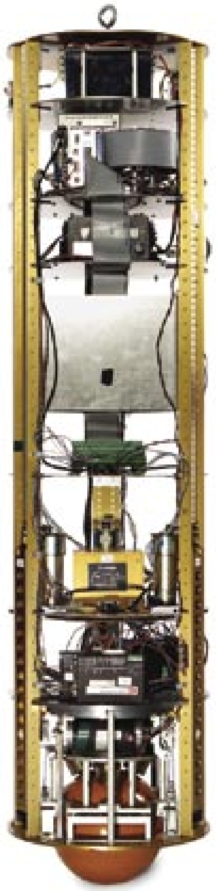
A new mode of locomotion will enable mobile robots to stand tall and move gracefully through busy everyday environments

BALLBOTS

By Ralph Hollis

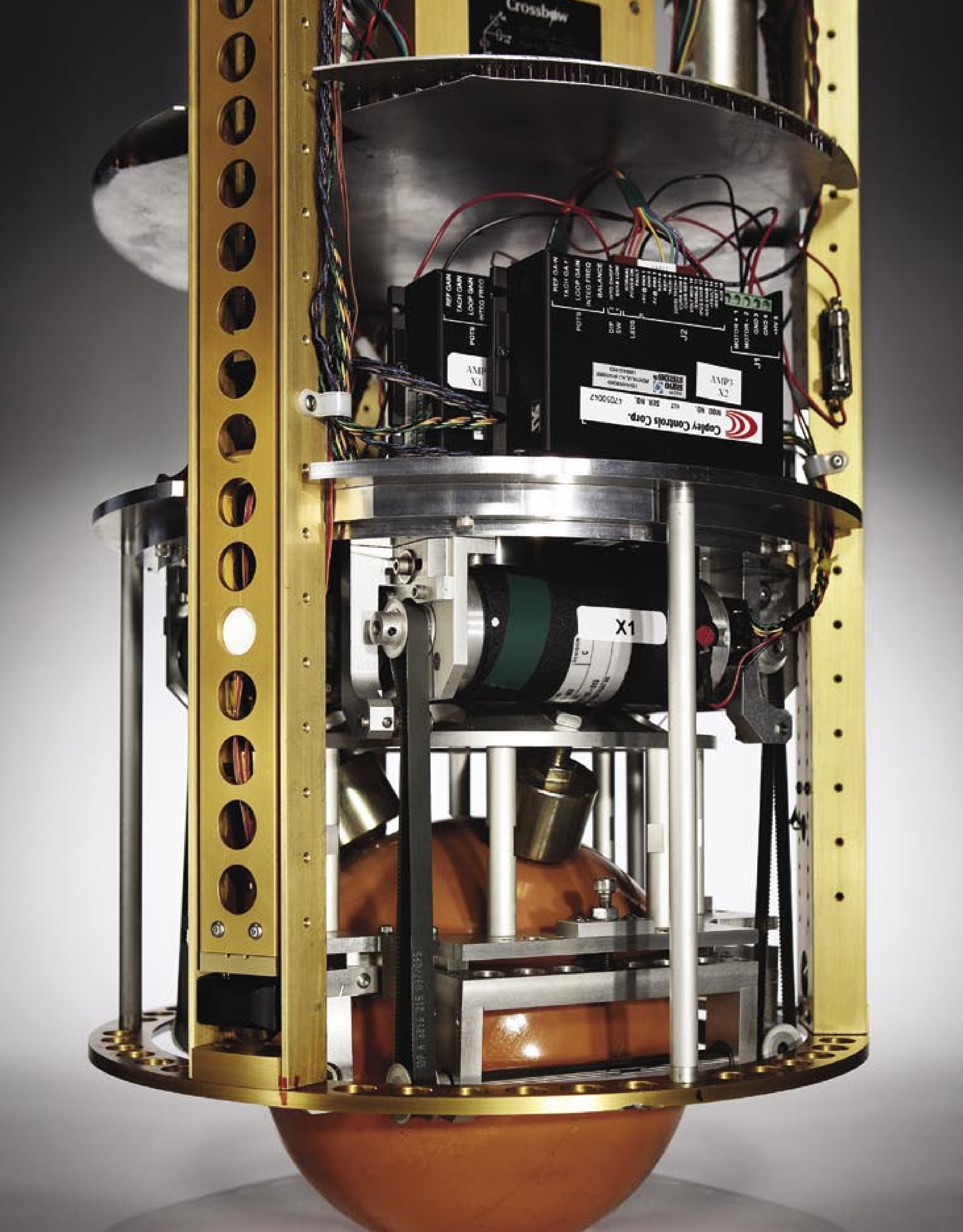
The dream of intelligent, mobile robots that assist people during their day-to-day activities in homes, offices and nursing facilities is a compelling one. Although a favorite subject of science-fiction writers and robotics researchers, the goal seems always to lie well off in the future, however. Engineers have yet to solve fundamental problems involving robotic perception and world modeling, automated reasoning, manipulation of objects and locomotion.

