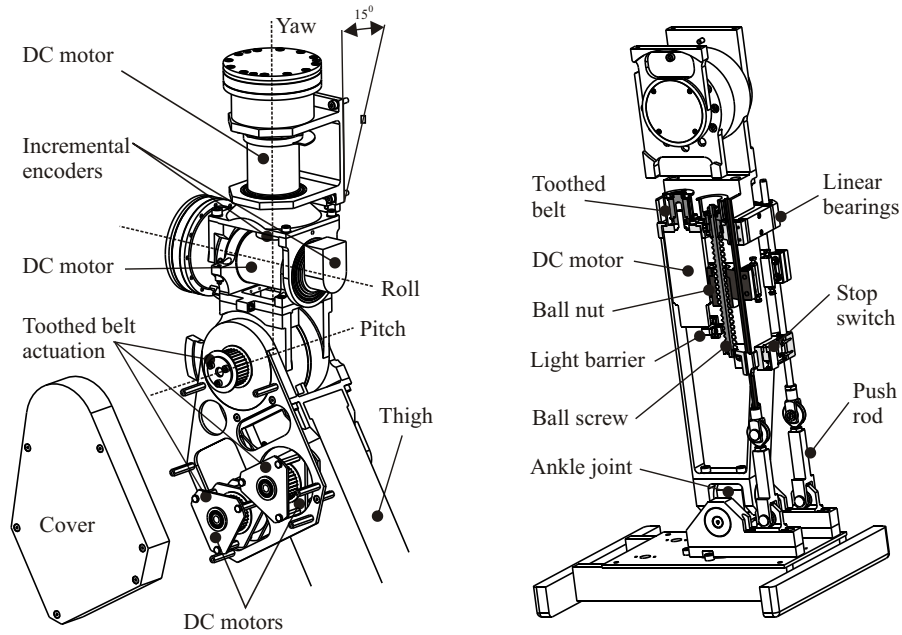


Fig. 2. Left: Hip joint with 3 joints. Right: Ankle joint with parallel ball screw actuation.

concepts [9]. The thigh includes the PWM-amplifiers for the knee joint actuation. The design of the knee joint is similar to that of the hip pitch joint.

The actuation of the ankle joint was realized with two linear drives based on ball screws (Fig. 2 right). Two motors drive the ball screws via timing belt. A motion of the sliders in the same direction leads to a pitch motion of the foot, the roll motion is realized by moving the sliders in reverse direction.

0.3 Sensors and computer system

The measurement state of the robot consists of joint angles, joint velocities, ground reaction forces and the spatial orientation and angular velocity of the robot's upper body.

The joint angles and joint angular velocities are measured by incremental encoders attached to the motor shafts. Light barriers are used to determine the absolute position of the encoders with respect to the joint's center. The high resolution of the motor-side encoders allows for an exact control of the joint position. The joint velocity is identified by numerical differentiation.

The ground reaction forces are measured by two six-axes force/torque sensors that are integrated in the foot. The sensors consists of a monolithic aluminum part with twelve strain gauges applied to the three deformation beams. Two opposing strain gauges operate as half bridge such compensating for temperature

drift. Thin membranes mechanically decouple the individual beam deflections to a far extent and such reduce cross talk [16,25].

The spatial orientation of the upper body is determined by an inertial sensing unit that combines three single-axis gyroscopes and a 3d acceleration sensor. The sensor fusion follows a complementary filtering approach. The basic idea is to weight the sensor data in frequency ranges in which the respective sensor can be considered as ideal. More details are given in [11].

Johnnie's sensor acquisition and real-time control is calculated on a fast on-board PC (2.8 GHz Pentium processor). The interface to the sensors and the motor electronics consists of a custom-made PCI extension board. It integrates 24 A/D converters to acquire the analog sensor signals (force and inclination), six digital outputs to calibrate the force / torque offsets, 17 digital encoder processing units for the motor-side joint angle measurements, and 20 PWM units to drive the motors. The hardware and software structure of the system is described in more detail in [23].

