Dynamic Walking with Dribbel

Design and Construction of a Passivity-Based Walking Robot

BY EDWIN DERTIEN

This article describes the design and construction of Dribbel, a passivity-based walking robot. The robot has been designed and built at the Control Engineering group of the University of Twente. The current version of the robot can be seen in Figure 1. Passivity-based walking, or dynamic walking, is an approach to walking research focused primarily on the dynamics of the mechanical system used for walking; control and actuation come second. This article focuses on the practical side: the design approach, construction, electronics, and software design. After a short introduction of dynamic walking, the design process, starting with simulation, will be discussed.

Dynamic Walking

Tad McGeer started this field of research in the early 1990s with the design of totally passive (unactuated) mechanical walking constructions. His walkers were able to walk down a shallow slope without any form of active control or actuation. Based on the same dynamics principles, actuated (but still underactuated) walkers are being built today. These walkers can walk stably on a flat floor. Dribbel, the walker that is decribed here, has five joints, one of which is actuated.

Simulation

A number of simulation models preceded the working robot.

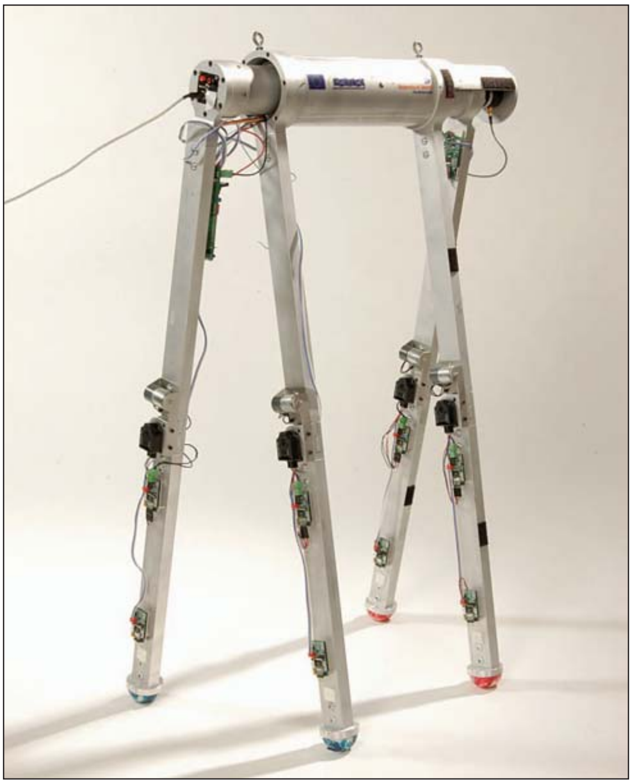

Figure 1. *The current design of the walking robot Dribbel.*

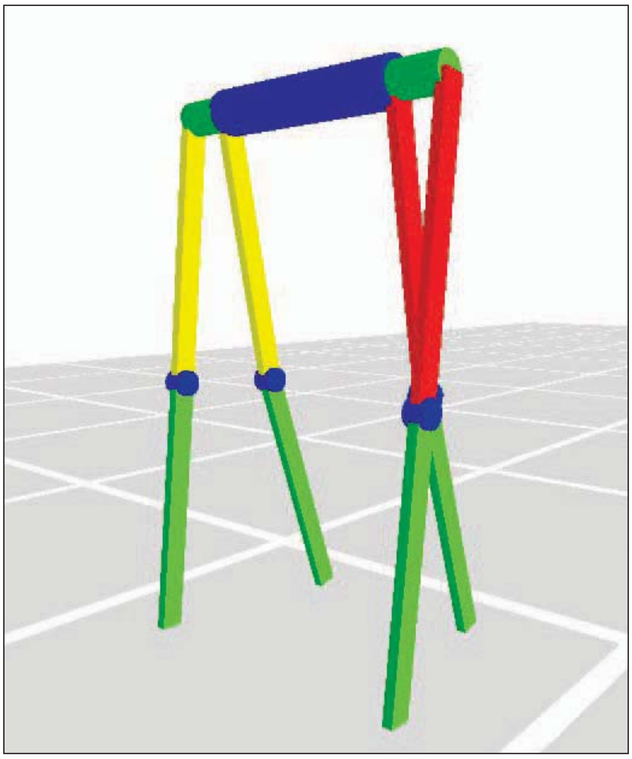

Figure 2. *Screenshot of the 3-D simulation model made with the 20-sim 3-D mechanics editor.*