Researchers have produced robots that, while falling far short of the ideal, can do some remarkable things. In 2002 one group dropped off a robot at the entrance to the annual meeting of the American Association for Artificial Intelligence in Edmonton, Alberta. The clever machine soon found its way to the registration booth, signed up for the conference, was assigned a lecture room, proceeded to that location and finally presented a brief talk about itself at the appointed hour. Some robots have in the meantime served effectively as interactive museum tour guides, whereas others show promise as nursing home assistants. Computer scientists and engineers have also equipped mobile systems with arms and hands for manipulating objects. All these experimental devices travel



MOBILE ROBOTICS takes a different path with the ballbot's unique single, spherical drive wheel design.

BRIAN MARANAN PINEDA


Crossbow
AMP1 X1
AMP1 X2
Copley Controls Corp.
X1

about on bases supported by three or four wheels. Designers call this configuration “statically stable” because it keeps the robots upright even at rest.

Robots tall enough to interact effectively in human environments have a high center of gravity and must accelerate and decelerate slowly, as well as avoid steep ramps, to keep from falling over. To counter this problem, statically stable robots tend to have broad bodies on wide wheelbases, which greatly restricts their mobility through doorways and around furniture or people.

Several years ago I decided to sidestep the need for large wheelbases by designing and building a tall, skinny and agile robot that balances on, and is propelled by, a single spherical wheel. Such a simple machine, with its high center of gravity, would be able to move quickly in any direction. The system would rely on active balancing and thus be “dynamically stable”—that is, it would remain erect only if it made continual corrections to its body attitude. I realized this design would constitute a hitherto unstudied class of wheeled mobile robots. For lack of anything better I called it a ballbot.

My students and I have operated our ballbot now for more than a year, studying its stability properties and suitability for operating in human environments. During that time, many visitors to our laboratory have found its uncanny ability to balance and roam about on a single spherical wheel to be quite remarkable.

Maintaining Balance

WE HUMANS KEEP BALANCE with help from the vestibular senses in our inner ears. This information is combined with input from other senses, such as vision, to control muscles in our legs and feet to enable us to stand upright without falling down. A ballbot maintains equilibrium in a somewhat analogous fashion. First, the machine must have some goal to achieve, such as to remain in one place or to move in a straight line between two locations. Second, it must always know the direction of gravity’s pull and be able to measure the orientation of its body with respect to this vertical reference. Third, it must have means to rotate the ball in any direction and to measure its travel along the floor. Finally, the ballbot must have a method, or control policy, that processes the sensor data it measures to generate commands for ball rotation that attempt to satisfy the goals.

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Solving the “problem of the vertical” has proved to be a challenging exercise throughout history [*see box on page 76*]. Our solution takes advantage of tremendous recent advances in computing, fiber optics and microelectromechanical systems (MEMS) that have enabled the production of low-cost devices that emulate the function of the traditional spinning gyroscope.

We use a system that features three fiber-optic gyroscopes mounted orthogonally (at right angles to one another) in a box that is rigidly attached to the ballbot body [*see box on opposite page*]. These gyroscopes contain no rotating masses. Each gyroscope features a light source, a detector and a coil of optical fiber. Light waves travel around the coil in opposite directions and interfere with one another at the detector. During operation, the ballbot body, with its three gyroscopic, angular-motion sensors, rotates in various directions, but the light waves inside them travel at a fixed speed regardless of any movement. Accordingly, a small path difference between the clockwise- and counterclockwise-propagating waves results in each sensor. In each case, the path difference causes the interference fringes at the detector to shift, producing an output that is proportional to angular velocity, an effect noted by French physicist Georges Sagnac as far back as 1913. A small computer integrates the three angular velocities to produce pitch (forward/backward tilt), roll (left/right tilt) and yaw (rotation around the vertical) angles taken by the robot’s body.