0.4 Control Architecture

The employed control architecture is depicted in Fig. 3 and consists of three layers. The highest layer refers to the global coordination of the gait pattern, and is realized by a state machine. The trajectories are generated on the second level, and the control of the trajectories is performed on the lowest level.

0.5 Trajectory Generation

The second layer is responsible for generating the trajectories of the robot. The trajectories are defined in Cartesian coordinates for the overall center of gravity (CoG), the rotation of the upper body and the position and orientation of the swing foot, as well as the pelvis and arm joints. The reference trajectories of the CoG are computed based on the Zero-Moment-Point (ZMP) formalism [31] with an inverted pendulum model. In this model, it is assumed that the mass of the robot can be lumped to the CoG, and that the motion of the CoG in the forward direction is independent of the motion in the lateral direction. The motion of the ZMP is defined as piecewise polynomials corresponding to the single and double support phases of the gait cycle. During the single support phase, the lateral position of the ZMP is kept constant with respect to the supporting foot. At the same time, the ZMP moves from the rear edge of the supporting foot to its front edge in the walking direction. This allows to keep the CoG velocity almost constant while it is above the supporting foot. During double support the CoG is smoothly interpolated with fifth order polynomials. More details can be found in [14,27]. An example for ZMP and resulting CoG trajectories is depicted in Fig. 4. The motion of the swing foot and the remaining variables is defined in fifth-order polynomials.

