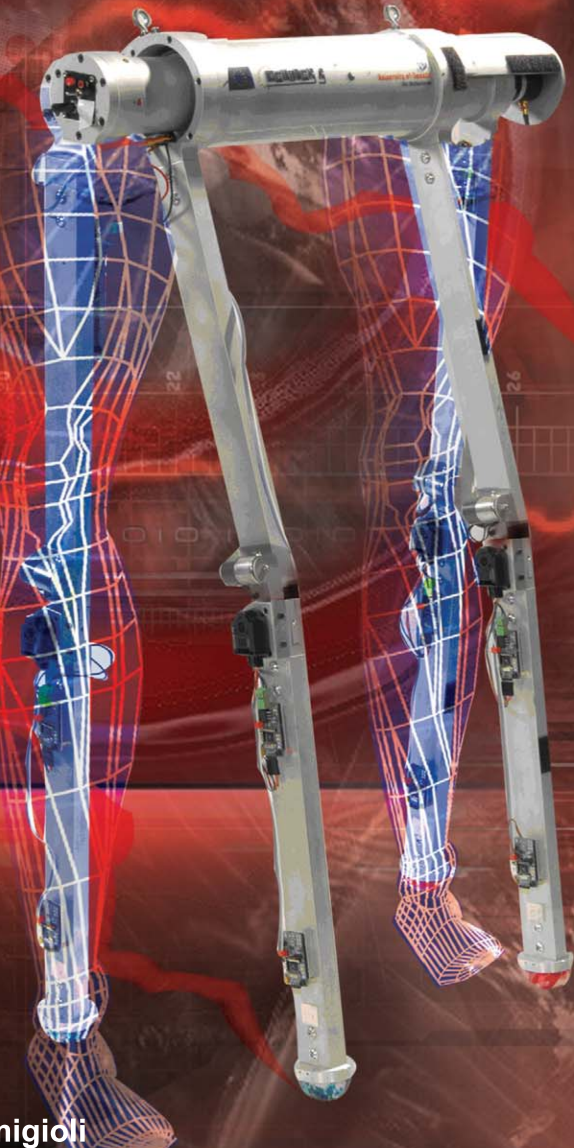
cover story

Controllab Products

Dribbel 10 kg robot walking on 16 penlites



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20-sim
The power in modeling

At the Control Engineering group of the University of Twente a lot of research is spent on various types of robots. This article describes the work on the design and construction of Dribbel, a passive dynamic walking robot. Dribbel is a '2D-biped': he can not fall sideways because four legs in a row are used (comparable to a person walking on crutches). This construction is chosen to focus on the forward motion, without having to solve the complex 3D stabilization.

Dynamic walking means that the motion of the robot is induced mainly by the internal dynamics of the machine. Active energy input by the actuators is only used to stabilize the motion or force the robot to increase its walking speed. The international naming convention for this type of research is Dynamic Walking. Passive dynamic walking means that a system must show a good walking from itself (passive) without feeding external energy, comparable to the motion of a pendulum. Human walking is an example of such a pendulum like motion.

The starting point for any dynamic walking robots is a simple pendulum. The goal is to realize a robust energy efficient walking motion. This is contrary to the well-known Japanese walking robots such as Honda's ASIMO, where all degrees of freedom are controlled by conventional, energy wasting actuators.

This article focuses on the practical aspects of the work on Dribbel: the design strategy, the mechanical construction and the electronics.

Dynamic Walking

The idea of using a set of pendulums to create a walking robot originates from the patents on toys in 1888. Real research was started by Tad McGeer in the early 1990s. His constructions were able to walk down a shallow slope without any form of active control or actuation. Based on these fully passive 'slope walkers' a number of robots have been built that do use actuators and control. Dribbel is one of these robots.

By using an motor in the hip, a slope is no longer necessary. The robot can walk on a level plane. The rest of the robot (knees and feet) are still fully passive.

Simulation

During the design of the robot, computer simulations have been extensively used. First some simple models were created to find the optimal weight distribution of the robot. The size of the robot was chosen 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 software package 20-sim 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 1). The interface of this toolbox is comparable to a 3D CAD environment. Internally, this package derives equations using screw theory. In 20-sim the resulting kinematics and dynamics model is coupled with the power interaction of the motors and the environment.