To report the correct vertical orientation, all gyroscopes must take into account the earth’s rotation. They are also subject to numerous other small effects that cause errors and drift over time. Our system incorporates three MEMS accelerometers, set orthogonally in the same box alongside the gyroscopes. As the ballbot moves around, these sensors report the resulting instantaneous acceleration values for each orientation, which the computer then combines to yield an overall acceleration direction and magnitude that can be averaged over time. (The accelerometers’ readings cannot be used directly for balancing.) The outcome is a reliable long-term indicator of the direction of gravity that the system uses to correct the drift of the fiber-optic gyroscopes.

Moving with the Ball

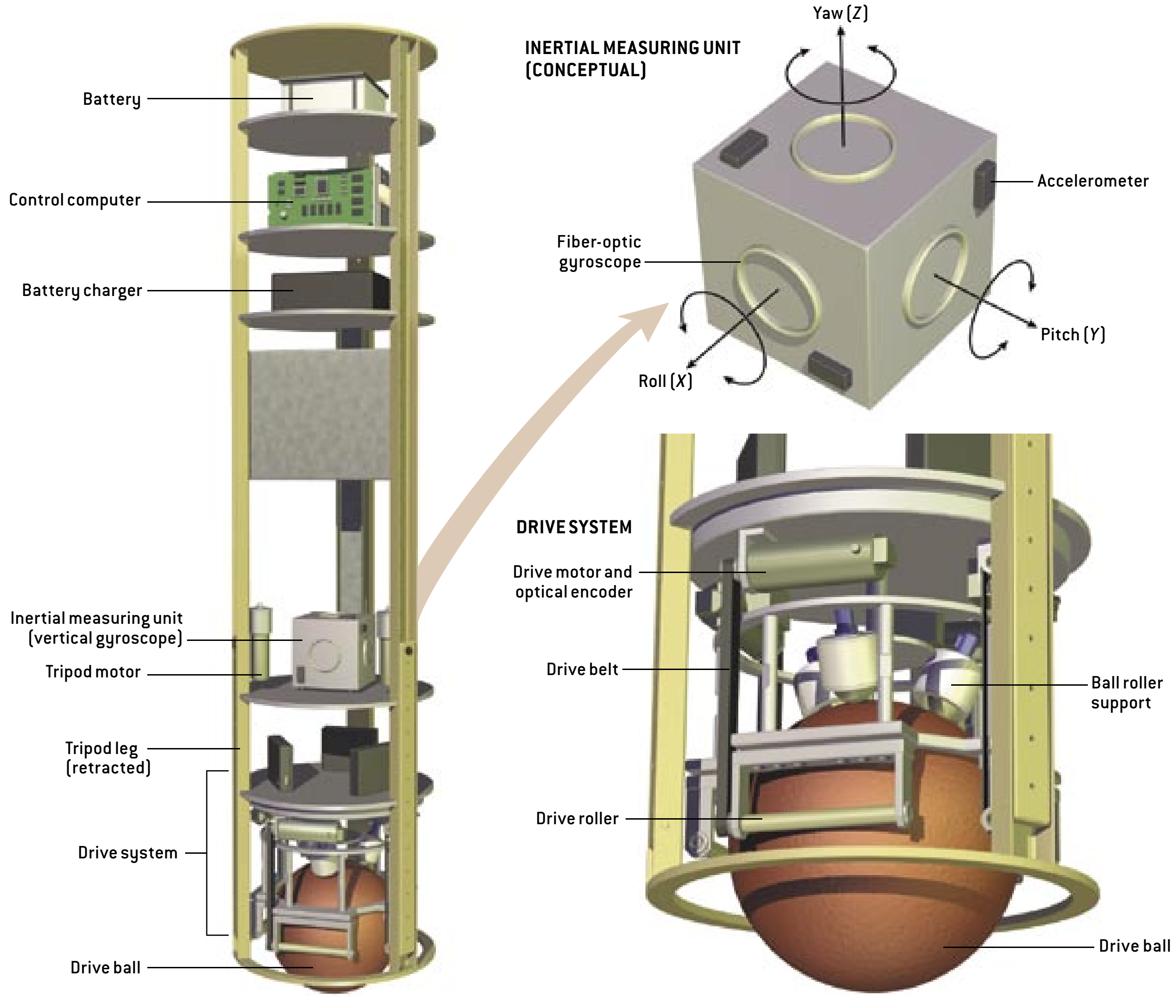
SEVERAL METHODS EXIST for driving a ball in various directions using motors. We strove for simplicity in our design for the ballbot’s drive mechanism. When one moves a mechanical comput-

Overview/*Mobile Robots*

- To interact with people in their everyday environments, intelligent mobile robots will need to stand tall, as well as to move surely and gracefully.
- Most current experimental mobile robots feature wide wheelbases, which hinder their movements through cramped, chaotic human settings.
- A ballbot—a tall, thin robot that travels about on a ball-shaped wheel that enables it to move rapidly in any direction—may provide the flexible locomotive capabilities that future robots will need to aid people in their daily lives.

