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An Emulation Environment for the Development of a Vision-Based Virtual Walking Machine

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Abstract:
Smooth vision-based walking is a fundamental problem in legged locomotion. In this paper a virtual walking machine is emulated together with hardware-in-the-loop stereo vision components. A cascaded control structure to realize smooth machine walking is presented being applicable to various types of walking machines. The guidance system controls the walking process based on environment perception using stereo image processing. The controlled virtual walking machine is visualized in an augmented reality display. Experimental results in a prototype scenario are presented to validate the proposed emulation and vision-based guidance approach.

1 Introduction

Intelligent walking machines have the potential to find various applications in areas relevant to industry and society. They can be employed for inspection and servicing tasks in hazardous environments, e.g. in nuclear facilities, disaster areas or in outer space. Other applications exist in the household or in similar indoor and outdoor environments, which are typically designed to suit human locomotion requirements. In such situations the application of walking machines, in particular biped humanoid robots, seems to be much more appropriate than of wheeled robotic systems. Figure 1 shows a vision-based walking robot in a typical prototype scenario including obstacles, stairs, and a step trace.

In the past, research activities were mainly focused on the design, simulation, stabilization and construction of various types of walking machines (Fujimoto and Kawamura, 1998; Lee et al., 1998; Chevallereau et al., 1997; Laci et al., 1996; Arakawa and Fukuda, 1997; Kanehiro et al., 1996; Inaba et al., 1996). Today, there exist many robots which can walk in more or less structured environments. They even have the capability to avoid or surmount simple obstacles or to climb stairs. A more recent and rather advanced example of a biped humanoid walking machine is P2, developed by the Honda company (Hirai,

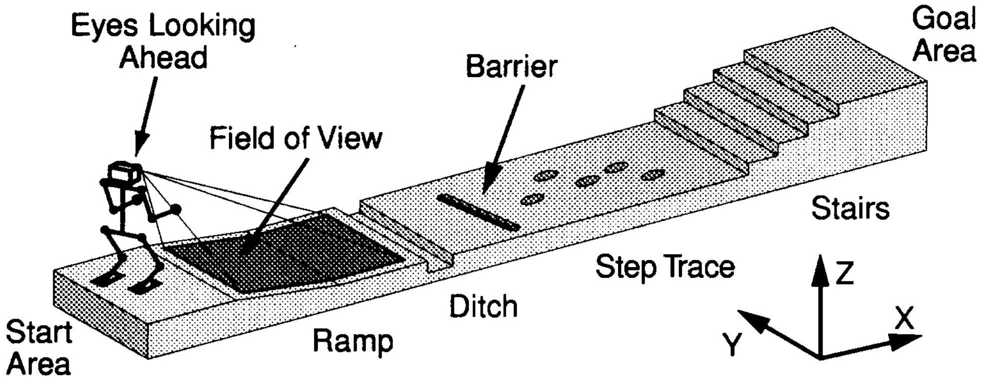

Figure 1: Vision-based walking robot in prototype test scenario.

1997; Hirai et al., 1998), and the new version P3. These robots show mobility features which are rather close to human locomotion capabilities.

However, there still remains a most prominent difference between current robotic and biological or human walking. Human walking is typically goal or task-oriented, i.e. locomotion is guided and controlled by visual perception to achieve task goals according to the underlying intentions. This capability can hardly be found in current walking machines. Even P2, which is equipped with a set of cameras, does not seem to make use of visual information for navigation, guidance, obstacle detection and avoidance, or the selection and adaptation of situation-dependent walking patterns. It is noteworthy that past robotics research has shown only minor interest in studying the important relationship between locomotion and vision, although it seems to be a key issue in the development of an intelligent autonomous walking robot. Some ideas in this direction have been reported by (Pack, 1996; Hosoda et al., 1997; Kagami et al., 1998).

This article is concerned with issues of vision-based guidance and control of walking machines. For this purpose, both, systems and algorithms are required to perceive and analyze the environment, plan and execute steps for safe and efficient walking. With P2, Honda has shown that major mechanical and control problems even for humanoid walking robots have been solved.