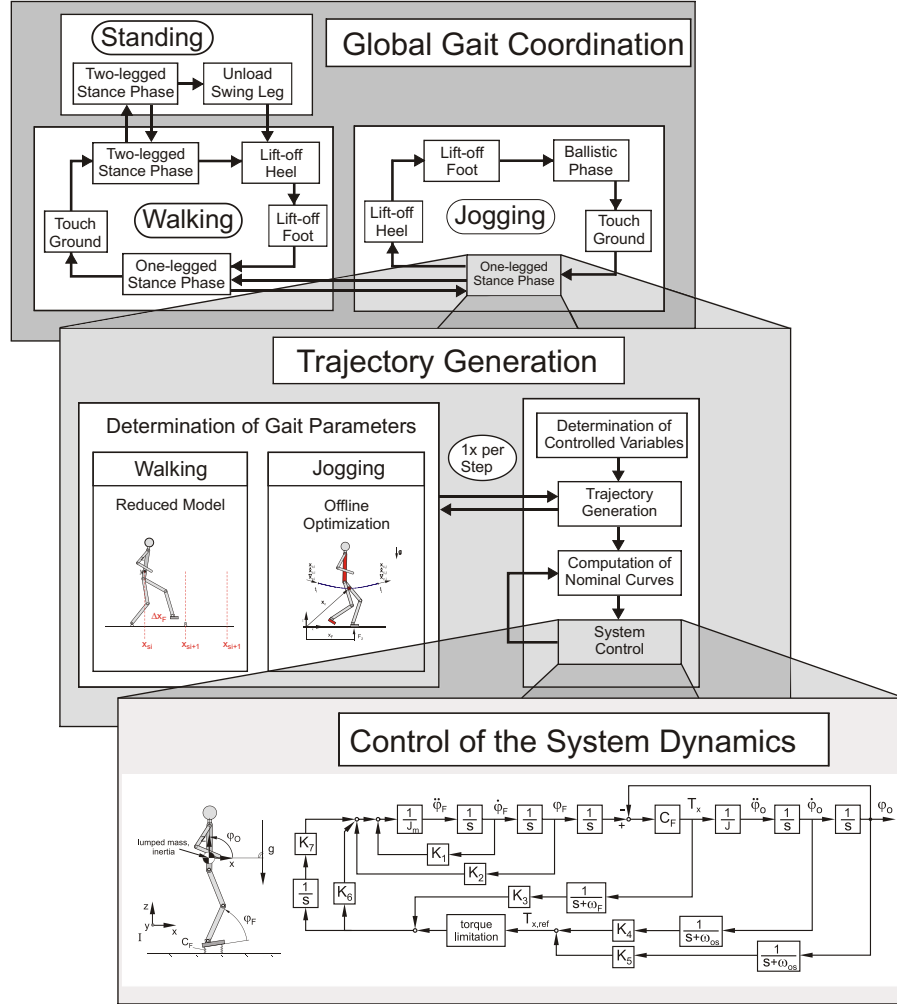


Fig. 3. Three-layered control architecture.

0.6 Motion Control

The lowest layer of the control architecture is responsible to track the desired trajectories while keeping the system stable. In a first approach, the control system on the lowest level was based on a Computed Torque concept. While this concept considered the overall system dynamics of the robot, only lower walking speeds of about 1 km/h could be achieved. Higher speeds were limited mainly by the low feedback gains due to analog sensors [16,22].

A more effective approach was found to be based on independent high-gain joint PD controllers. Here the Cartesian trajectories are mapped onto joint space

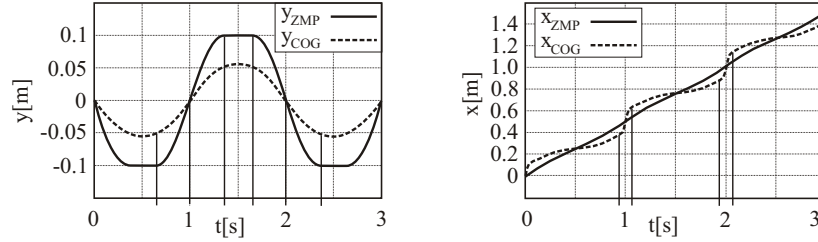


Fig. 4. Example for ZMP and CoG trajectories in lateral and forward direction.

using Inverse Kinematics. Similar concepts are used in many other biped robots that can perform a stable walking motion. The implementations differ in terms of the variables that are used to adapt the trajectories. In most cases the orientation of the supporting foot i.e. the ankle joint is used to control the foot torques in order to stabilize the robot. Add to this it is possible to accelerate the upper body horizontally to keep an upright posture. A very popular approach is to vary the step length in forward and lateral direction. In order to reduce impacts when the swinging foot hits the ground, it is possible to introduce some impedance in the vertical position of the feet, or to vary the vertical position of the feet with respect to the upper body. In *Johnnie* all these approaches have been verified experimentally. The most effective approach turned out to be the control of the foot rotation which is described in detail in [17,27].

0.7 Results

The walking performance of *Johnnie* was verified in a number of experiments. The top row of Fig. 5 shows a sequence of snapshots walking on a treadmill. *Johnnie* could achieve stable walking up to 2.4 km/h and step lengths of 55 cm. Additionally, the robot can step over obstacles and climb up stairs with a height of 12.5 cm per stair, such as shown in the bottom rows of Fig. 5. In 2003, *Johnnie's* locomotion abilities have been exploited by integrating a visual guidance system [8]. This enabled the robot to react to sudden changes in the environment, for instance by placing an obstacle in front of the robot during walking [8].