BALLBOT ARCHITECTURE

In some ways, a ballbot (*left*) resembles a ballpoint pen that is five feet tall. The fiber-optic gyroscopes and accelerometers (*top right*), which are mounted at right angles to one another to sense motion in the pitch, roll and yaw directions, generate the vertical orientation data the computer control policy needs to determine how to maintain balance [*see box on next page for explanation of underlying principles*]. The drive ball mechanism (*bottom right*), which operates something like an inverse computer mouse, provides the ballbot's motive force. Motorized drive rollers turn the ball, and optical encoders measure the ballbot's travel. To stay upright when shut down, the machine deploys its tripod legs.



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er mouse about on the desktop, the rubber-coated ball on the underside causes a pair of orthogonally mounted rollers to turn. The measured rotation of the rollers provides input to the computer to traverse the cursor across the screen. Just the opposite happens in the ballbot: output from the ballbot's computer commands a set of motors to turn rollers that rotate the ball, thus causing the robot to travel in any direction along the floor. It is essentially an "inverse mouse ball" drive. Currently motors actuate the ball in the pitch and roll directions. An additional motor (not yet installed) will rotate the body in yaw, which will allow the ballbot to face in any direction.

Much as a circus clown might perch atop a ball, the ballbot's body stands atop the ball wheel. The ball is a hollow aluminum sphere covered with a thick layer of polyurethane rubber. Such a drive scheme exhibits frictional and damping behavior because sliding always occurs between the ball and rollers, for which compensation must be made. Three ball bearings between the ball and body support the body's weight.

To infer ball rotation and hence travel distance, we used optical encoders that are fitted to each of the drive motors. Each encoder has a fixed light source opposite a light detector. A transparent, rotating mask (with many fine opaque stripes) attached to the motor shaft sits between them. As the motor turns, the mask rotates, causing the striped pattern to alternately block and transmit the light beam. The ballbot's main computer counts these events to measure ball rotation and thus distance traveled.

Ball Control

SIMPLY STATED, the ballbot uses its knowledge of the vertical to determine how to rotate its ball to balance and move about. Fortunately, the ballbot is fundamentally an inverted pendulum, a mechanism that physicists have studied extensively. We use the techniques of optimal control theory to find a strategy or policy for driving the ballbot to its goal while simultaneously minimizing the effort it takes to get there. The ballbot has eight internal states that the policy must take into account: four for its forward/backward motion and four for its left/right motion. For each of these directions, the system measures or infers (from the onboard sensors) the robot's position and speed, and the tilt and tilt rate of the body.

We employ a simplified linear mathematical model to describe the ballbot's dynamics. Rudolf Kalman, a Hungarian-American mathematical system theorist, invented in 1960 an elegant method for deriving control policies for such systems, which he called the linear quadratic regulator. This approach considers the measurements of the system's internal states to be proportional to the values of the states themselves. Further, it assumes that the states change over time at a rate proportional to the values of the states plus a proportional contribution of any control actions that might occur, such as motor torques. Kalman's technique cleverly minimizes an integral function over time that includes a quadratic measure of the states plus a quadratic measure of the control actions. Its solution yields a final set of constants, which, when multiplied by each of the internal states, gives a recommended, or optimal, control action for the ballbot to take at each moment in time. These calculations run several hundred times a second in the ballbot's main computer.