Consequently, in this article we propose a novel emulation environment to support studies on vision-based goal-oriented walking. Head and thereby resulting camera motions of a computer simulated walking machine are emulated in a real environment. Information of visual perception and of image processing are coupled with this virtual walking machine—VWM. Its operation is visualized in an augmented display, where an image of an external camera observing the environment is overlayed with a virtual 3D visualization of the VWM.

Section 2 of this article describes major research directions in vision-based walking machine guidance and control. The emulation of the kinematically simulated walking motion for hardware-in-the-loop experiments and the overall system architecture is discussed in Section 3. An algorithm for adaptation of the walking pattern as a result of the information provided by a stereo camera pair is presented in Section 4. Experimental results confirming the usefulness of the emulation approach for the development of control algorithms towards perception-based goal-oriented walking are given in Section 5.

2 Research Directions

The overall objective of our research is the development of a vision-guided humanoid walking robot with the capability to walk safely and smoothly through a prototype environment as shown in Figure 1. To solve this challenging we propose the cascaded control structure shown in Figure 2.

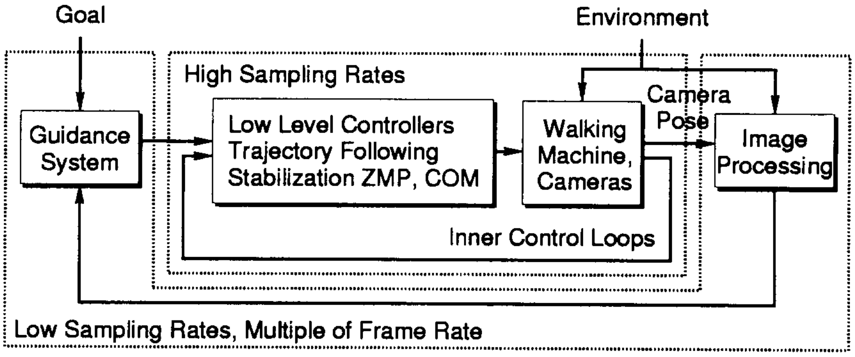

Figure 2: Vision-based walking control system.

Control Approach

The *inner loop* employs a trajectory following controller for each joint of the walking machine operating at high sampling rates, typically 100 – 1000 Hz. Joint reference trajectories are currently computed from desired step length and height by inverse kinematic models combined with heuristic insight. These step parameters are the control input to the *inner loop*, which also has to stabilize the pose of the walking machine by controlling its zero moment point—ZMP and its center of mass—COM (Hirai et al., 1998; Fujimoto and Kawamura, 1998).

The *outer loop* implements the guidance system to realize goal-oriented locomotion of the walking machine by reacting to information sensed by the vision-based environment perception module. The *outer loop* typically operates at lower sampling rates derived from the camera frame rate. The image processing algorithms form the sensing part of this *outer loop* and are further discussed in Sections 3.6 and 4.

For the development of a vision-based walking robot the understanding of this cascaded control loop is of utmost importance. To facilitate development and evaluation of such a guidance control scheme — although a physical walking machine hardware is currently not available in our laboratory — we propose to use an hardware-in-the-loop emulation approach presented in the following.

3 Emulation of a Virtual Walking Machine

As part of the walking machine emulator an ideal simulation of the *inner loop* including all dynamical effects of the walking machine mechanism and its interaction with the environment — such as contact situations between feet and objects — would be required. This simulation would deliver realistic head/camera motions of the walking machine as a result of the controlled walking process. However, hardware-in-the-loop experiments require on-line simulation of the *inner loop*, which currently seems to be unfeasible for non-simplistic mechanical models due to the neccessary computational effort and in lack of suitable on-line applicable numerical integration algorithms.

In our emulation approach the *closed inner loop* behavior is therefore approximated by a pure kinematic model. This somewhat ideal assumption means that the controllers in the *inner loop* work perfectly and that there is no uncontrolled, unknown or undesired head movement. More realistically one would expect residual head motion as the result of imperfect controller performance. Here, we substitute these residual motion by typical human head movements measured during human walking experiments.

Figure 3 shows the architecture of the emulator consisting of the VWM simulation part, the head motion generation part using a mobile platform and the augmented reality visualization part.

