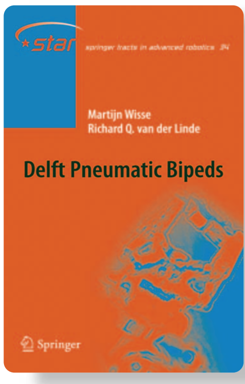
IEEE Control Systems Magazine welcomes suggestions for books to be reviewed in this column. Please contact either Michael Polis or Zongli Lin, associate editors for book reviews.



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Delft Pneumatic Bipeds

by MARTIJN WISSE and RICHARD Q. VAN DER LINDE

The field of bipedal robotics has grown to the point where one can identify several schools of thought on the subject. Most visible to the general public, and probably to most of the readers of this magazine, is the part of the field focused on building humanoids, robots that are inspired by human morphology. The best known of these robots is undoubtedly Honda's ASIMO. Other robots in this vein include HRP-2 (Kawada Industries, Japan) and Johnnie (Technical University of Munich, Germany). These machines are very complicated, high-degree-of-freedom prototypes built as part of an effort to develop robots that will be able to serve humans or even directly replace humans in the operation or service of other machines. These robots involve a broad-ranging development effort that includes machine vision, portable power sources, artificial intelligence, force sensing, durability, and packaging. As such, upright, stable bipedal locomotion is only one piece of the overall effort, and, largely for reasons of expediency, the designers of these robots have adopted one of the simpler notions of gait stability. For the robots mentioned above, the stabilization algorithm boils down to maintaining the center of pressure of the ground reaction forces of the stance foot strictly within the convex hull of the foot. The resulting walking motions are flat footed and distinctly not human like.

At the opposite end of the complexity spectrum in terms of technology are the "minimalist" bipeds, whose designers seek the minimal assembly of links, joints, sensors, and actuators that can accomplish a given locomotion task. This area of bipedal locomotion was inspired by the pathbreaking work of Tad McGeer, who, in the late 1980s and early 1990s, analyzed and built planar bipedal robots that can walk stably (in the sense of possessing an exponentially stable periodic orbit) down a slight incline with no sensing or actuation whatsoever. Such robots are termed "passive" because they employ no active power source other than the effort of the person who places them at the top of the incline. For these devices, walking is purely the outcome of the interplay between gravity and the geometric and inertia properties of the robot. The legs move freely as pendula under the influence of gravity, and, if their masses and lengths are tuned just right, they can produce stable periodic motions without any feedback control. Further impetus to this area was provided by Collins, Wisse, and Ruina with their three-dimensional (3D) (spatial) passive walker [1]. There is a general feeling in the robotics community that the walking gaits of passive robots seem natural.

THE BOOK

Passive walking is the starting point for the book under review. In the context of their Ph.D. research, Wisse and van der Linde constructed at Delft, The Netherlands, a series of five bipeds, starting with a McGeer-like planar, torso-less, passive walker and finishing with Denise, a 3D-biped with torso and arms, which uses arguably the simplest possible sensing, actuation, and feedback control system capable of achieving stable walking on a flat surface. Throughout the series of robots, the objective with each increase in electromechanical complexity was to characterize the resulting contribution to bipedal walking, in terms of enhanced capability, such as flat ground versus inclines, or spatial versus planar walking, and enhanced stability, in terms of a larger basin of attraction and the ability to tolerate deviations in the walking surface without falling. The authors have an interesting and coherent story to tell. While the book is based on their dissertations, they have done extensive rewriting and editing to arrive at a very compact, informative, and enjoyable presentation of their work.

Chapter 1 provides some of the basic motivation for research on bipedal robots and gives a terse but adequate summary of the state of the art. Chapter 2 provides an excellent technical summary of the passive walking literature, with ample citations. The hybrid nature of bipedal walking models is explained, and the primary mathematical tool for evaluating the existence and stability of periodic orbits, namely the Poincaré map, is reviewed. The authors confirm their mastery of McGeer's work by successfully building their own version of his famous robot. The chapter concludes with a discussion of useful tips for passive robot construction.

Chapter 3 focuses on the practical design and dynamic characterization of pneumatic actuators, in the form of McKibben's muscles, for bipedal robots. The McKibben's

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muscles are arranged in antagonistic pairs and used to actuate the sagittal-plane hip motion of a 3D biped named Baps; two additional muscles provide leg extension at the "prismatic knees." Sensing consists of a single gyroscope. A stable rocking motion in the frontal plane was sought through a shaped foot as in [1]. This 3D powered robot achieves autonomous walking on flat ground but falls frequently, just like the purely passive walkers. The authors attribute this behavior to the sagittal plane (fore-aft) motion not being sufficiently synchronized with the frontal plane (side-to-side) motion.

This experience motivates a return to planar bipeds in Chapter 4, where Mike is designed with the aim of avoiding falls in the forward direction. The authors start by providing numerical estimates of the basin of attraction of walking motions for the simplest walking model and thereby identify possible failure modes of falling forward or backward. Inspired by stability studies of the rimless wheel, a swing-leg control strategy is considered. Its purpose is to diminish the possibility of falling forward by rapidly placing the swing leg at a proper angle in front of the stance leg; to avoid falling backward, though, the swing leg should not be placed too far in the front of the stance leg. Despite the fact that this strategy does not address the problem of falling backward, it dramatically enhances stability; in fact, without swing-leg control, the basin of attraction is 0.3% of the basin of attraction with swing-leg control. The authors successfully implement this control strategy on Mike by alternating the states of antagonistic pairs of McKibben's muscles located at the hip based on feedback from foot contact sensors responsible for detecting heel strike.