When the ballbot's goal is to stand still, its control policy tries to simultaneously drive the body's position and speed as well as its tilt and tilt rate to

The Problem of the Vertical

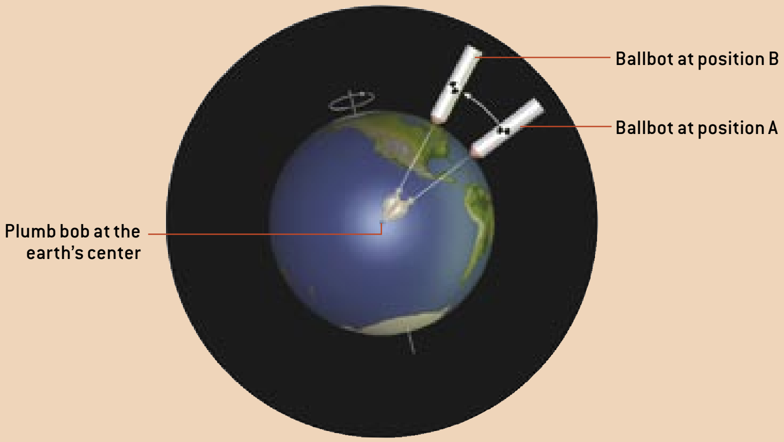
Finding the up/down orientation, what early aviators called the problem of the vertical, continues to be difficult even today. A plumb bob hanging from a string reveals the vertical, but a ballbot equipped with such a pendulum reference would become confused because motion (say, from position A to B, below) would cause the bob to swing to and fro.

Alternatively, the ballbot could rely on a gyroscope. The gyro's wheel would be supported by gimbals, which would allow its axis to point arbitrarily. By driving the wheel with a motor, it could be spun rapidly with its axis aligned vertically before the ballbot began to operate. The inertia of such a gyro would keep it pointing in the same direction regardless of movement. Equipping the gimbals with angle sensors would allow measurement of the body's forward/backward (pitch) and its left/right (roll) attitudes. This approach has problems, however. The gyro's axis would remain fixed in space while the earth rotates and hence would depart from the vertical.

German engineer Maximilian Schuler first formulated a solution to this problem in 1923 by imagining a pendulum string long enough to reach the center of the earth. Such a long string would always point downward regardless of motion. This pendulum would, in fact, have a period of about 84.4 minutes, the so-called Schuler period, which corresponds to the earth's orbital period at its surface on the equator. He showed how small torques exerted on a gyroscope could increase the period of a short, practical pendulum to 84.4 minutes (and thus make it behave like a Schuler pendulum), which would keep it oriented along the direction of gravity.

The ballbot could, in theory, use such a gyro with a short pendulum. As the ballbot moves, the directions of the pendulum's swing could be measured over time and averaged to yield a value that faithfully represented the vertical (because the lateral accelerations would cancel out over time, leaving gravity dominant). The result could be used to exert torques on the gyro to make it stay vertical.

We opted for another solution. Our ballbot uses fiber-optic gyroscopes and microelectromechanical accelerometers that together emulate the functions of a mechanical gyro and pendulum that behaves like a Schuler pendulum. The result is a gravity-seeking, or "vertical," gyro that serves as a reference for balancing. *—R.H.*



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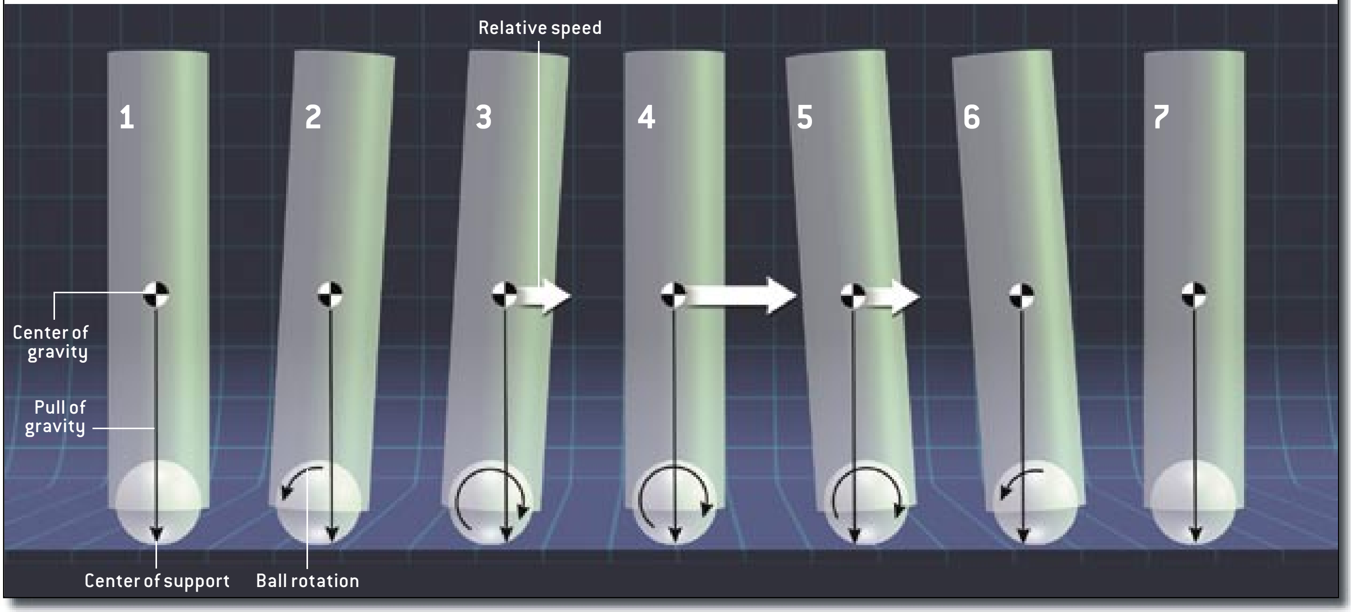
TRAVELING FROM HERE TO THERE