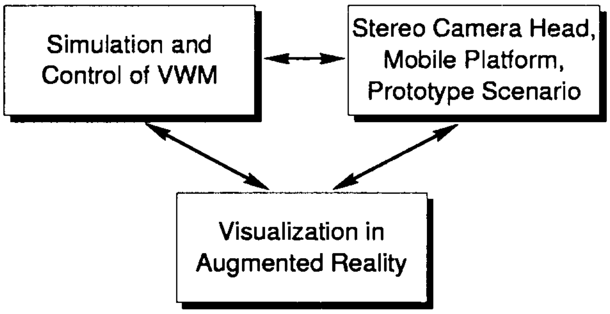

Figure 3: Emulator architecture.

3.1 VWM Kinematics and Scenario

The kinematic model of the VWM including 10 degrees-of-freedom (DOF) is shown in Figure 4. The walking scenario similar to Figure 1 has been physically built including prototype obstacles. It comprises 5 obstacle modules, which can be arranged arbitrarily into different configurations. To keep this experimental setup manageable in our laboratory, all components, such as the height of the VWM, stair height, stair depth etc., are scaled down by a ratio 3 : 2. This means that the VWM height is 1.2 m as compared to the 1.8 m height of a standard male. Consequently the stereo camera system is located approximately 1.12 m above the ground.

3.2 Human Head Motion

To get an estimate of motion patterns to be expected, the head motion of a human during two forward steps over flat terrain is shown in Figure 5. The data[1] shows, in contrast to vehicle motion, that walking motion in the vertical direction and rotation around the longitudinal-axis is substantial and cannot be neglected. The rotational motion is approximately sinusoidal with an amplitude of 5° and a walking speed dependent frequency. The z-translation shows the double frequency with an amplitude of 20 mm.

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[1] This data was provided by E. Hartmann, Neurological Clinic Bad Aibling and C. Lutzenberger, Technische Universität München and is in good correspondence to other biomechanical studies (Perry, 1992).

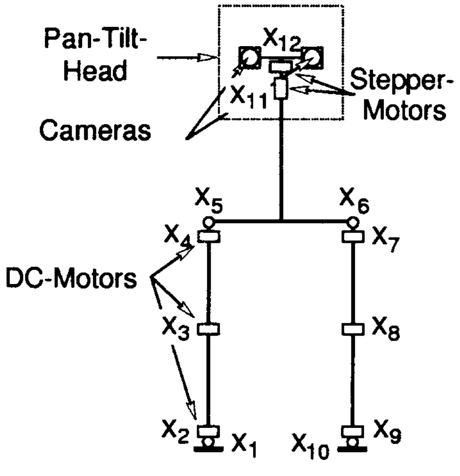

Figure 4: VWM kinematics and actuators.

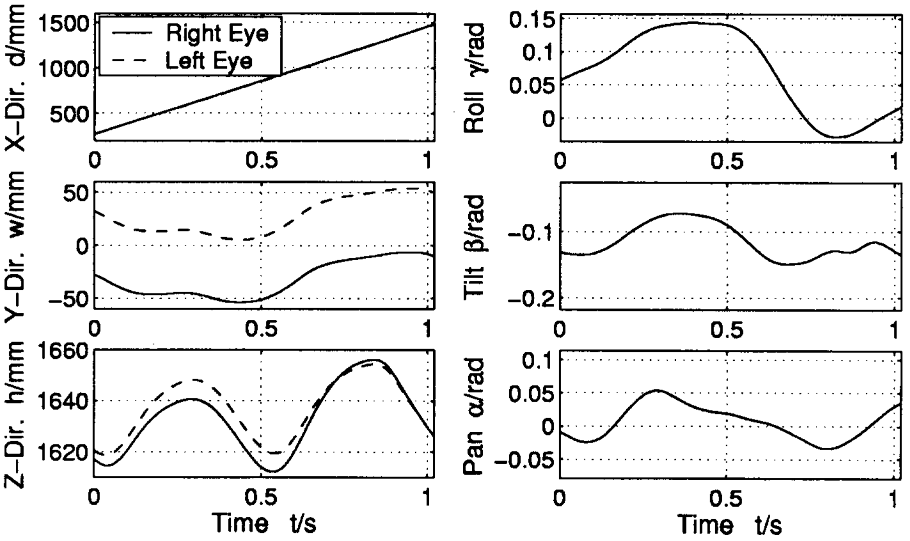

Figure 5: Head motion during human walking with a forward speed of 1.22 m/s.