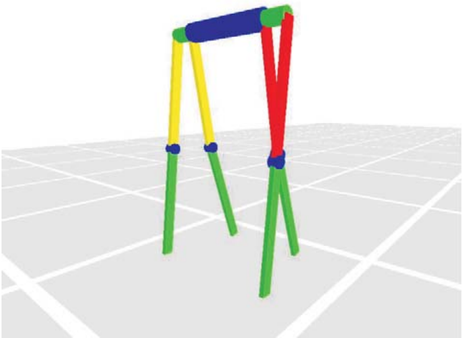

Figure 1: Screenshot of the 3-D simulation model made with the 20-sim 3-D mechanics editor.

The resulting model was used for testing the controller algorithm, testing the effect of adding extra battery weight, but also the effects of various materials on the foot soles. After the mechanical prototype was built, the simulation model has been fine tuned to match the exact robot behavior. For future experiments a very accurate model is available. Figure 2 shows the similarity between the hip angle in simulation and measurements during a test-run. Recently the simulation model has been extended with actuated ankles. The actuated ankles are currently added to the real robot and we hope to do test runs in the fall of 2007.

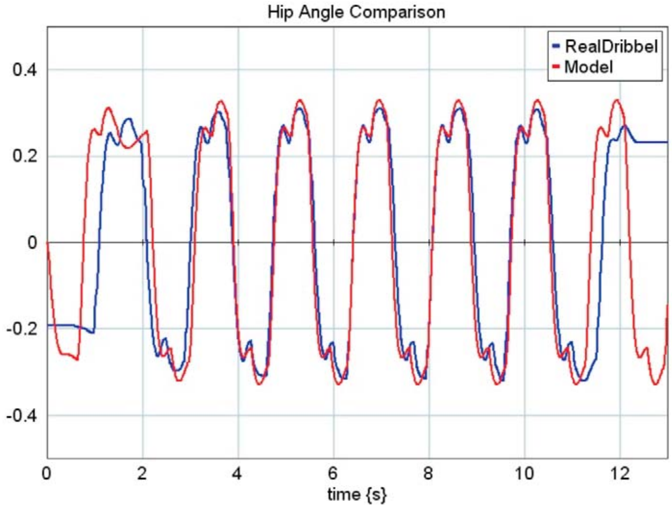

Figure 2: Hip angle during a short, straight walk in both the simulation and real robot.

Control

For the hip actuator in both the simulation environment and the real robot, a simple PD-controller is used. The setpoint for the controller is switched on foot impact. This simple control has been used by other powered “passive” designs. 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 can be seen as 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.

In order to create a pure passive mechanism with an electric motor, the mechanism must move freely when the motor is turned off (back-driveability). Although the gearbox has a high efficiency, some resistance is measured. Using a torque sensor at the right place and a proper control algorithm, this resistance can be canceled out. Using this 'zero torque' control algorithm, the combination of motor and gearbox behaves as an additional mass, without damping the motion.

Mechanics

The hip is the most important joint in this robot, being the only one actuated. The knees and ankles are passive joints. The hip is thus designed around the main actuator: a Maxon RE40 150-W brushed DC motor connected with a gearbox with a large gear ratio (1:73).

The mechanical design of the hip consists of a 50-cm aluminum 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 3. The tubular design was chosen because a tube has the best known stiffness-to-weight ratio for a hollow object. Moreover, it is a mounting space for the motor, gearbox and batteries.

The legs consist of rectangular hollow aluminum bars that can be bolted onto couplings to 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.

So far two sets of feet have been tested: the first feet where small and flat with a thin layer of anti-slip rubber glued to the sole. The second set had a thick layer of rubber. Simulations showed that the extra compliance of the second set results in a more efficient walking motion. This was verified by mounting a set of bouncing balls under the feet.

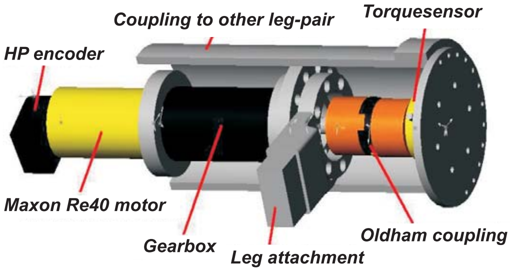

Figure 3: SolidWorks drawing of the drivetrain.

For the knees, a locking mechanism had to be designed. Although the knees are not actuated during motion, they have to be locked, as soon as the weight of the robot is carried.