First, a simple model investigating the basic weight distribution and power requirements for the robot was made. The size of the robot chosen was roughly at human size, with legs 1 m in length, a weight of roughly 10 kg primarily located in the hip. From this model, the required hip torque for the robot was derived, requiring peaks of 10 Nm.

Confident about the chosen components and sizes, a start was made designing the robot's mechanics in SolidWorks, while simulating the robots behavior in more detail in the simulation environment.

For the simulations, the power-port-oriented package 20-*sim* [5] was used. This package uses bond-graph notation (besides standard block diagrams and equations) in order to make power-continuous domain-independent models. For the three-dimensional (3-D) kinematics and dynamics, the special 3-D mechanics toolbox in 20-*sim* has been used, which provides the user with a simple drag-and-drop drawing interface for kinematic structures (see Figure 2). Internally, this package delivers equations using screw theory [4].

The model was used for testing the controller algorithm, testing the effect of adding extra battery weight, etc. After the mechanical prototype was built, the simulation model has been tuned to match the exact robot behavior so that with future experiments even more accurate predictions could be made based upon simulation results. Figure 3 shows the similarity between the hip angle in simulation and measurement after tuning the simulation.

In order to approximate the behavior of a purely passive mechanism, the desire was to build the actuated part backdrivable. With a geared motor, this is only possible by adding control. By means of a torque sensor, the hip joint can be controlled to a zero-torque state, in doing so acting as a complete passive joint. Other mechanical elements such as springs can be superimposed to this zero-torque system, emulating the behavior of a passive joint with springs.

Control

For the hip actuator in both the simulation environment and the real robot, a simple proportional-differential (PD) control algorithm is used: the setpoint for the controller is switched on foot impact. This simple control has been used by other powered "passive" designs [3]. By changing the setpoint and controller gain, the walking gait of the robot can be influenced. The controller is tuned to have a very weak action. The swing leg will reach the setpoint but will fall back immediately due to gravity so that the angle between the legs on impact is much smaller than the given setpoint. At the start of the swing phase, the controller gain can be seen as the spring constant of a passive spring connected between the stance leg and swing leg. The product of the setpoint and the gain is a measure for the amount of initial torque with which the leg is being swung forward.

Mechanics

The hip is the most important joint in this robot, being the only one actuated. The hip is thus designed around the main actuator: a Maxon RE40 150-W brushed DC motor with heavy (1:73) gearbox. The mechanical design of the hip consists of a 50-cm aluminium tube 6 cm in diameter. With large SKF bearings, an 8-cm-diameter tube is fitted around this tube. The outer legs are mounted on the inner tube, the inner legs on the outer tube. The motor is mounted in the inner tube, and the output power is transferred using an Oldham coupling, via a torque sensor, to the outer tube as can be seen in Figure 4.

The tubular design was chosen because a tube has the best known stiffness-to-weight ratio for a hollow object; it is a nice way to have mounting space for the motor and electronics while accomodating the joint. Not very scientific but equally important, it looks cool.

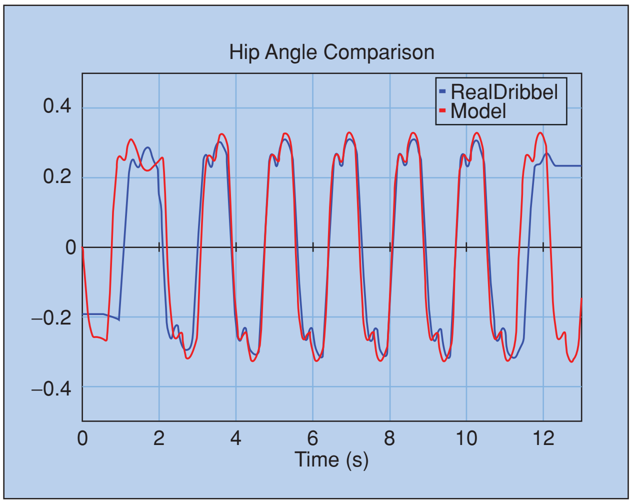

Figure 3. Hip angle during a short, straight walk in both the simulation and real robot.