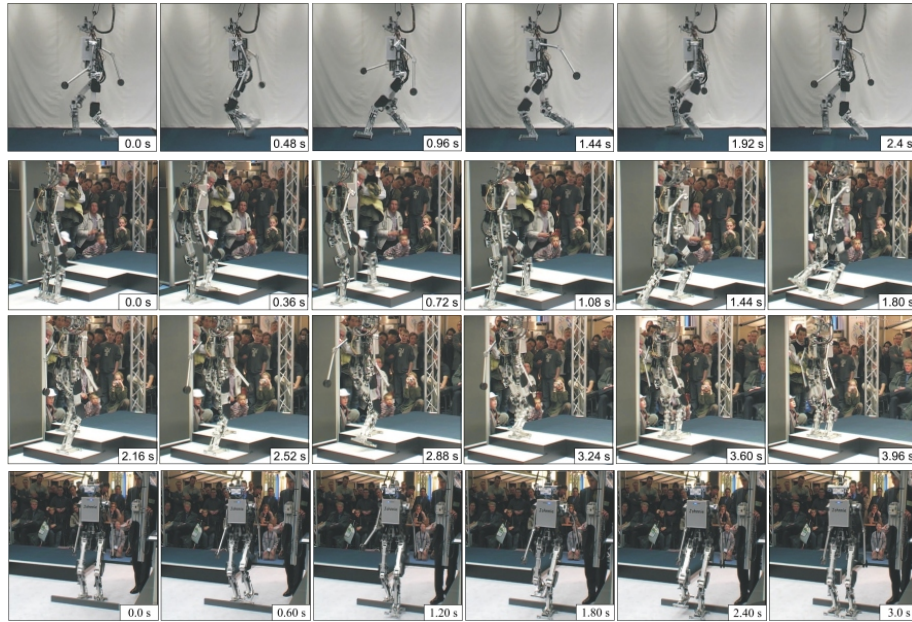


Fig. 5. Upper row: Treadmill walking with 2.4 km/h. Middle rows: Walking up stairs. Lower row: Stepping over obstacle (From [14])

The Biped Lola

The biped robot *Lola* was developed from 2004 to 2012 as part of a research effort funded by the DFG, but minor hardware improvements, as well as major upgrades to the control are continuing at the time of writing (August 2015). Initial project goals were a mechatronic re-design and improved control system to enable faster walking and improved autonomy. Ongoing work is focused on flexible online motion generation and more robust walking control.

0.8 Hardware Overview

The following subsections outline the mechanical design, electronics and sensor system. A more detailed discussion of *Lola*'s hardware design is given in the Chapter "Leg Mechanism of *Lola*."

Mechanical Design *Lola* has very similar proportions to *Johnnie*, is also electrically actuated and uses a similar sensor suite. It was, however, completely re-designed to improve performance, mainly through more powerful drives, better sensors, a high-performance communication system and stiffer structural components. The robot is 180 cm tall, weighs approximately 60 kg and has 24 actuated DoFs (see Fig. 6). *Lola* added actuated toe joints, two actuated pelvis joints, as

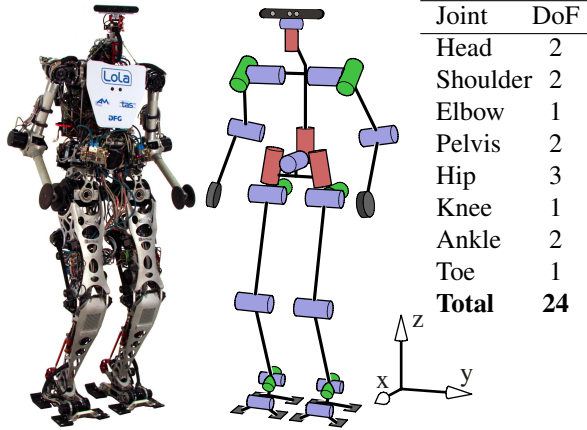


Fig. 6. The biped robot *Lola* (left) has 24 actively driven joints. The kinematic structure is shown on the right. Recent experiments have used the 2-DoF head with an RGB-D sensor shown above. Previous work also used a 3-DoF head with two cameras and actively controlled camera vergence angle.

well as active shoulder abduction/adduction and elbow flexion/extension joints to the kinematics developed for *Johnnie* (*Johnnie*'s pelvis joint was not used). The added joints make the robot kinematically redundant with respect to the task of biped locomotion.