3.3 Head Motion Emulation

Currently a wheeled mobile platform is used to carry the pan-tilt-head (PTU-46-17.5, Directed Perception Inc.) driven by stepping motors and a pair of NTSC-cameras (XC-999, Sony), see Figure 4 and left side of Figure 6. With the mobile platform for translation in x-direction and the pan-tilt-head for view direction — orientation around the y- and z-axis — the cameras can travel over the scenario and emulate the VWM head motion in 3 DOFs.

3.4 Augmented Reality Approach

To visualize the operation of the VWM, an image of an external scene camera observing the scenario is overlayed with a 3D-animation of the VWM, see Figure 6. Figure 7 shows the prototype environment including the VWM graphics overlay.

The results of a coupling of image processing data on the walking patterns are visualized

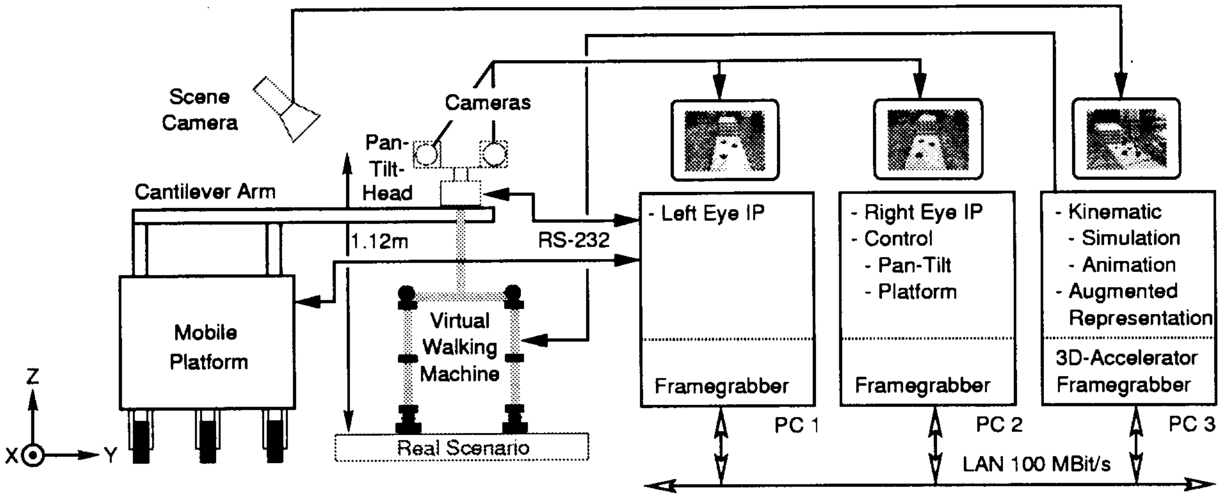

Figure 6: Overall system architecture.

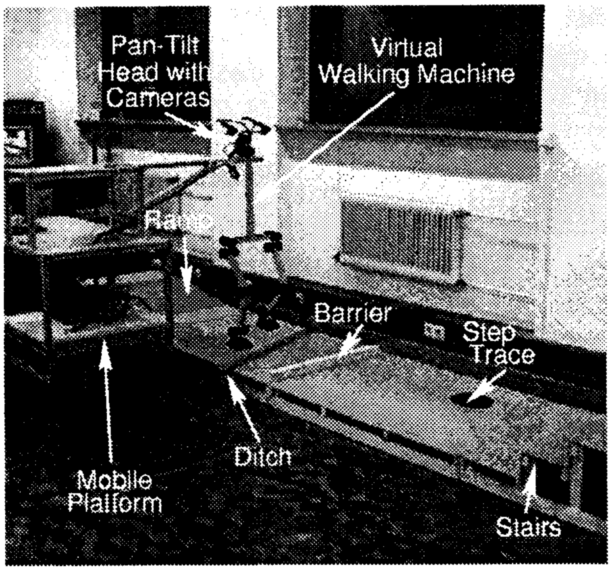

Figure 7: Experimental setup with the overlayed VWM.

by the VWM. Thus details of the walking process can be demonstrated. During an experiment the movement of the real camera-head above the walking trail and the gait of the VWM overlayed on the image of an external camera on a monitor can be observed simultaneously. As a result head motion of the VWM corresponds with the camera motion performed by the mobile platform and the pan-tilt-head.