The upper and lower legs consist of rectangular hollow aluminium bars that can be bolted onto snug fitting pieces on the hip tube, knees, and feet. All joints can be disconnected by simply removing four screws, so the design is very modular and allows for easy installment of different knees or feet modules.

Already two sets of feet have been tested: 1) simple measuring feet (including an encoder), which are critically damped, almost all energy is immediately lost on impact, and 2) also a set of more compliant feet has been designed and tested, resulting in a more efficient walking motion [7].

For the knees, a latching mechanism had to be designed. The first design consisted of a latching system where a solenoid had to retract a locking pin. This system failed terribly. When the leg was under stress, the solenoid could never generate the amount of force necessary to retract the locking pin. A quick-and-dirty solution was a completely different design using door locking magnets. This system required an opposite scheme of powering: active locking instead of active unlocking. Both of the mechanisms can be seen in Figure 5.

Electronics

The tasks for the electronic system consist of measuring, sensing, and control: measuring for evaluation purposes and sensing for the control system.

It was decided to use a distributed control network, where each joint and each foot has its own controller board that interfaces the HP5540-series encoders, switches, and solenoids at the joint. The board as used in the knees and feet is displayed in Figure 6. The boards are interconnected using a TWI bus (two-wire interface, also known as Philips' I^2C bus). Therefore, only four wires (including power supply) are needed to connect everything on the robot.

On the boards, Atmel ATmega8 RISC microcontrollers are used. These small microcontrollers are capable of nearly 16 MIPS at 16 MHz. Hardware and interrupt service for the TWI bus is already implemented inside the controller. The encoders are polled with a relatively high frequency (40 kHz), and the signals are encoded in quadrature. The maximum resolution for the standard HP55xx series is 500 ppr (pulses per rotation). In quadrature, this results in 2,000 ppr, yielding a resolution of 0.18°. Angular velocities are calculated using an Euler differentiation algorithm executed in the microcontroller. The AVR controllers were programmed using a propriarity C compiler from Codevision (http://hpinfotech.ro). The TWI routines from the AVR library from procyon (http://hubbard.engr.scu.edu/avr/avrlib/) were adapted for this compiler.

Testing and debugging the TWI system took quite some time, especially to get the correct responses to fault states on the bus. An Angilent 500-MHz oscilloscope with logic analyzer and I^2C support proved to be a very valuable tool in this process. A typical screenshot while debugging the communication between two modules can be seen in Figure 7.

For debugging purposes, on each board four light emitting diodes (LEDs) were placed, along with an RS-232 port, which can be connected to a terminal emulator on a PC.

The motor amplifier was designed to be connected by the same TWI bus, so the same microcontroller was used on that design. For the bridge amplifier itself, a custom H-bridge was designed using IR2110 half-bridge drivers. Safety-monitoring, temperature-sensing, and current-limiting functions are performed by the microcontoller. A central relay can be used to turn off the power stage. Also, an automatic fuse is added in the power stage. For noise-reduction spike-suppresion diodes, big chunky capacitors and a small snubber network were added.

