Obstacle avoidance in a simple hopping robot

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Abstract— **Obstacle avoidance in bipedal robots is achieved with the help of sensory feedback and closed loop control. Although computational power increased exponentially during the last years it is still the limiting factor for dynamic locomotion in uneven terrain. We introduce a simple robot architecture based on compliant leg behavior. With minimal sensory feedback we can derive stable 2D locomotion. By tuning a single parameter we can adjust the hopping height which can be used for obstacle avoidance.**

Keywords— **SLIP, robustness, stability, obstacle avoidance, hopping robots**

I. Introduction

For designing robots for legged locomotion it is mandatory to take in mind the natural paradigm. In most of the existing systems this has yielded a biomimetic approach ([1], [2]). In most of these biped robots rigid mechanics with joint actuators represent the muscosceletal system and stability is established with multiple sensor feedback and closed-loop control. A bionic approach for bipedal robots implies the identification of biological principles underlying legged locomotion and the transfer of these solutions into technical systems. Due to the enormous complexity of natural systems we have to remove the redundancy and have to keep the minimal setup for a desired behaviour. By building simple models for running and walking we explored the mechanics and the control underlying bipedal locomotion [3]. Especially for running robots a compliant leg design can enhance energy efficiency [4]. Additionally it provides a background stability which can be used in a technical system with minimal sensory feedback. In the following paper we will present the design and the control of a simple hopping robot based on compliant leg design.

II. Selfstability and leg retraction

The leg design of running and hopping robots is usually described by the spring loaded inverted pendulum (SLIP) model [5]. The SLIP model represents the dynamics of the contact phase with a point mass rebounding on a massless, linear spring. Although the stance phase dynamics of the model matches experimental observations, a natural swing-leg control leading to the touchdown angle is not predicted. However, previous simulations revealed that for a given system energy and leg stiffness the model shows self-stable behaviour when aligning the swing leg at a fixed angle of attack [6]. Stability is dramatically increased when implementing leg retraction during swing phase [7]. To accomplish this, leg retraction is started at the highest point during flight phase (apex) self-adapting the landing angle for different apex heights.

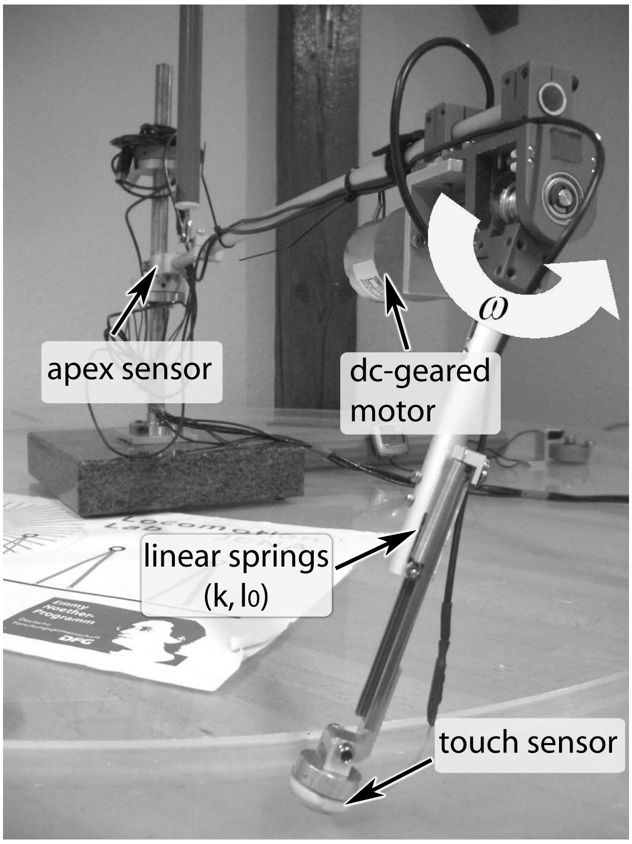


Fig. 1. Experimental setup for the SLIP based hopping robot.

III. Hardware

To verify this control strategy within a real robot we implemented the following setup. The design of our robot (mass $m = 0.35\,kg$, leg length $l_{0R} = 0.19\,m$) is shown in Figure 1. The leg consists of two aluminium parts connected by a passive prismatic joint with two linear springs in parallel. For the actual setup a spring constant of $k_{spring} = 120\,Nm^{-1}$ is used, leading to an overal leg stiffness $k_{leg} = 240\,Nm^{-1}$. The springs can be replaced easily to vary leg stiffness. The lower leg shaft slides along the upper leg supported by a linear ball bearing reducing friction. The foot is made of rubber material provided by Adidas (Adiprene+). This minimizes impact forces and improves ground stiction. For leg rotation (hip joint) a geared DC motor (RB-37GM) with a gear ratio of 1:100 and rated output of 3 W, equally representing the centre of mass is used. The motor is attached to a boom allowing only saggital plane motions (horizontal and vertical directions).