3.5 Overall System Architecture

For all computations in the VWM emulator several standard PCs running the LINUX operating system are used. Computer communication is performed via sockets in a 100 Mbit LAN. Common frame grabbers with the bt848 chip and a Voodoo-II 3D-add-on-card are used. The 3D-animation procedures are implemented using OpenGL compatible software. All libraries and drivers are open source and freely available on the Internet.
To control the stepping motors of the pan-tilt-head the desired angles are transmitted via

a RS-232 interface to an external controller. The desired speed of the mobile platform ($< 0.8\,\mathrm{m/s}$) is also controlled via a RS-232 interface.

In agreement with the walking speed in x-direction as shown in Figure 5, the speed of the mobile platform is chosen to be constant. The trajectory calculation for the walking machine is performed in the augmented visualization PC. The joint trajectories are calculated as follows: assuming constant forward speed in both the head and hip of the VWM, the joint angles are calculated based on inverse kinematics. The free foot moves along a half sine curve while the other foot is fixed on the ground. Both foot trajectories describe alternating half sine curves.

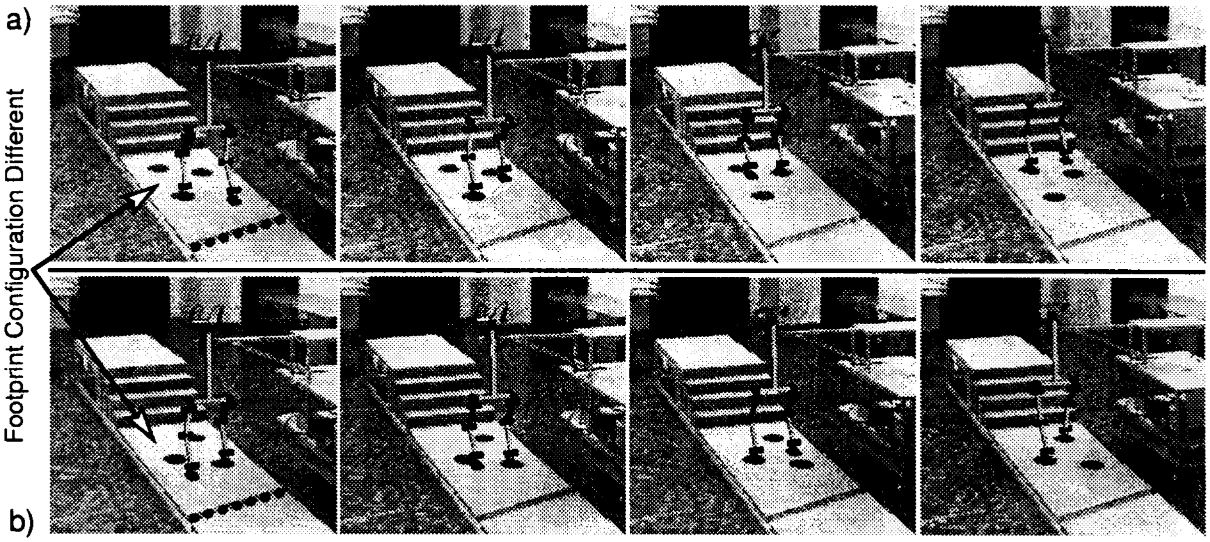

Figure 8: Step sequence over the scenario with obstacle configurations a) and b), both visualized with the external scene camera image overlayed with the VWM (ditch is shown as dotted line).