Hardware development was guided by the following design goals: 1) low weight, 2) high effective stiffness, 3) low leg inertia and 4) high center of gravity (CoG) [21,19]. Low leg inertia and high CoG can both be achieved by shifting heavy components in the legs as closely towards the hip as possible. In *Lola*'s leg this was done by designing a linear knee actuator based on a roller screw and choosing a parallel mechanism for the ankle actuation (see Fig. 7).

The ankle joint drives are based on two parallel spacial slider-crank mechanisms driven by roller screws. The motors are located at the top of the thigh and drive the mechanism via timing belts and bevel gears located in the knee joint axis. This design also greatly reduces the shank inertia compared to a Harmonic Drive-based design, while the mass is approximately the same.

Both designs greatly improve the acceleration capability of the legs, which is important in high-speed walking (for detailed discussion see [19]).

Sensor And Computer System *Lola* uses nine local controllers to handle device-specific interfaces to sensors and servo drive controllers and communicate with an on-board PC via the Sercos-III real-time Ethernet system. The real-time bus has sufficient bandwidth for running joint control on the PC or local controllers while sending all sensor data the central controller.

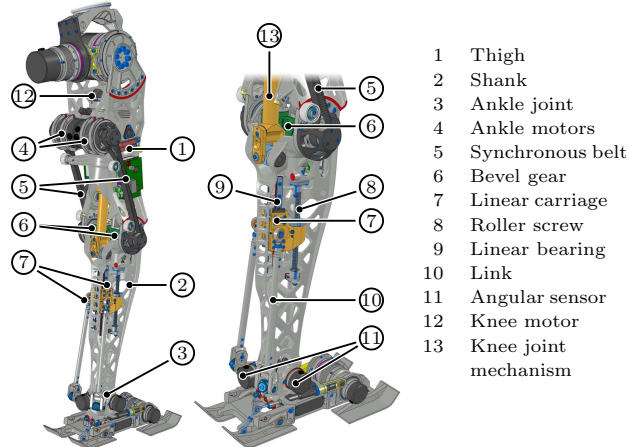


Fig. 7. Leg design with linear drive mechanisms for ankle and knee joints.

Lola has incremental encoders on the motor shafts that are used for low-level control of the brushless motors. Leg and arm joints also have absolute link-side sensors and optical limit switches. Custom-made strain gauge-based six-axis force/torque sensors (FTS) are integrated into the feet. A commercial inertial measurement unit (IMU) based on fiber optic gyroscopes and MEMS accelerometers is mounted on the upper body.

0.9 Walking Control

This section describes the walking control architecture developed for *Lola*, as well as the most important control and planning modules. The basic design owes much to *Johnnie*'s walking controller (see above and [14]): reference trajectories are planned in task-space coordinates and basic stabilization is based on controlling contact forces via an inner position control loop. However, significant improvements were made to trajectory generation and stabilizing control and new components for collision avoidance, angular momentum minimization, obstacle avoidance and stepping control were added.

Fig. 8 shows an overview of *Lola*'s hierarchical walking control system. The desired actions are specified by high-level commands such as walking direction and speed, which are modified and refined by lower layers.

Real-Time Trajectory Generation Foot trajectories are kinematically planned using piecewise polynomials. The corresponding foot placements are used to compute dynamically feasible CoG trajectories using a model with three point masses for the torso and the legs. Real-time numerical solution is based on a spline collocation method [4,1]. The difference to a multibody model can be

