解説

The Biped Walking Robot Lola

—Hardware Design and Walking Control—

Thomas Buschmann*, Markus Schwienbacher*, Valerio Favot*, Alex Ewald* and Heinz Ulbrich*

*Institute of Applied Mechanics, Technische Universität München

1. Introduction

This paper gives an overview of our recent work on humanoid robots and reviews central results. We have addressed the design of hardware and control systems suitable for fast and autonomous biped locomotion. In order to experimentally verify the proposed methods we have developed the biped robot Lola shown in **Fig. 1**. During the development we took a systems engineering approach, emphasizing the fact that control methods, sensor system, mechanical components and actuators must be designed as an integrated system in order to optimize the walking performance.

There is a large body of related work on the design and control of walking machines. We have omitted a review here for the sake of brevity. Please refer to [1]~[6] for surveys of related research.

The rest of this paper is organized as follows. Section 2 reviews the mechanical design, electronics architecture and sensor system. The architecture of the walking controller, the approach to trajectory generation, walking stabilization and redundancy resolution is described in Section 3. Some experimental results are shown in Section 4 and Section 5 concludes the paper.

2. Hardware Design

The following subsections outline the mechanical design, electronics and sensor system.

2.1 Mechanical Design

Lola is 180 [cm] tall, weighs approximately 60 [kg] and has 25 actuated degrees of freedom (DOFs). A picture of the robot and the kinematic structure are shown in Fig. 1. The kinematics are similar to those of an adult male. Due to the actuated toes, arm and pelvis joints,

the robot is redundant with respect to the task of biped locomotion.

The 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) [3] [7]. 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 we achieved this by designing a linear knee actuator based on a roller screw and choosing a parallel mechanism for the ankle actuation (see **Fig. 2**). Since motors account for a significant portion of the overall weight of typical robotic drives, the location of the motors is very important with respect to our design goals.

The motor of the knee joint drive is located directly below the hip, reducing the thigh inertia by 85.5% and the mass by 35.8% when compared to a Harmonic Drive-based design where the drive is located at the knee joint.

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

Fig. 1 The biped robot Lola (left) has 25 actively driven joints. The kinematic structure is shown on the right

原 2012 年 3 月 5 日

キーワード: Biped Robots, Humanoid Robots

*Boltzmannstr. 15, 85748 Garching, Germany

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. A detailed discussion of the mechanical design and a comparison with other designs can be found in Ref. [7].

2.2 Electronics and Sensor System

Fig. 3 shows an overview of Lola's electronics architecture. Nine local controllers handle the device-specific interfaces of sensors and servo drive controllers and communicate with an onboard PC via the Sercos-III real-time Ethernet system. The high performance of the Sercos-III system allows us to execute low-level control loops such as joint position control either on the PC or on the local controllers, thereby providing a very flexible research platform.

Lola has incremental encoders on the motor shafts that are used for low-level control of the brushless motors. All joints except for the three in the head are also equipped with absolute link side sensors and optical

Fig. 2 Leg design with linear drive mechanisms for ankle and knee joints

Fig. 3 Lola's sensor-actuator network with local controllers and a central PC-based control unit

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 and provides inclination and angular velocity information.

3. Walking Control

The following subsections outline Lola's walking control system.

3.1 System Overview

Fig. 4 shows an overview of Lola's hierarchical walking control system. The desired actions are specified by high-level commands that can be sent via a graphical user interface, a joystick or a computer vision system capable of autonomously determining the desired walking behavior (see Ref. [8] and **Fig. 5** (a)).

3.2 Real-Time Trajectory Generation

Lola's reference motions are generated in real-time on the onboard PC. From the given input the robot first generates a sequence of footstep locations and desired gait parameters. This step sequence serves as input to the generation of ideal task-space and contact force trajectories. CoG trajectories are calculated using a collocation method based on a reduced three-point-mass model of the robot [1] [9].

3.3 Stabilizing Control

When the task-space reference trajectories are simply tracked, the robot quickly becomes unstable and falls.

Fig. 4 Outline of Lola's control system (λ are contact forces, x task-space coordinates, θ joint angles and φ the upper body orientation. Indices *id* and *d* indicate ideal and modified references, no index sensor data

(a) Autonomous navigation among unknown obstacles [8]

(b) Fast walking at 3.34 [km/h] [4]

(c) Reactive stabilization while walking over unmodelled terrain (the board is 4 [cm] thick)

Fig. 5 Examples of walking experiments with Lola

This is caused by errors in the robot and environment models and the compliance of the foot-ground contact. Stability and robustness can be improved by modifying reference trajectories through sensor feedback and introducing contact force control.

The desired contact forces are determined by a feed-forward plus PD feedback control. The feed-forward term is obtained from the walking pattern generator. The feedback is calculated from a tracking error relative to the inertial frame estimated by the IMU.

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

Fig. 6 Animation of the simplified geometry model for self-collision avoidance together with the CAD-geometry. Lines indicate the shortest distances between two segments, the distance is indicated by the color of the corresponding SSVs [5]

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 Ref. [2] for details).

3.4 Redundancy Resolution

Since Lola is redundant with respect to walking, it is possible to minimize auxiliary cost functions while following the task-space trajectories. We use a velocity-level inverse kinematics algorithm based on the framework proposed by Liégeois for locally minimizing cost functions in the task's nullspace.