To maintain balance when still, the ballbot must keep its center of gravity directly over its center of support (*1*). Orientation sensors determine the vertical direction, which the machine then compares with its current attitude. During movement, the ballbot manipulates its center of gravity to best effect. To go from one point to another on level ground, for example, the drive ball first rotates slightly in the direction opposite to the intended direction of travel (*2*), which tilts the body forward a bit to initiate the move. Next, the ball spins in the direction of motion to accelerate ahead (*3*). While the ballbot is at constant velocity, the body must remain nearly vertical (*4*). The opposite actions must occur to decelerate the machine (*5*) and then prepare it to halt (*6*), which together bring it to a stop (*7*). When traversing inclines, the body must lean into slopes to keep its equilibrium.



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zero in each direction, while minimizing the actions needed to do so. When its objective is to go from one place to another, the control policy automatically institutes a retrograde ball rotation to establish a body tilt, allowing it to accelerate forward. As the goal position is approached, the ball automatically speeds up to reverse the tilt and bring the ballbot to rest [*see box above*].

Moving Ahead

WE HAVE JUST BEGUN to experiment with the ballbot, interacting with it over a wireless radio link. We plan to add a pair of arms as well as a head that pans and tilts, with a binocular vision system and many other sensors in an effort to develop the machine into a capable robot with a significant degree of autonomy. Our goals are to understand how well such robots can perform around people in everyday settings and to compare quantitatively its performance, safety and navigation abilities with those of traditional, statically stable robots. Our hypothesis is that the latter may turn out to be an evolutionary dead end when it comes to operating in such environments.

We are not alone in betting on the notion of dynamically stable robots. Other research groups have produced two-wheeled robots that are dynamically stable in the pitch direction but statically stable in the roll orientation. Although these robots are not omnidirectional like a ballbot is, they show promise for agile mobility—especially outdoors.

It may turn out that dynamically stable biped robots, perhaps in humanoid form, will have the long-term edge—particularly for their ability to deal with stairways. Research teams worldwide are working intensively to develop these complex and often expensive machines. Meanwhile it would seem that ballbots will serve as interesting and effective platforms for studying how mobile robots can interact dynamically and gracefully with humans in the places where people live. SA

MORE TO EXPLORE

For a discussion of gyroscopic principles, see **Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance.** Reprint edition. Donald MacKenzie. MIT Press, 1993.

A Dynamically Stable Single-Wheeled Mobile Robot with Inverse Mouse-Ball Drive. T. B. Lauwers, G. A. Kantor and R. L. Hollis in *Proceedings of the 2006 IEEE International Conference on Robotics and Automation (ICRA '06),* May 2006.

One Is Enough! Tom Lauwers, George Kantor and Ralph Hollis in *Robotics Research: The Twelfth International Symposium.* Springer Tracts in Advanced Robotics (in press).

Ballbot information (including demonstration videos): **www.msl.ri.cmu.edu/projects/ballbot/**

GRACE: The Social Robot: **www.palantir.swarthmore.edu/GRACE/**

Information on fiber-optic gyros: **http://leoss.feri.uni-mb.si/dip_vedran.html**

Information on the linear quadratic regulator: **http://en.wikipedia.org/wiki/Linear-quadratic_regulator**

Information on MEMS accelerometers: **www.designnews.com/article/CA294124.html**