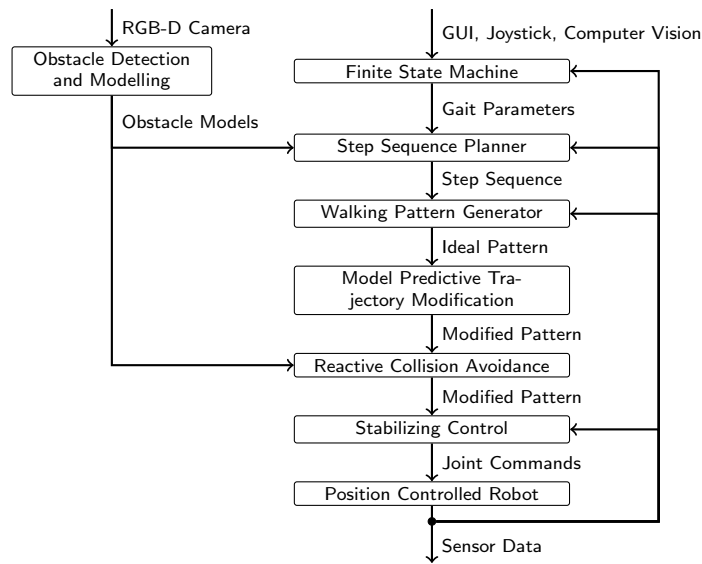


Fig. 8. Outline of *Lola*'s layered control architecture, which is coordinated by an FSM. Ideal step sequences and walking patterns are planned based on user input and detected obstacles. Stepping is modified online by a predictive, model-based component for stabilization, as well as through local 3D collision avoidance and local stabilizing control with contact force regulation [6,32,13].

taken into account in real-time planning, either through directly tracking contact forces as part of an extended inverse kinematics-like block, or via model error compensation methods (see [7]).

Local Trajectory Optimization Because *Lola* is kinematically redundant, auxiliary cost functions can be minimized while following the task-space trajectories. A velocity-level inverse kinematics algorithm based on the framework proposed by Liégeois is used for locally minimizing such a cost function in the task’s nullspace [28].

The cost function for *Lola* penalizes self-collision, joint limit violations and favors naturally looking poses. Angular momentum about the vertical axis can be treated either within the nullspace cost term, or by using the angular momentum Jacobian in the resolved motion rate control cost matrix [29]. In both cases, the angular momentum term produces naturally looking arm movements that reduce the friction torque acting at the ground contact and minimizes the risk of slipping. Self-collision avoidance is based on a simplified swept spheres volumes (SSVs) geometry of the robot (see Fig. 11). A detailed discussion of the method is given in [28].

Stabilizing Control Stabilizing control is based on the observation that since the global trajectory of the system can only be changed through contact forces, stabilization must be based on regulating contact forces.

The basic layer of the stabilizing control is based on regulating contact forces around the ideal forces computed during trajectory planning, corresponding to feed-forward plus PD feedback control. The feedback is calculated from a tracking error relative to the inertial frame estimated by the IMU, as well as the CoG’s tracking error. The magnitude of possible contact force modifications is limited by the foot size and placement, as the unilateral contact will only allow positive normal forces.

Contact force control is realized via an underlying joint position control loop. Controlling contact forces requires a modification to the planned task-space trajectories. This leads to a hybrid force/position control, since some task-space dimensions are fully position controlled, while others are modified by force feedback. The modifications of the task-space position trajectories required for contact force control are determined from a physical model of the compliant contact, the multibody model of the robot and the forces currently acting on the system (see [6] for details). The basic structure is very close to the second version of *Johnnie*’s controller developed by Löffler [14], where the inclination error is used to change contact torque references which are tracked via a modification of the foot orientation. Impacts for *Johnnie* were damped via parallel admittance-type position/force control. *Lola*’s controller, by contrast, uses an explicit contact model and is able to handle the multi-segmented foot with a toe. It also does not use parallel force/position control, but instead directly controls normal forces when possible and uses these for stabilizing the torso. Fig. 9 shows *Lola* walking with this controller at 3.6 km/h.

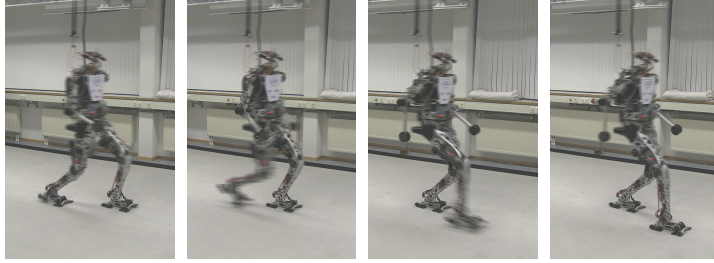


Fig. 9. *Lola* walking in the lab at 3.6 km/h.