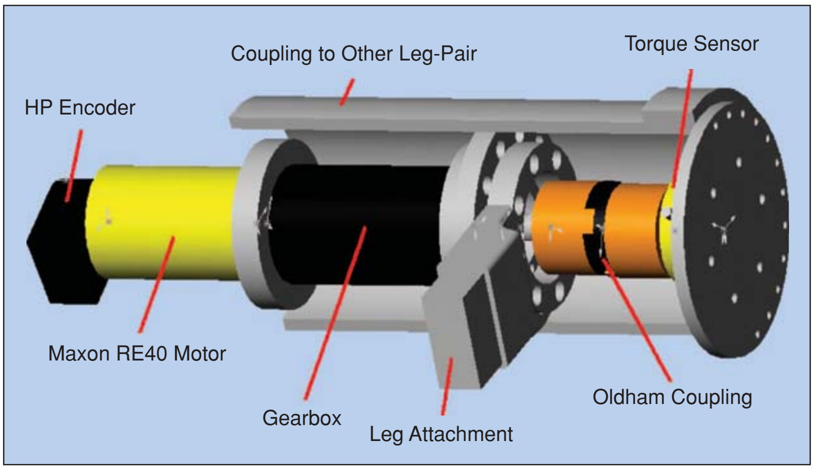

Figure 4. *SolidWorks drawing of the drivetrain.*

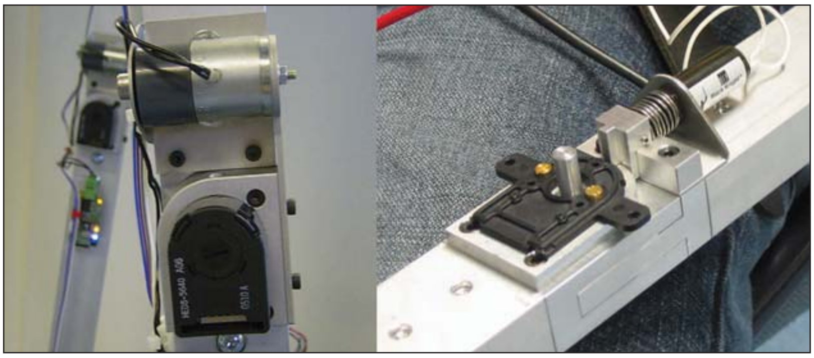

Figure 5. *The new knee-lock mechanism with locking magnet and the old mechanism with solenoid-driven retracting pin.*

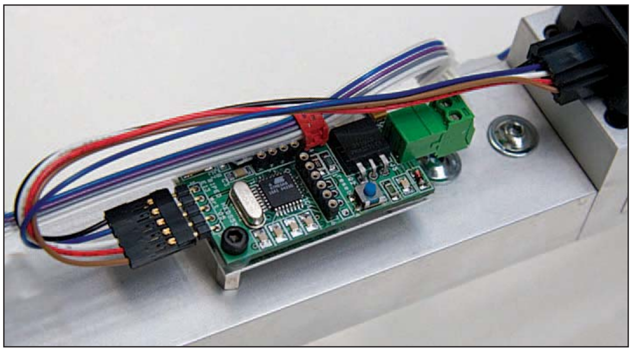

Figure 6. *The joint module located on the knee. This board interfaces the encoder, controls the knee-lock magnet, and is connected to the TWI interface using the four colored wires.*

The motor amplifier board interfaces with an HP55xx sensor mounted on the motor output shaft. The microcontroller executes a proportional-integral-derivative (PID) control loop at 1 kHz with setpoint and gain values recieved over the TWI bus.

The most difficult part regarding the motor amplifier was designing a printed circuit board (PCB) that could be fitted inside the tube with a diameter of 6 cm. Especially the heat sink, relay, capacitors, and power regulators had to be placed with care. After several attempts, even using cardboard mock-ups, a 5.5-cm-wide and 18-cm-long PCB design was made, containing all components. Figure 8 shows the breadboard design and the cardboard mockup.