3.6 Image Processing Algorithms

Head and resulting camera motion in general may cause critical robustness problems for the image processing algorithms to be used in any vision-based walking robot. Elementary modules for image processing are already available as real-time image processing soft- and hardware. Currently we use XVision, a C++-library of image processing algorithms (Hager and Toyama, 1998).

All relevant features tracked in the image streams are initialized by the user at the start of an experiment. Therewith the stereo correspondence problem is also solved by specifying trackable features for each eye in the appropriate order. The results of the image processing algorithms (rather than raw images) are communicated among the PCs. Hence, image processing can be performed at camera frame rate with satisfactory 3D-reconstruction results.

4 Vision-Based Kinematic Step Planning

For vision-based step planning it is not sufficient to plan just one step ahead. Smooth walking requires planning of a sequence of steps. In addition physiological studies of human walking indicate that obstacle information provided by eye-vision is used in a feedforward control mode rather than in feedback mode (Patla and Vickers, 1997). In our experiments we chose a three steps ahead strategy. Based on the kinematic model of the walking machine the homogeneous transformation matrix $^{Foot(l,r)}T_{Cam}$ can be computed, which is used to translate a 3D-reconstructed obstacle in camera-coordinates into foot-coordinates of the actual fixed foot.

Like in biological walking it is not possible to adapt or change an already initiated step currently under execution by means of image processing results. For this reason the distance to an obstacle relative to the expected ground contact point of the swinging foot is computed. If the distance to an obstacle is less than the threshold of three times the normal (scaled) step length of 25 cm, 2 or 3 steps are sufficient to avoid the obstacle smoothly. The step planning algorithm is shown in Figure 9.

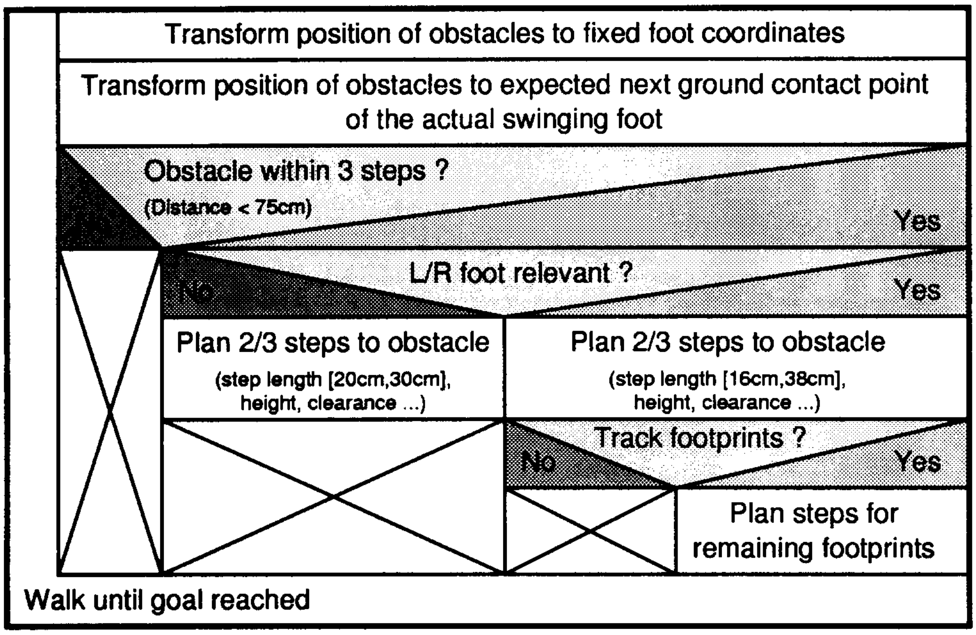

Figure 9: Step planning algorithm.

5 Experimental Results

While walking over the complete scenario in Figure 7 (see also Figure 1), the first 8 and last 8 steps are predefined. Hence, the slope with the following ditch are surmounted without the use of sensor information. Furthermore the distance of the stairs relative to the initial VWM position is assumed to be known *a priori*.

A vision-based adaptation of step parameters using the above step planning strategy is started 2 m after the initial position. It stops with the planning of the last 2 or 3 steps in front of the stairs. From this location the walking machine climbs the stairs in a predefined way.