To distinguish between contact and flight phase we implemented a force-resistive touch sensor within the rubber foot. To detect when the robot reaches its highest point during flight(i.e. apex), we used an incremental sensor in the tilt joint between boom and base. For controlling the hip angle a second incremental encoder is fixed at the motor shaft. The sensory signals (contact, apex and hip angle) are fed into a Fujitsu micro controller (MB90F867). The hip angle sensor is sampled at 1 kHz. For the contact and apex sensors a sample rate of 100 Hz was sufficient.

The pulse width modulation signal (abbr. PWM) generated by the Fujitsu micro controller is fed into a motor amplifier driving the hip actuator. A host computer running Matlab version 7.1 (The MathWorks Inc.) is connected via the serial interface to the micro controller. This link is used for compiling code and to change parameters online during operation (see Figure 2). For easy adjustment of control parameters a graphical user interface was implemented in Matlab.

To allow stationary conditions for measurement a turning treadmill with adjustable speed is installed. A long suspension spring connected to the boom allows reductions of the effective gravity. Changing the effective gravitational acceleration has a direct influence on the dynamic parameters of the whole system. For example simulating reduced gravity will lower the stride frequency and the compression of the leg.

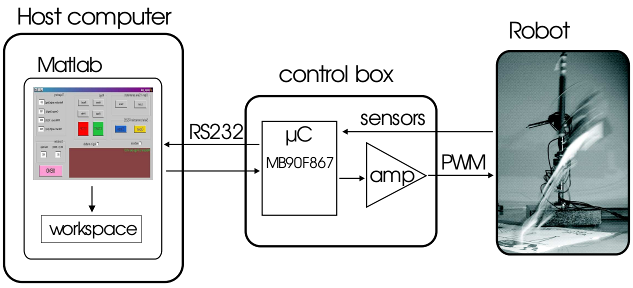


Fig. 2. The computer and signal structure for controlling the robot. The real time control loop comprises the control box and the robot. Parameters can be updated via the RS232 interface.

IV. Control

The control scheme is divided into three parts (see Figure 3). After starting at an initial leg retraction angle α_R at apex, the leg swings backwards with a given rotational velocity protocoll. The leg angle trajectory can be linear

$$\alpha(t) = \omega * t + \alpha_R \qquad t \geq t_{apex} \tag{1}$$

or nonlinear. Any trajectory within the limitations of the motor can be implemented. To achieve this, the actual leg angle α_{actual} at each sampling point of the trajectory is compared to the desired angle following PD control:

$$PWM = K_p(\alpha_{desired} - \alpha_{actual}) \tag{2}$$

where PWM correponds to the applied motor voltage and K_p is the gain factor. When the leg touches the ground the stance scheme is activated. In the SLIP model, hip torque is zero. In the current construction the leg can not be decoupled from the motor. For minimizing the influence of the hip motor on the robot dynamics the PD control is replaced by applying a constant voltage during contact compensating energy losses during the cycle of steady state running. After take-off, the leg approaches the retraction angle α_R in preparation of the next apex.

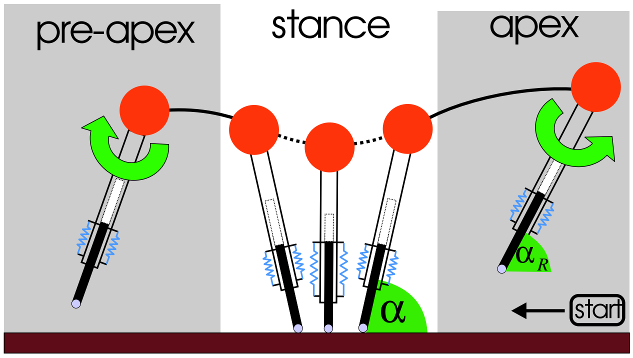


Fig. 3. Leg retraction is applied during the apex-phase untill the robot touches the ground (stance phase). After take-off, the leg is protracted to reach the apex leg angle.

V. Experiments

A. Stable hopping at slow forward speed

For running with a fixed angle of attack α_0 the model (leg length $l_{0M} = 1\,m$, $g = 9.81\,ms^{-2}$ predicts minimum forward speed $v_{model} = 3\,ms^{-1}$ resulting in stable solutions. Expressing this number as the dimensionless speed $\tilde{v} = v_{model}/(\sqrt{l_0 g})$ we can directly compare it to our robot with a leg length $l_{0R} = 0.19\,m$ and $g_{susp} = 3\,ms^{-2}$. Whereas in the human-like model the minimal dimensionless speed $\tilde{v} = 0.96$, the comparable abolute speed for the smaller suspended robot yield to $v_{robot} = \tilde{v}\sqrt{l_{0R}\, g_{susp}} = 0.72\,ms^{-1}$. By implementing linear leg retraction (see equation 1) at speeds lower than $v_{robot} = 0.72\,ms^{-1}$, periodic steady state running is approached. When switching off retraction the running pattern became unstable. Although the robot did not stop completely, due to the motor momentum during stance phase, a fixed angle of attack increased the impact at touchdown and the leg angle swept during stance phase became asymmetric with respect to the vertical. However, even with leg retraction we could not observe completely symmetric contact phases. Only without effective motor torques during stance phase the robot motion could fit to the model kinematics.