Large disturbances require changes in the planned footstep locations that allow the required contact force modifications required to avoid falling. *Lola*'s controller implements an approach based on modeling the robot's underactuated dynamics with its basic stabilization layer. This model is capable of predicting upper body inclination due to strong disturbances and is used to determine adequate changes to the footstep locations for stabilization via online optimization ([32]). Correctly predicting the dynamics strongly depends on the estimate of the initial state, which is determined using a filter incorporating contact forces, inertial measurements and the multibody model [33]. Fig. 10 shows snapshots from experiments dealing with uneven ground and external disturbances.

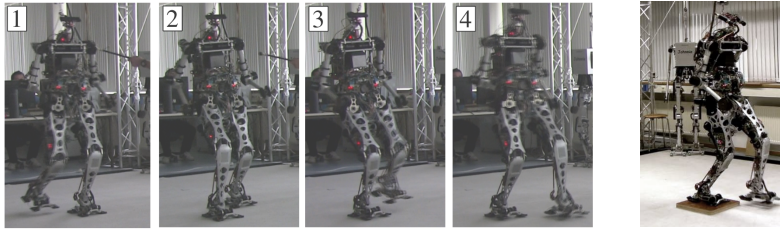


Fig. 10. *Lola* stabilizing herself while walking and being pushed (left, pushes performed with a rod instrumented with a load cell, see [32]) and stepping on obstacles (right, [2]).

0.10 Online 3D Obstacle Avoidance

Lola is equipped with perception, planning and real-time motion generation modules for avoiding obstacles (see Fig. 11). The key idea is to use a fast SSV-based geometry representation with different levels of detail for planning and reactive motion generation. Obstacles are detected with an on-board RGB-D

sensor while the robot navigates through an environment which is modeled on-line using SSVs. A step-planner reacts to high-level user commands like desired velocity and direction or changes in the environment within less than one step. Instead of investigating only the footholds, an articulated 3D approximation of the lower leg and the foot is used to find feasible and optimal footstep locations. The planner's output is used as an initial solution for the swing-foot movement. The final motion is generated in the feedback layer using an augmented collision avoidance scheme which adds environment obstacles to the self-collision model described above and additionally modifies a subset of task space coordinates to avoid collisions based on the full 3D environment and robot models, which cannot be avoided within the robot's nullspace (details see [13]).

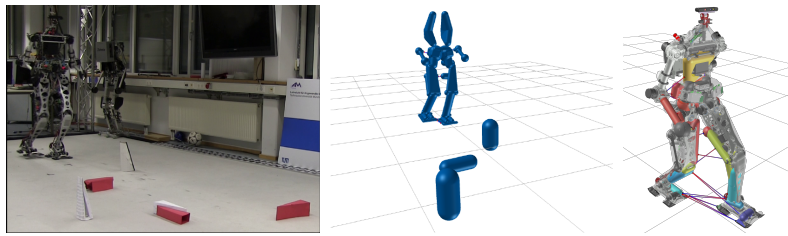


Fig. 11. *Lola* walking among obstacles (left), with on-line generated geometry for planning and control (center, rendered from logged data). Note that only obstacles considered relevant for the next few steps are used for collision avoidance and shown in the figure. Detail of self-collision model with color coding for distances (right).

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Cross-references

(To be updated when all parts are submitted)

- Hardware design section with *Lola* leg design (Sebastian Lohmeier/Heinz Ulbrich)

- LIP-based gait generation (Shuuji Kajita)
- TBD

Keywords

Walking Control, Hardware Design, Gait Generation, Collision Avoidance.