The first design consisted of a locking 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 better solution was the use of door locking magnets. Although this solution is not energy efficient (during walking 70% of the energy is used by the locking magnets) is turned out to work very well. Both of the locking mechanisms can be seen in Figure 4.

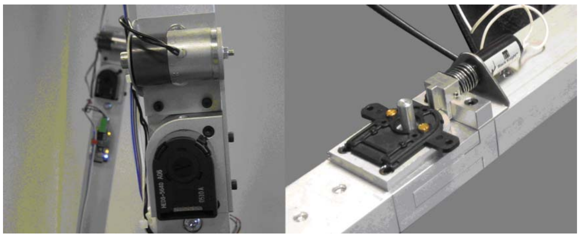

Figure 4: The knee-lock mechanism with locking magnet and the mechanism with retracting pin.

Electronics

The tasks for the electronic system consist of measuring, sensing and controlling the robot. A modulated distributed network is used on the robot. This will prevent the use of loose cables and allow to add extra modules and degrees of freedom afterwards.

Each joint has its own controller board to read the sensors (encoders and foot sensors) and steer the actuators (knee locking magnets). The boards are connected by a TWI bus (two-wire interface, also known as Philips' I2C bus). Therefore, only four wires (including power supply) are needed to connect everything on the robot, as shown in Figure 5. A frequency of 100 Hz is used to collect all data in the robot for the main controller. The internal data rate of the board is 40 kHz (see figure6).

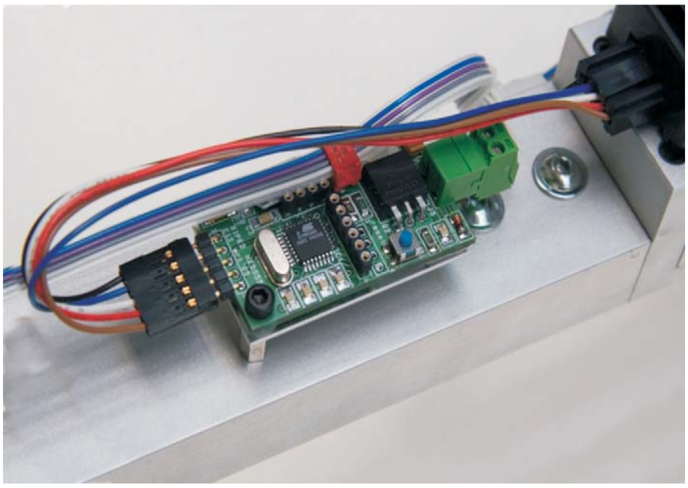

Figure 5: The joint module located on the knee. This board interfaces the encoder, controls the knee-lock magnet, and is connected to the TWI interface using the four colored wires.

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

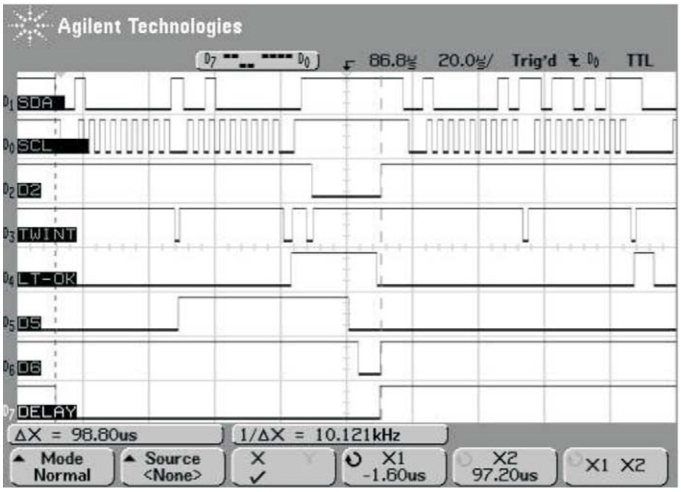

Figure 6: A screenshot of the oscilloscope displaying TWI bus data.

Each board contains four LED's to indicate the status of the board and an RS-232 port for communication and fault detection. The motor amplifier is connected to the TWI-bus, with the same ATmega8 microcontroller as used for the knee and feet joints. The motor amplifier consists of a custom designed H-bridge using IR2110 half-bridge drivers. Safety-monitoring, temperature-sensing, and current-limiting functions are performed by the microcontroller. 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-suppression diodes, capacitors and a small snubber network were added.