Chapter 5 presents Max, which is a planar biped similar to Mike, but this time a torso is included. The authors start by analyzing an extension of the simplest walking model that includes an inverted pendulum attached at the hip representing the torso. Through this analysis, it is deduced that, with the upper body slaved to be at the middle of the two legs by means of a suitable holonomic constraint, stable walking can be achieved. Surprisingly, the model reveals that walking with an upper body is almost twice as efficient as walking with no upper body, while changes in the mass and size of the upper body have little effect on stability. Consistent with the spirit of passive dynamic walkers, the authors use a passive, mechanical means, namely, a bisecting mechanism, to keep Max's torso upright. Actuation is included to inject the energy required to compensate for losses at heel strike and to enhance stability in the sagittal plane through rapid recirculation of the leg, just as was done in Mike. The control system requires feedback only from foot contact switches triggering the hip actuators and releasing the knee latches of the swing leg at the early stages of the protraction phase.

Chapter 6 concludes the story with the 3D biped Denise. Here, the focus is on extending passive walking in three dimensions and achieving stability in the frontal plane, that is, side-to-side stability. Contrary to most of the 3D walkers, stability is not sought by weakening the coupling among the fore-aft, sideways, and turning modes of the robot's motion. Instead, the central idea is to take advantage of such coupling by specifically designing the ankle joint of the robot so that leaning to one side results in turning in that direction, which provides a restoring moment. This approach is consistent with the "passive dynamics" point of view, which seeks solutions that bring the unactuated dynamics of the system into effective use. The authors, after performing a series of simulations to elucidate their concepts, implement their ideas on Denise. By combining the swing-leg control strategy employed in Mike and the hip-bisecting mechanism developed for Max with the new ankle joint design that couples leaning with steering, Denise successfully demonstrates autonomous stable 3D dynamic walking on level ground. Like its ancestors, Denise exhibits natural motions combined with improved energy efficiency. The book ends with Chapter 7, in which the authors discuss next steps in their research program.

COMMENTS

In control-theoretic terms, Wisse and Van der Linde are emphasizing the proper design of the "bipedal plant" to make the control problem (that is, achieving asymptotically stable, periodic, bipedal locomotion) as easy and natural as possible. Feedback control is being used. For instance, implementation of the leg recirculation strategy to enhance sagittal plane stability requires event-based triggering of the hip actuators. Furthermore, feedback control laws are embedded through mechanical design into the morphology of the robots; for example, the hip-bisecting mechanism imposes (mechanically) a holonomic constraint, which essentially reduces the stability problem to one that can be addressed by the leg recirculation controller. Such mechanical solutions combined with minimal feedback control laws are consistent with the scope of this book, whose emphasis is on achieving energy-efficient walking on flat ground through the effective use of the natural dynamics of highly underactuated machines. The flip side of the coin is that these mechanisms exhibit a limited notion of locomotion. The remarkable elegance and economy of these walkers comes at the cost of poor ability in achieving tasks other than walking at a fixed speed, such as climbing stairs, standing, turning, or running. On the other hand, the impressive versatility demonstrated by robots such as ASIMO comes at the cost of increased power consumption, heavy actuators, and expensive electronics.

It is therefore natural to ask how the efficiency and elegance of the minimalist walkers can be combined with the versatility of robots such as ASIMO. In addressing this question, two issues are of central importance [2]–[4]. First, it must be determined which aspects of the behavior need to be embedded in the robot's structure and morphology, and which need to be implemented through software control, thus allowing for diverse behavior patterns. Second, novel feedback laws must be developed that work in concert with—and not against—the natural dynamics of the system in achieving stability and robustness of the implemented behaviors.

As soon as enough actuation is included to allow both slow and fast walking, walking on flat ground, climbing and descending stairs, running, and transitioning among these modes, nonlinear feedback control can play a key role in achieving stable, elegant, energy-efficient gaits [3], [5]–[8].

—Reviewed by Jessy Grizzle and Ioannis Poulakakis

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REVIEWER INFORMATION

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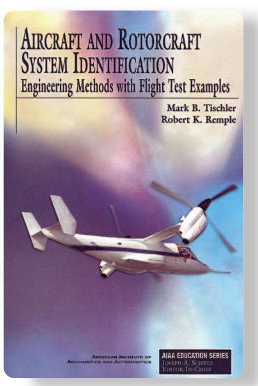

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Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples

by MARK B. TISCHLER and ROBERT K. REMPLE

I have always been amazed at the volume of quality research devoted to the synthesis of feedback control systems. There are many elegant theories for control designers to choose from, and virtually all of these theories begin with a model of system dynamics. In control theory, the plant dynamics are simply a given, a starting point for the successful design of a control system. But in the world of aircraft flight dynamics and control, development of the dynamic model is not at all trivial. Aircraft dynamics are driven by complex aerodynamic forces, and accurate models based on fundamental physics are not easily derived. Experimental data from wind tunnel testing and other sources is a valuable tool in dynamic model development, but quality test data are typically expensive and almost always incomplete. Some might even say that knowledge of the aircraft dynamics is more than half the journey toward the design and implementation of a successful control system.

System identification is the process of deriving a dynamic model through experimentation. Known inputs provide excitation of the system, outputs of the system are measured, and a model is derived that best represents the experimental data. The methodology has been applied to many different engineering and nonengineering disciplines to model dynamic systems. System identification is now a vital aspect of aircraft flight control design and testing. In fact, identified models of aircraft have many applications beyond control design, including validation and refinement of flight simulation models, structural mode analysis, and flying qualities analysis. Several textbooks cover the most common algorithms used in system identification [1]–[4], which serve as both references for practicing engineers and as textbooks for graduate-level courses. However, none of these texts focus on the specific application of identification of aircraft dynamics. Additionally, there are unique challenges associated with the application of system identification to aircraft, not the least of which are related to the inherent cost and risk associated with flight testing. Intelligent and *efficient* application of system

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