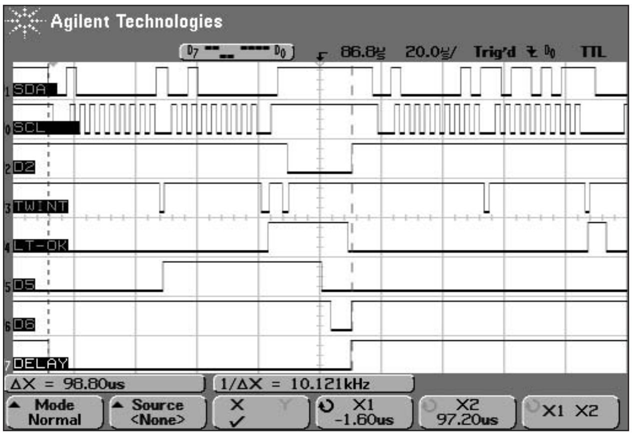

Figure 7. A screenshot of the oscilloscope displaying TWI bus data.

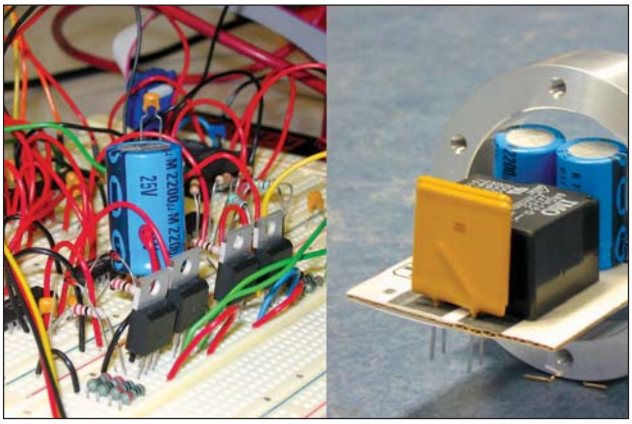

Figure 8. A working breadboard design of the 150-W motor amplifier and a cardboard mock-up of the PCB design.

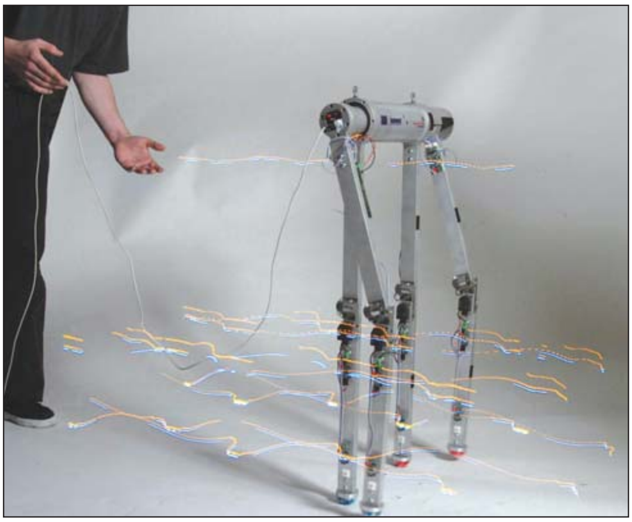

Figure 9. A time-lapse shot of the walking robot.

Besides the encoders for measuring all angles, a torque sensor was added in the hip joint too. A rotational torque sensor from TRT was incorporated in the mechanical design from an early stage. For this sensor, an interface containing a MAX1452 strain-gauge amplifier and again the ATmega8 controller was designed. Getting the MAX1452 amplifier stage (a clever chip with a lot of temperature and drift compensation possibilities) to work without the development kit proved somewhat of a challenge. The ATmega on board fulfilled the tasks of TWI interface and analog to digital (AD) converter and, using its serial interface, acted as a programmer for the MAX1452 IC.

The last microcontroller circuit (bringing the total to a staggering 11 microcontoller boards connected to the same bus) is used as central communication processor and main walking algorithm controller. It is dubbed the *brain-module*. This board is equipped with an ATmega128 running at 16 MHz. This controller acts as the TWI bus master, gathering status data from all slaves (joints, torque sensor, motor amplifier) and sending commands to the knee locks and motor amplifier. The brain-module can send a full robot state (all angles, switch status, power consumption, and torque) to a host PC with a rate of 100 Hz for data-logging purposes.