The hip motor uses the same HP5540-series encoder as used for the knees and feet. A PID control loop with an update frequency of 1 kHz is used to drive the motor. The setpoint and gain values are received 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 7 shows the breadboard design and the cardboard mockup. At the back of the motor a pack of 16 NiMh penlites has been placed. This pack can yield a voltage of 19, V and has enough capacity to let the robot run for more than 30 minutes.

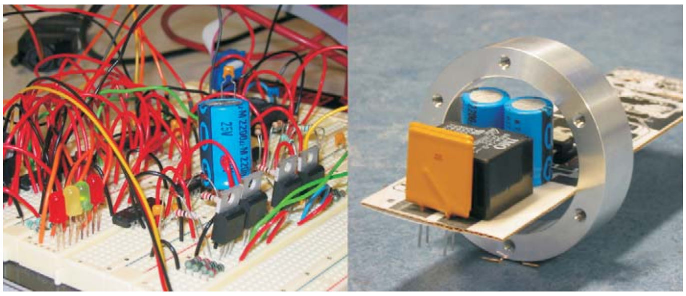

Figure 7: A working breadboard design of the 150-W motor amplifier and a cardboard mock-up of the PCB design.

Besides the encoders for measuring all angles, a torque sensor is used in the hip joint. For this sensor an amplifier board was designed that is connected with the TWI-bus. The system can also be coupled to the local SPI-bus of the motor amplifier, to implement the 'zero torque' control algorithm. For the torque sensor, an interface containing a MAX1452 strain-gauge amplifier and again the ATmega8 controller was designed. The ATmega on board fulfilled the tasks of TWI interface and analog to digital (ADC) converter and, using its serial interface, acted as a programmer for the MAX1452 IC.

The last microcontroller circuit (bringing the total to a total of 11 microcontroller boards connected to the same bus) is the 'brain' of the robot. It is used as central communication processor and main walking algorithm controller. 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 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. Data logging and analysis of the robot data is performed in 20-sim.

Experiments

The robot has been walking around for almost two years. Most of the walking experiments took place in a small laboratory where a stretch of 10 m can be used to let the robot walk. Figure 8 shows a time-lapse shot of the robot while walking. For the first tests, a safety line was used. The initial test boosted confidence in the stability and the safety lines were removed.

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). Some students overestimated the stability, causing the robot to fall on the ground before they could catch it. However, the robot survived all falls, with a couple of bent knee-caps and a broken encoder-casing being the main damage.

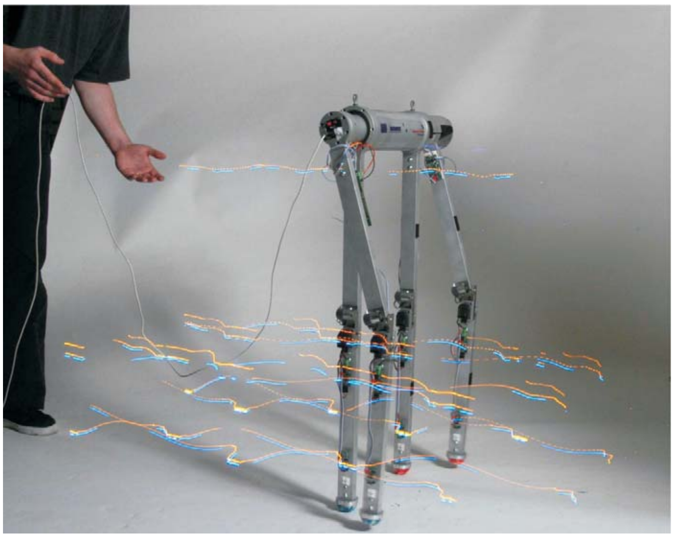

Figure 8: A time-lapse shot of the walking robot.

While being controlled by a single actuator, the robot can walk at various speeds, using various types of walking. The robot is able to walk with a power consumption of only 1.6 W. This makes the robot a lot more efficient than the Japanese ASIMO which uses around 100 W. To make a fair comparison, the efficiency of robots is expressed as the costs of energy to carry a certain weight over a certain distance. For Dribbel, this cmt-value is 0,06, which is very low, even when compared with other passive dynamic walking robots.

Conclusion

The design trajectory as described here worked well. The parallel use of simulation and real-world testing yielded a 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.

More Information

More information on the building and construction of the robot can be found on the web-site of Control Engineering (http://www.ce.utwente.nl). The progress of the walking robot can be monitored on the project website 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.