Our cost function penalizes self-collision, joint limit violations, unnaturally looking poses and angular momentum about the vertical axis. 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. 6). A detailed discussion of the method is given in Ref. [5].

4. Experimental Results

We have performed a number of walking experiments in order to investigate the performance of the proposed robot design as well as the control methods.

One of our research goals is to improve the walking speed of biped robots. The maximum walking speed we have demonstrated in experiments with Lola is 3.34 [km/h] (see Fig. 5 (b)). This is slow compared to human walking, but still makes Lola one of the fastest electrically driven biped walkers. However, both Honda and Toyota have shown significantly faster running and Boston Dynamics has shown faster walking with a hydraulic biped (see Ref. [4] for a more detailed discus-

sion).

Autonomous, vision guided navigation has been a second area of research. Using a vision system developed at the Institute for Autonomous Systems Technology, University of the Bundeswehr Munich, we have demonstrated autonomous navigation in unknown environments using only onboard vision (see Fig. 5 (a) and Ref. [8]).

More recently, we have been addressing the issue of locomotion over rough, unmodelled terrain. Using a reactive replanning strategy Lola is capable of walking over 4 [cm] high, unmodelled obstacles (see Fig. 5 (c)).

5. Conclusion

We have given an overview of our recent work on biped robots. Lola was designed for fast walking experiments by optimizing the mass distribution, stiffness and kinematics of the system. The walking controller is implemented as a hierarchical system running on the onboard computer and local controllers. Real-time planning and stabilizing control allow the robot to quickly react to changing environments by replanning its steps, to resist external disturbances such as uneven terrain and to achieve fast and stable walking.

Acknowledgements This work is supported by the “Deutsche Forschungsgemeinschaft” (grant UL-105/29 and UL-105/34-1).

References

- [1] T. Buschmann, S. Lohmeier, M. Bachmayer, H. Ulbrich and F. Pfeiffer: “A collocation method for real-time walking pattern generation,” 7th IEEE-RAS International Conference on Humanoid Robots, pp.1–6, 2007.
- [2] T. Buschmann, S. Lohmeier and H. Ulbrich: “Biped walking control based on hybrid position/force control,” IEEE/RSJ International Conference on Intelligent Robots and Systems 2009, pp.3019–3024, 2009.
- [3] S. Lohmeier, T. Buschmann and H. Ulbrich: “System Design and Control of Anthropomorphic Walking Robot LOLA,” IEEE/ASME Trans. Mechatron., vol.14, no.6, pp.658–666, 2009.
- [4] T. Buschmann, V. Favot, S. Lohmeier, M. Schwienbacher and H. Ulbrich: “Experiments in fast biped walking,” 2011 IEEE International Conference on Mechatronics (ICM), pp.863–868, 2011.
- [5] M. Schwienbacher, T. Buschmann, S. Lohmeier, V. Favot and H. Ulbrich: “Self-collision avoidance and angular momentum compensation for a biped humanoid robot,” 2011 IEEE International Conference on Robotics and Automation (ICRA), pp.581–586, 2011.
- [6] S. Lohmeier, T. Buschmann, M. Schwienbacher, H. Ulbrich and F. Pfeiffer: “Leg design for a humanoid walking robot,” 2006 6th IEEE-RAS International Conference on Humanoid Robots, pp.536–541, 2006.

- [7] S. Lohmeier: Design and realization of a performance enhanced humanoid robot, Ph.D. dissertation, Technische Universität München, 2010. [Online]. Available: <http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20101126-980754-1-4>
- [8] T. Buschmann, S. Lohmeier, M. Schwienbacher, V. Favot, H. Ulbrich, F.V. Hundelshausen, G. Rohe and H.-J. Wuensche: “Walking in Unknown Environments—a Step Towards More Autonomy,” Proc. IEEE-RAS Int Conference on Humanoid Robotics (Humanoids), 2010.
- [9] T. Buschmann: Simulation and control of biped walking robots, Ph.D. dissertation, Technische Universität München, 2010. [Online]. Available: <http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20101201-997204-1-6>

Thomas Buschmann

Received his Diploma (2003) and Ph.D. (2010) degrees in M.E. from TUM, Germany. He has been a visiting researcher at Tokyo University (2003–2004). Currently he is working as a researcher and project leader for humanoid robotics at the Institute of Applied Mechanics at TUM. His research interests include walking robots, multibody dynamics and control.

Markus Schwienbacher

Received his Diploma (2007) degree in M.E. from TUM, Germany. He is a Ph.D. student at the Institute of Applied Mechanics. His research interests include walking robots, multibody dynamics, collision avoidance and control.

Valerio Favot

Received his M.Sc. (2007) degree in mechatronics engineering from Politecnico di Torino, Italy. He is a Ph.D. student at the Institute of Applied Mechanics. His research interests include walking robots, electronics and control.

Alex Ewald

Received his Diploma (2008) degree in M.E. from TUM, Germany. He is a Ph.D. student at the Institute of Applied Mechanics. His research interests include walking robots, multibody dynamics and control.

Heinz Ulbrich

Received his Ph.D. (1979) and habilitation dissertation (1986) from TUM, Germany. From 1979 to 1988 he worked as chief engineer at TUM. After a year as senior research fellow at NASA Lewis Research Center he was appointed as professor at first TU Braunschweig (1990), then at Essen University (1994) and the Institute of Applied Mechanics at TUM (2001). His main research fields are modelling, simulation, control and realization of mechatronic systems.