B. Leg retraction for overcoming obstacles

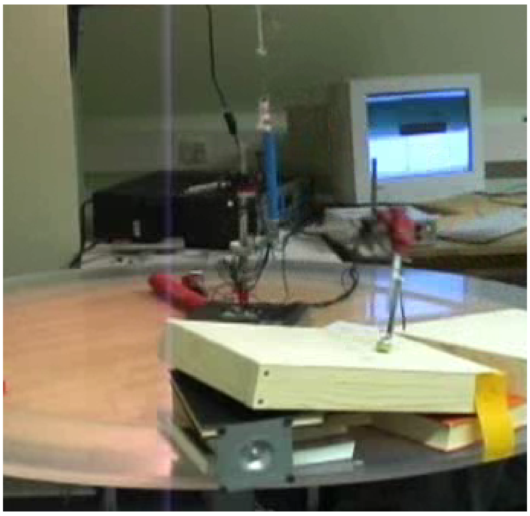
Proper adjustment of the angle of attack is crucial for distributing the mechanical energy of the flight phase into elastic energy of the spring and kinetic energy. If the leg touches the ground in a too flat configuration the spring compresses to much, taking forward energy out of the system. The robot will slow down. If the angle of attack is too steep, missing enough leg compression will lead to flat flight trajectories where the ground clearance of the foot is not sufficient to swing forward. Stepping over large obstacles (with contact on the obstacle) will change the system energy of the robot. With a fixed angle of attack stable locomotion can only be achieved for very small changes in system energy. Retracting the leg following equation 1 adapts the angle of attack depending on the duration of the flight phase. Figure 4a shows a slope integrated in the experimental setup. When the robot jumps off the obstacle the increased system energy is redistributed by using a steeper angle of attack. Following equation 1 the angle of attack increases linearly with the length of the flight phase. With this simple control strategy the robot can overcome obstacles and after few steps return back to the original steady state running pattern.

C. Adjusting apex height for obstacle avoidance

As predicted by the simulation model, the apex height can be directly steered by the selected angle of attack α. For instance, by lowering the angle of attack the apex height of the flight phase can be increased. Following equation 1 this can be controlled by decreasing the apex leg angle α_R. As predicted, the robot changes apex height and can therefore adapt to different terrains. At even ground the robot can run with a low apex height (using a steep apex angle, e.g. $70°$) at higher locomotion velocity, whereas a higher apex height with better ground clearance is needed to overcome obstacles. As shown in Figure 4b, the robot can overcome obstacles about as high as its leg length.

VI. Conclusion

The robot demonstrates that it is possible to manoeuvre in uneven terrain with minimal sensory feedback taking advantage of the natural dynamics of the robot. This supports the theoretical control concepts based on the SLIP model. Although the real robot only approximates the SLIP model the main control strategies can be still inherited. In the next version of this robot high-power DC motors without a gear box will be used. This allows rotating the leg freely around the hip by switching off the motor. Only during a fraction of the stance phase the motor will be active to compensate energy losses due to friction. This approach simulates the function of the muscular system spanning the hip joint. Only if needed the muscle produce a joint torque allowing the system to exploit its own dynamics. Such behavior could also be imitated by using motor-controlled strings acting on the hip joint.



(a)

(b)

Fig. 4. Obstacle avoidance in the experimental setup. Figure 4a shows the robot overcoming a slope returning to steady state running afterwards (not shown). The robot can cope with obstacle of about the size of its leg length (Figure 4b)

In the present study, we could verify the concept of swing leg retraction in legged locomotion based on a robot system. We believe that simple control strategies with low sensory demands as shown here, could also be useful for the control design of more complex legged systems relying on compliant leg behaviour. This may not only hold for running but also for walking, where elastic mechanisms might equally be of importance [3].

References

[1] M. Gienger, K. Loeffler and F. Pfeiffer, Towards the design of a biped jogging robot., Proceedings-IEEE International Conference on Robotics and Automation 4, pp. 4140-4145, 2001.

[2] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura, The intelligent ASIMO: System overview and integration., IEEE International Conference on Intelligent Robotics and Systems 3, pp. 2478-2483, 2002.

[3] H. Geyer, A. Seyfarth and R. Blickhan, Compliant leg behaviour explains basic dynamics of walking and running., Proceedings of the Royal Society B: Biological Sciences, London, 2006.

[4] M. Ahmadi and M. Buehler, ARL monopod II running robot: control and energetics., Proceedings - IEEE International Conference on Robotics and Automation 3, pp. 1689-1694, 1999.

[5] A. Sato and M. Buehler, A planar hopping robot with one actuator: design, simulation and experimental results., in Proceedings of 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp 3540-3545, 2004.

[6] A. Seyfarth, H. Geyer, M. Guenther and R. Blickhan, A movement criterion for running, Journal of Biomechanics 35(5), pp 649-655, 2002.

[7] A. Seyfarth and H. Geyer, Natural control of spring-like running: Optimised selfstabilisation., in Proceedings of the Fifth Conference on Climbing and Walking Robots (CLAWAR02), pp 81-85, 2002.