Experiments

At this time (May 2006), the robot has been walking around for almost a year. Most of the walking experiments took place in a cluttered lab where a stretch of 10 m (with the lab door open) can be used to let the robot walk. Figure 9 shows an open-shutter picture of the robot while walking. For the first tests, a safety line (sort of backyard-zip-line construction) was used. After some time, most of the students working and walking with it did not bother to fiddle with the safety lines, which resulted in some collapses. A well-established criterion for the stability of a walking robot is the distance between the robot and its designer during a test walk (attributed to Tad McGeer). However, the robot still survived all falls, with a couple of bent knee-caps and a broken encoder-casing being the main damage.

During walking experiments, the main controller executes the walking algorithm with preset values for gain and setpoint, while sending state information at 100 Hz to a host PC performing the data logging.

This setup has proven to be very effective for doing measurements. The main conclusion from the measurements, so far, is that the robot can walk with different gaits at different speeds. Regarding energy consumption, c_{mt}-values [1] as low as 0.06 have been measured, making it very efficient in comparison to other existing walkers.

Conclusions

The design trajectory as described here worked well. The parallel use of simulation and real-world testing yielded a good working prototype robot that is robust enough for the daily lab experimental work. The matched simulation models proved valuable in testing new controller algorithms and predicting the behavior of new mechanical additions, such as the compliant feet [7]. The robot can be used very reliably for doing various measurements.

Further Reading

The design and construction of the robot are discussed in more detail in the M.Sc. thesis of the author [6], which can be found at the publication section of http://www.ce.utwente.nl. The design and construction process has also been documented on the Web, at http://www.ce.utwente.nl/biped.

Acknowledgments

The design and construction of Dribbel has been a group effort: Niels Beekman, Gijs van Oort, Eddy Veltman, and Vincent Duindam contributed heavily to this project under supervision of Prof. Stefano Stramigioli. The work on walking robot systems at the University of Twente is performed at the IMPACT institute and located at the Control Engineering group of the faculty of Electrical Engineering.

Keywords

Passive dynamic walking, bipedal walking.

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INDUSTRY/RESEARCH NEWS

M.S.E. in Robotics at the University of Pennsylvania

The GRASP Lab at the University of Pennsylvania has announced a new Masters of Science and Engineering in Robotics. According to GRASP Director George J. Pappas, the academic mission of this exciting program is the education of next-generation engineers in the interdisciplinary science and technology of robotic and intelligent machines.

This multidepartmental, multidisciplinary program provides preparation for industrial jobs in robotics, defense, aerospace, medical device, and automotive industries as well as various government agencies. In addition, it provides a foundation for doctoral studies in robotics and related fields.

More details about the curriculum, application process, and deadlines, are at: http://www.grasp.upenn.edu/index.html.

New Robotics and Intelligent Machines Center at Georgia Tech

The College of Computing and College of Engineering at the Georgia Institute of Technology has announced the establishment of the Robotics and Intelligent Machines center (RIM@Georgia Tech), a new interdisciplinary research center that will draw on the strengths and knowledge of robotics experts from both colleges. According to robotics industry associations in North America and Japan, the global robotics market is expected to significantly expand over the next five years, including gains in both the service and personal robotics fields. Dr. Henrik Christensen, the first KUKA Chair of Robotics and distinguished professor in the College of Computing, will direct the new research center.

DARPA Challenge Moves to the City

The U.S. Defense Advanced Research Projects Agency (DARPA) announced plans to hold its third Grand Challenge competition on 3 November 2007. The DARPA Urban Challenge will feature autonomous ground vehicles executing simulated military supply missions safely and effectively in a mock urban area. Safe operation in traffic is essential to U.S. military plans to use autonomous ground vehicles to conduct important missions.

DARPA will award prizes for the top three autonomous ground vehicles that compete in a final event where they must safely complete a 60-mi urban-area course in fewer than 6 h. First prize is US$2 million, second prize is US$500,000, and third prize is US$250,000. The rules do not restrict the citizenship of any member of the team, except the team leader. All Urban Challenge events and meetings take place in the United States. Visit the DARPA Grand Challenge Web site: http://www.darpa.mil/grandchallenge.